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CELEBRATING GOVIND SWARUP'S 90TH BIRTHDAY

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Papers on all aspects of astronomical history are considered, including studies that place the evolution of astronomy in political, economic and cultural contexts. Papers on astronomical heritage may deal with historic telescopes and observatories, conservation projects (including the conversion of historic observatories into museums of astronomy), and historical or industrial archaeological investigations of astronomical sites and buildings. All papers are refereed prior to publication. There are no page charges, and *in lieu* of reprints authors are sent a pdf or Word camera-ready version of their paper so that they can generate their own reprints on demand.

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Professor Wayne Orchiston
Editor, *Journal of Astronomical History and Heritage*
523 Moo 1, Soi Ban Cholae, Mae Taeng,
Chiang Mai 50150, Thailand.

Book reviews should be sent to Dr Clifford Cunningham (Cliff.Cunningham@usq.edu.au).

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For all enquiries, email the Editor (wayne.orchiston@gmail.com).

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COVER IMAGE

This issue of *JAHH* celebrates the recent 90th birthday of the Indian radio astronomer, Govind Swarup, and the cover shows a recent portrait of Govind and one of the 45-m antennas in the Giant Metrewave Radio Telescope at Khodad, India. Professor Govind Swarup, BSc, MSc, PhD, FRS, is one of the world's foremost radio astronomers, and has made important contributions to Indian and international radio astronomy. He was responsible for the design and construction of two innovative radio telescopes, the Ooty Radio Telescope (later the Ooty Synthesis Radio Telescope) and the Giant Metrewave Radio Telescope, the largest low-frequency array in the world. Apart from inventing new radio telescopes and conducting cutting-edge research, Govind has shown an on-going commitment to education: for example, he has supervised 23 doctoral students, and he helped set up the Khodad Rural Science Center. For further information about the life and scientific achievements of this remarkable man, 'The Father of Indian Radio Astronomy', refer to the paper by Wayne Orchiston and Sudhir Phakatkar on pages 3–44 in this issue of *JAHH*.

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CONTENTS

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EDITORIAL

Dear Colleagues,

Without doubt, the most important news is that *JAHH* now has a new website, which you can visit at www.jahh.org. This site includes guidelines for paper submission (which now is all electronic), our ethics and malpractice statement, the Editorial Board, and of course access to all back issues. For the time being, back issues will remain on the NARIT website until they have all been transferred to the new site (and of course you can continue to access them through the ADS web site). We have details about impact factors, and *JAHH* is now being reviewed by Scopus for inclusion in their databases with a new standardised metric. During its history, the journal has moved from institution to institution in Australia and Thailand. The new site provides a permanent, central home for *JAHH* with an easy to remember URL, regardless of which institution might host it in the future. We are extremely grateful to Associate Editor Dr Duane Hamacher for developing and financing the new site. He has launched a GoFundMe campaign, which has already raised $303.64. Duane will put this into a fund for *JAHH*. You can contact us at jahh.editor@gmail.com.

In another key development, *JAHH* now maintains a social media profile on Facebook (https://www.facebook.com/AstronomyHeritage/) and Twitter (https://twitter.com/AstroHeritage). We are indebted to Irma Valladares for all the hard work she has put into achieving this. Irma manages the Facebook page and makes daily posts, which are widely shared and liked. The page now has about 500 followers. We also thank Mel Miles for her work in managing the *JAHH* Twitter account in 2018; soon this also will be managed by Irma. We invite those of you on Facebook and Twitter to like and follow ours pages!

After the personal traumas of 2018 it was pleasing to enter a new *JAHH* year on a positive note. This is best reflected in the size of this issue of *JAHH*: almost 200 pages. Having the time, energy and right frame of mind to assemble *JAHH* made this possible, but there also were those surplus papers from last year that we were unable to include in the December 2018 issue. Here they all are, along with a number of other contributions. And so we have 12 papers in this issue of *JAHH*—a new record—although the number of books reviews is markedly down on the record number included in the December 2018 issue.

Readers will note that we have decided to introduce two new concepts, both of which are on display in this issue of *JAHH*. Firstly, sometimes we will lead off an issue with a biography review of a notable astronomer, when possible published close to a notable birthday, and secondly, from time to time we will publish previously-unpublished important—or at very least interesting—astronomical manuscripts.

On this occasion our chosen 'Birthday Boy' is Professor Govind Swarup, who conveniently turned 90 on 23 March, not long before this issue of *JAHH* was due to be 'published'. Govind is arguable India's leading astronomer, and he is also one of the world's foremost radio astronomers. Although I have known him for decades and we have worked together on international committees and on historical research projects, I found that examining his major achievements and then presenting them all together in the one review paper was inspirational. But I could not prepare such a paper by myself, which is why there is a co-author, Sudhir Phakatkar. who has worked with Govind day-in day-out at the National Centre for Radio Astrophysics in Pune and can provide a personal local perspective. We hope that you also enjoy reading about Govind's lifetime contribution to Indian and international radio astronomy, and even if your own research field is not radio astronomy that our paper will still provide you with ample food for thought. As the opportunity arises, we look forward to including more of these biographical reviews.

As indicated above, the second innovation is the publication of selected astronomical MSS. The MS that we publish here is an account of the Great Comet of 1807 (C/1807 R1) that was written by the Acting Astronomer of Madras Observatory, and was sent by him to the Royal Astronomical Society. Professor Ramesh Kapoor came upon this MS in the course of a long-term project about Indian cometary astronomy and approached *JAHH* with a view to publishing it (subject to RAS approval). We thought this was a good idea.

The fact that Govind Swarup is an Indian astronomer and that the 1807 Comet MS also relates to Indian astronomy is co-incidental, but by publishing these papers in *JAHH*, along with two papers on Indian cometary astronomy (by Ramesh Kapoor) *and* a paper on Indian ethnoastronomy (by Ganesh Halkare and colleagues), this merely reinforces the key role that India has played—and continues to play—in the history of astronomy. This meshes well with *JAHH's* policy of documenting the history of astronomy world-wide rather than focussing only on key developments in Britain, Europe and North America.

We also aim to make *JAHH* a major publication outlet for papers on the history of radio astronomy, and ethnoastronomy, which is partly why two of the four Associate Editors (Drs James Lequeux and Peter Robertson) are experts in this field, while another Associate Editor, Dr Duane Hamacher, is an authority on ethnoastronomy. Meanwhile, happily my own research includes both fields.

Finally, I join the Associate Editors (Drs Clifford Cunningham, Duane Hamacher, James Lequeux and Peter Robertson) in welcoming you to the first issue of *JAHH* in 2019. We hope you enjoy reading the papers herein, and that you like the new format of the journal (with reversed print for headings and Abstracts and different shades of blue for colour masks).

Professor Wayne Orchiston
Editor

A TRIBUTE TO PROFESSOR GOVIND SWARUP, FRS.: THE FATHER OF INDIAN RADIO ASTRONOMY

Wayne Orchiston
National Astronomical Research Institute of Thailand, 260 Moo 4, T. Donkaew, A. Maerim, Chiang Mai 50180, Thailand, and Centre for Astrophysics, University of Southern Queensland, Toowoomba, Queensland 4350, Australia.
Email: wayne.orchiston@gmail.com

and

Sudhir Phakatkar
National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune University Campus, Pune 411007, India.
Email: sudhir@gmrt.ncra.tifr.res.in

Abstract: In this paper we pay a tribute to the 'Father of Indian Radio Astronomy', Professor Govind Swarup, BSc, MSc, PhD, FRS, by celebrating his 90th Birthday (which occurred on 23 March 2019) and recounting his remarkable scientific achievements in three disparate regions of the globe: the Indian Subcontinent, Australia and the United States of America.

Between 1953 and 1955 Govind served what was effectively an 'apprenticeship' in radio astronomy while on a Colombo Plan Fellowship at the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics in Sydney, Australia. After a short time back in India, he moved to Harvard University's Fort Davis Radio Astronomy field station in Texas, USA, and one year later, in September 1957, began a PhD in radio astronomy under the guidance of Professor Ron Bracewell at Stanford University.

Soon after completing his doctorate and accepting a faculty position at Stanford, Govind and Bina Swarup returned to India so that Govind could launch a radio astronomy program at the Tata Institute of Fundamental Research in what was then still known as Bombay (present-day Mumbai). In 1963 this led to the construction at Kalyan, near Bombay, of India's first radio telescope, an array of 32 six-feet (1.8-m) diameter parabolic dishes that served as a 610 MHz solar grating interferometer. This innovative T-shaped radio telescope was a rebadged version of the 1420 MHz East-West solar grating array that was designed by Dr W.N. (Chris) Christiansen and erected at the Potts Hill field station in Sydney in 1952. But it had a special place in Govind's heart because back in 1955 he and fellow Colombo Plan student, R. Parthasarathy, had reconfigured this as a 500 MHz grating array and used it to search for evidence of solar limb brightening.

Govind's next radio telescope was a solely Indian affair and an ingenious concept that took full advantage of southern India's geographical location near the Equator. The Ooty Radio Telescope was built between 1965 and 1970 and comprised a N-S oriented 530-m × 30-m parabolic cylinder that was located on a hill with the same slope as the latitude of the site, i.e. 11°. This *de facto* 'equatorial mounting' meant that radio sources could be tracked continuously for 9.5 hours every day. The Ooty Radio Telescope was used mainly to measure the positions and angular sizes of faint radio galaxies and quasars.

After abortive attempts to erect a Giant Equatorial Radio Telescope (GERT) of similar design, first in Kenya and then in Indonesia, in 1984 Govind conceived the idea of constructing a low frequency synthesis radio telescope in India. During the 1990s this emerged as the Giant Metrewave Radio Telescope (GMRT) near Pune, an array of 30 45-m diameter fully-steerable parabolic dishes that has been used over the past two decades by Indian and overseas radio astronomers to investigate a variety of discrete sources at decimetre and metre wavelengths.

In March 2019 the National Centre for Radioastrophysics, held an international conference in Pune to celebrate Govind's 90th Birthday and the recent major upgrade of the GMRT. Govind, you truly are the 'Father of Indian Radio Astronomy', and with affection and profound admiration for all that you have achieved in a lifetime devoted to radio astronomy we offer you this paper as an additional—if slightly belated—birthday present.

Keywords: History of radio astronomy, India, Govind Swarup, CSIRO Division of Radiophysics, Stanford, Tata Institute of Fundamental Research, Dr Homi Bhabha, radio telescopes, Kalyan Array, Ooty Radio Telescope, Giant Equatorial Radio Telescope, Giant Metrewave Radio Telescope

1 INTRODUCTION

Radio astronomy was born in 1931 when Karl Guthe Jansky (1905–1950) serendipitously discovered radio emission from our Galaxy (see Sullivan, 1984), but only blossomed after World War II (WWII) when nations like Australia, Canada, England, France, Germany, Japan, the Netherlands, Russia and the USA for the most part took advantage of WWII radar developments and applied them to peace-time research (Sullivan, 2009). In the process a new science was born, one that initially was viewed with suspicion by many optical astronomers (e.g. see Jarrell, 2005). Indeed, it is slightly misleading to refer to the earliest developments as 'radio astronomy' because this term was only coined

Figure 1: Professor Govind Swarup (RAIA).

(by Joe Pawsey) in 1948. Before this, the focus was on cosmic or solar 'noise' and cosmic or solar 'static' (Sullivan, 2009).

Figure 2: Indian localities mentioned in this paper (map: Govind Swarup and Wayne Orchiston).

Figure 3: Govind's father, Ram Raghuvir Saran, and his mother, Gunvavati Devi (courtesy: Govind Swarup).

In 2003 the first author of this paper launched the IAU Historic Radio Astronomy Working Group, one of the aims of which was to tap into the memories, photographs, letters and other records maintained by the international pioneers of radio astronomy, while many of them were still alive. Working Group members were particularly active in the Greater Asian region where New Zealand and Australia both began radio astronomical research in 1945, followed by Japan in 1948 (see Orchiston, 2017b; Orchiston and Ishiguro, 2017; Orchiston and Slee, 2017). In the early 1960s two other Asian nations, China and India, joined the radio astronomy 'club'. This paper is about the remarkable achievements of Professor Govind Swarup (Figure 1), one of radio astronomy's pioneers, and the 'Father of Indian Radio Astronomy' (see Swarup, 2014; 2017).

2 GOVIND SWARUP'S EARLY YEARS

Govind Swarup was born on 23 March 1929 in Thakurdwara, a small town in the Moradabad district of Uttar Pradesh (Figure 2) and was influenced in his early years by his grandfather and his parents. His grandfather Brijpal Saran was a landlord, owned a textile mill, and lived in a mansion. In 1895 he had graduated in philosophy from Allahabad University, and was fluent in Persian and English.

Govind's father was Ram Raghuvir Saran (Figure 3), who established the first theatre in Delhi, the capital of India. He also started a motor car garage, and purchased land for farming. Govind's mother was Gunvavati Devi (Figure 3), a housewife, who subscribed to an Indian magazine and encouraged Govind to read.

During his childhood Govind used to go to school with his brothers, but sometimes he was also taught at home by his grandfather. When Govind was 12 years of age the family moved to Moradabad, and while he was living there Govind

> … occasionally rode an elephant to school; the elephant was bought by his father to go to the farm during the wet season, but whenever there was no work for the elephant, it was available for Govind. (Phakatkar, 2015; our English translation).

Govind's personality began to develop while he was at Coronation Hindu High School in Moradabad, and this is where he learnt English. In 1944 he matriculated with distinction, and then went to Ewing Christian College in Allahabad (Figure 4) for his intermediate college studies. These were unforgettable years. He learnt to swim at the confluence of the Ganges and Jamuna Rivers—a talent that would come in handy later at Potts Hill reservoir in Sydney. He saw first-hand the dreadful effects of drought as he watched people from the State of Bengal migrating to Allahabad. And he became secretary of the College's Physics Club, and was the one who invited Professor K.S. Krishnan to deliver a lecture at the College. Little did Govind realize at the time that this famous scientist and co-discoverer of Raman Scattering would later attend to his first year university training and then employ him at the National Physical Laboratory in New Delhi, thereby opening the way for him to create an illustrious career in radio astronomy.

After Govind completed his College education his mother wanted him to study engineering in Benares (Varanasi) because her brother was already studying there (Phakatkar, 2015), but Govind had other ideas: he rolled for a BSc at Allahabad University (Figure 5), graduating in physics in 1948. In his first year at the University (1946) he learnt electricity and magnetism from Professor K.S. Krishnan (1898–1962), who later that same year would be knighted and become Sir Kariamanickam Srinivasa Krishnan, and in 1947 would accept the inaugural Directorship of the Physical Research Laboratory in New Delhi.

During his undergraduate years Govind witnessed great change in Indian society. This was a transition period as India struggled to gain its independence from British rule. Govind subscribed to *Harijan* (a weekly journal published by the visionary leader Mahatma Gandhi) and he greatly admired Gandi.

In 1949, when he was enrolled for an MSc in physics at Allahabad University, the 36th Indian Science Congress was held in Allahabad. One of those who attended was the legendary Indian physicist Professor C.V Raman (1888–1970), co-discoverer of Raman Scattering, for which he received the Nobel Prize for Physics in 1930. Govind suggested to his friends that they invite Professor Raman to their hostel for an evening lecture, followed by dinner. Professor Raman agreed, but on the condition that all of the physics students attended his lecture. After the lecture and dinner Professor Raman spent three hours with the students discussing the future development of science and technology in India. As he left the hostel Professor Raman reminded the students of Thomas Edison's famous quote: "Genius is one percent inspiration and ninety nine percent perspiration".

Another famous personality who attended the Allahabad Congress was the British mathematician and geophysicist Professor Sydney Chapman (1888–1970). Govind showed him some of the historical highlights of the city and afterwards Professor Chapman told Govind and his friends:

> India is now an independent nation and from now on new opportunities and challenges will arise. Concentrate on new and innovative concepts in science and technology. (cited in Phakatkar, 2015; our English translation).

Figure 4: The main building at Ewing Christian College in Allahabad (https://www.stalkram.com/media/1866207356117834317_4631851150).

Figure 5: The main historic building at Allahabad University (https://www.indiatoday.in/education-today/government-jobs/story/allahabad-university-invites-application-to-fill-550-vacancies-check-how-to-apply-1478507-2019-03-15).

Figure 6: The National Physical Laboratory in New Delhi (after Phakatkar, 2015).

Govind recounts that

> After obtaining an M.Sc. degree in Physics from Allahabad University (India) in 1950, I joined the National Physical Laboratory (NPL) of the Council of Scientific and Industrial Research (CSIR) in New Delhi [see Figure 6], and worked in the field of paramagnetic resonance under the guidance of K.S. Krishnan … the Director of the Laboratory … he asked me to develop equipment that could be used to investigate the phenomena of electronic paramagnetic resonance at a wavelength of 3 cm. Over the next eighteen months, I was able to set up equipment by cannibalizing surplus radar sets procured by the NPL, and by studying parts of the remarkable set of twenty eight volumes of the Radiation Laboratory Series that described almost all the radar techniques that were developed during World War II. (Swarup, 2006: 21–22).

As it turned out Govind's future research direction was determined in August 1952 when Dr Krishnan was one of three Indian scientists who attended the Tenth General Assembly of the International Radio Scientific Union (URSI) in Sydney, Australia (Goss, 2014). This was the first time that an URSI General Assembly was held outside of Europe or North America, and Australia was selected because of its long and distinguished research tradition in atmospheric physics and by Australia's rapid emergence as arguably the world's leading nation involved in the new post-war field of radio astronomy (Robinson, 2002).

The 1952 URSI General Assembly ran from 8 to 22 August and was attended by 63 overseas delegates from 13 countries and a large number of Australian scientists. "This large and representative gathering ensured a very successful meeting." (Kerr, 1953: 59). About one-third of the overseas contingent were radio astronomers, and

> At last the RP staff could associate faces with names like Jean-Louis Steinberg from France, Robert Hanbury Brown from Jodrell Bank, F. Graham Smith from Cambridge, C. Alexander Muller from Holland and H.I. 'Doc' Ewen from the United States. (Sullivan, 2017: 483).

Among the Australian radio astronomers was John Bolton, leader of the galactic radio astronomy group based at Dover Heights, and he reported that

> Commission V (Radio Astronomy) was well represented at the conference, as members of all the major research organizations engaged in the field attended. Four formal sessions were held on Radio Astronomy –"The Sun", "Dynamics of Ionized Media", "Interstellar Hydrogen" and "The Discrete Sources". (Bolton, 1953: 23).

Apart from the paper sessions, during the Radio Astronomy business meetings, there were discussions about solar observations, instrumentation, nomenclature and frequency preservation, and the conference also included

> … official visits to two of the Radiophysics Laboratory's field stations—at Dapto on the South Coast where a spectrum analyser operating over a wavelength range of nearly ten to one is installed to observe solar noise bursts; and to Potts Hill where the remainder of the solar work is carried out and where new Hydrogen line equipment is being set up. Private visits were made to the other stations engaged on galactic work. (Bolton, 1953: 26).

Dr Krishnan attended some (if not most) of the Radio Astronomy sessions and went on the two field trips, and

> … he was struck by the dramatic and remarkable discoveries being made in the field of radio astronomy by staff from the CSIRO's Division of Radiophysics (RP). Under the inspired leadership of J.L. Pawsey … several ingenious radio telescopes had been developed by the Australian scientists to investigate radio emission from the Sun and distant cosmic sources in our Galaxy … (Swarup, 2006: 22).

When he returned to the National Physical Laboratory, Krishnan described these developments in a colloquium that Govind attended, and he reports that the Australian research also

> … caught my imagination. I then visited the NPL library, where I studied some of the thirty papers that had been published by the RP scientists in the *Australian Journal of Scientific Research* and in *Nature* describing these discoveries. I was told that these were almost half of the papers on radio astronomy that had been published worldwide up to that time. I, too, was fascinated by this new field. (ibid.).

Krishnan wanted to launch a radio astronomy research program at the NPL but there were no scientists in India with the necessary knowledge and experience, so he suggested that Govind spend a two year 'apprenticeship' working at the Division of Radiophysics in Sydney. Govind agreed to this attractive proposal, the application for a Colombo Plan Fellowship was successful, and soon Govind was on his way to Sydney. The rest … as they say … is history!

3 THE AUSTRALIAN 'APPRENTICESHIP'

In March 1953 Govind, and R. Parthasarathy from Kodaikanal Observatory in southern India[1] arrived in Sydney to begin their Colombo Plan Fellowships in radio astronomy.

Their host was the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics (henceforth RP), which had begun in 1939 as a secret research facility to develop radar. Understandably, this role expanded exponentially during World War II. Sullivan (2017: 453) describes how

> Australian radio astronomy has been at the forefront since its foundation during World War II, with imaginative scientists and engineers, innovative equipment, and strong sponsorship. Soon after War's end a multi-faceted program, by far the largest of its kind in the world, was well established at the Radiophysics Laboratory (RP) in Sydney and continually producing pioneering results. The Australians developed fundamental methods of interferometry, discovered the Sun's hot corona, pinpointed the location of solar bursts, and discovered numerous discrete radio sources.

The inspirational radio astronomy program was led by Dr Joe Pawsey (Figure 7). Joseph Lade Pawsey was born in 1908 in Ararat, Victoria (see Figure 8 for Australian localities mentioned in the text), and after excelling at secondary school he entered the University of Melbourne where he obtained BSc and MSc degrees. He then was awarded an Exhibition Research Scholarship and went to Cambridge where he carried out ionospheric research under J.A. Ratcliffe, graduating with a PhD in 1931. Then he stayed in England and worked on technical side of television before returning to

Figure 7: Dr J.L. Pawsey, leader of the radio astronomy group within the CSIRO's Division of Radiophysics (CSIRO Radio Astronomy Image Archive (henceforth RAIA) 7454-2).

Australia in 1940 and joining PR. There his back-ground in antennas and transmission lines proved useful for radar research, and later when radio astronomy was selected as one of the major post-war research fields of the Division. Joe Pawsey would go on to build an internation-al reputation in radio astronomy (Lovell, 1964), but he died from a brain tumor in 1962—he was only 53 years of age.

Whereas WWII radar research facilities in most other nations were disbanded after the war, Australia was able to retain RP because

> At this time, RP was CSIR's glamour Divis-ion, arguably containing within its walls the densest concentration of technical talent on the continent, and CSIR[2] was eager to keep this 'winner' intact. (Sullivan, 2017: 456).

Moreover,

> RP's assets included not only its scientists and engineers, but also its significant support staff of technicians, a camaraderie molded during the War, ample laboratory space and workshops, and bulging stores with the latest radio electronics. This last was considerably augmented shortly after the War's end by an extraordinary bonanza. A large amount of American and British equipment (including whole aircraft!) was being discarded by loading it on the decks of aircraft carriers, taking it a few miles off-shore, and bulldozing it into the sea. Bowen got wind of this, however, and for two or three weeks was allowed to take RP trucks down to the Sydney docks and load them up with radar and communications equipment, often in unopened original crates. For sev-eral years thereafter RP researchers drew on this surfeit. (ibid.).[3]

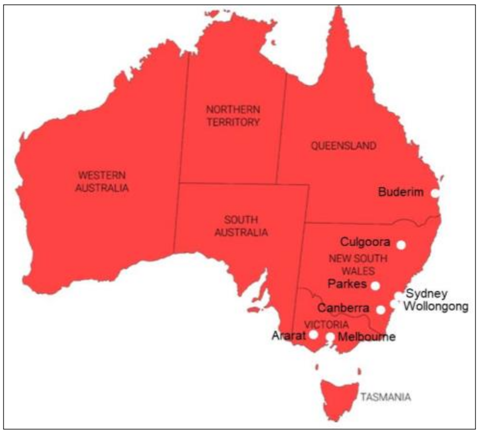

Figure 8: Australian localities mentioned in this paper (map: Wayne Orchiston).

RPs immediate post-war accomplishments in radio astronomy grew from the strong found-ation laid by radar research during the war, but almost all of the scientific staff had radio eng-ineering qualifications and employment back-grounds, and it would take time for them to come to terms with the astronomical nature of their new preoccupations.[4] Indeed, the term 'radio astronomy' was only adopted in 1948 after being introduced by Joe Pawsey.

The RP headquarters were located in the grounds of the University of Sydney, but much of the research took place at field stations scat-tered around Sydney, and in the case of the afore-mentioned Dapto, near the southern city of Wollongong. By February 1953 (when Govind arrived in Sydney) there were five functioning field stations, and their locations are shown in Figure 9, and the main research programs and their team leaders are listed in Table 1. While Dover Heights (number 3 in Figure 9) was a former WWII radar station, all the other field stations were purpose-built for radio astronomy at suitable radio-quiet locations (for a summary of each field see Orchiston and Slee, 2017; Robertson, 1992).

Each field station was home to one or occ-asionally more small close-knit research teams —generally of 2–4 individuals—who planned, built and maintained their own radio telescopes that were designed to address specific research problems. The field stations brought back fond memories for those who were lucky enough to experience them. Thus, the first author of this paper used to work at Fleurs field station in the early 1960s, before it was handed over to the University of Sydney, and he reminisces:

> … those of us lucky enough to have lived through this era remember the field stations with genuine affection. There was a freedom not experienced by those back at the 'Lab' (as the Radiophysics Laboratory was known): the pervading sunshine, the clean fresh air, those incident-packed return trips from home to field station by Commonwealth car, and the sense that we were somehow making history. There were also snakes to contend with, wet days when antennas still had to be aligned and observations made, floods that had to be negotiated, and those times—fortunately they were few and far between—when vehicles became bogged and had to be rescued by a co-operative local farmer …

Slide rules were the norm and computers but a future dream. Signal generators, not sources, provided calibrations, and results were displayed in real time on Esterline Angus and other all-too-familiar chart recorders. These were pioneering days. (Orchiston and Slee, 2017: 498–499).

This was the scientific and cultural milieu within which Govind would be immersed for the next two years.

From the start, Pawsey decided that Govind

… would work for three months each in the groups led by W.N. Christiansen, J.P. Wild, B.Y. Mills and J.G. Bolton … [who] had made important discoveries, and … were already acknowledged world leaders in their respective fields. I was to report back to Pawsey every two weeks. S.F. Smerd, a very pleasant man but a tough task master, was asked to coordinate my activities and to provide me with guidance on the rapidly-growing literature in radio astronomy… Then, after the first year, Parthasarathy and I would select a joint project. (Swarup, 2006: 23).

All of these RP radio astronomers are included in Figure 10, which was taken during the 1952 URSI meeting

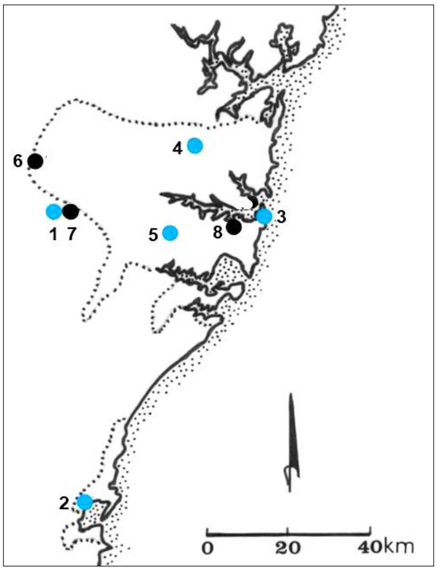

Figure 9: The location of the Radiophysics Laboratory (8) and the RP field stations that existed in 1953 (shown in blue), with the approximate boundaries of present-day greater Sydney and greater Wollongong shown by the dotted lines. Key: 1 = Badgerys Creek, 2 = Dapto, 3 = Dover Heights, 4 = Hornsby Valley, 5 = Potts Hill. An earlier field station, Penrith (6), and a later field station, Fleurs (7), are also mentioned in the text and therefore are included here (map: Wayne Orchiston).

Table 1: RP field stations, research programs and team leaders in February 1953.

Field Station	Founding Year	Research Program	Team Leader	Reference(s)
Badgerys Creek	1949	Discrete sources	Mills	Frater et al. (2013; 2017); Orchiston and Slee (2017)
Dapto	1952	Solar	Wild	Stewart (2011a)
Dover Heights	1945	Discrete sources	Bolton	Orchiston and Robertson (2017); Orchiston and Slee (2002; 2017); Robertson (2017)
Hornsby Valley	1947	Discrete sources	Shain	Orchiston et al. (2015)
Potts Hill	1948	Discrete sources	Piddington	Frater et al. (2013; 2017); Orchiston and Wendt (2017); Wendt (2011b)
		Hydrogen line	Kerr	
		Solar	Christiansen	
		Prototype Mills Cross	Mills	

Figure 10: Some of the radio astronomers who attended the 1952 URSI Congress. Chris Christiansen, Paul Wild and Bernie Mills (in the dark suit) are first, third and fifth from the left respectively, and Steve Smerd is in the front row immediate to the right of Mills. John Bolton is the man on the extreme right of the group photograph. The only person absent is Joe Pawsey (RAIA 2842-43).

Meanwhile, Govind's reference to Steve Smerd being 'a tough task master' is interesting because one of the authors of this paper (WO) worked closely with him during the 1960s and never encountered this. But perhaps Steve had mellowed by this time! Stefan Friedrich Smerd (1916–1978; Figure 11), or simply Steve Smerd to all who worked with him, was born in Vienna, but when the political situation in Austria worsened in 1939 he moved to England. There he obtained BSc and DSc degrees from the University of Liverpool. For part of WWII he worked on radar at the Admiralty Signals Establishment and in 1946 he accepted a post at RP and emigrated to Australia. Working closely with Pawsey, Steve Smerd soon became the Solar Group's resident theoretician. Later Smerd would lead RP's Solar Group, before dying prematurely in 1978 during a heart operation. He was only 62 years of age (Orchiston, 2014b; Wild, 1980).

After a crash course reading up on radio astronomy, Govind spent three month at Potts Hill field station working with Chris Christiansen

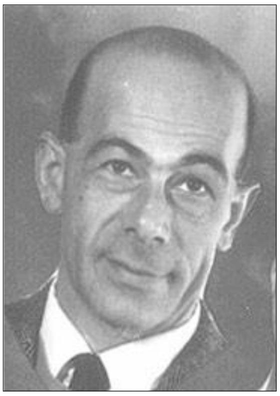

Figure 11: Steve Smerd in 1968 (adapted from an RAIA image).

and Joe Warburton. This field station was set up in 1948 beside a metropolitan water reservoir in what at that time was an outer southern suburb of Sydney (see Figure 12) and it quickly evolved into one of RP's leading field stations (see Davies, 2005; Wendt et al., 2011b). By early 1953, major radio telescopes at Potts Hill were:

Figure 12: View looking southwest across the two Potts Hill water reservoirs in 1953, showing Christiansen's solar grating arrays along the banks of the eastern reservoir. The E-W array consisted of thirty-two elements and the nearer N-S array just sixteen elements (RAIA 3475-1).

(1) An ex-WWII experimental radar antenna, used to observe discrete sources and galactic hydrogen line emission (see Orchiston and Wendt 2017).
(2) A 10-ft diameter ex-US WWII AN/TPS-3 parabolic antenna used to observe discrete sources (see Wendt and Orchiston, 2018).
(3) An E-W solar grating array that was completed in 1951 (Christiansen; 1953; Wendt et al., 2008b).
(4) A N-S solar grating array then under construction, which was completed during 1953 (ibid.).
(5) An 11-m parabolic transit dish, then under construction, which was completed in 1953 and dedicated to hydrogen line studies (ibid.).
(6) The prototype Mills Cross, completed in 1952 and used to test Mills' innovative concept of the cross-type radio telescope (see Mills and Little, 1953).

Govind was involved with the two solar grating arrays, which were the brain-child of Chris Christiansen. Wilber N. (Chris) Christiansen (Figure 13) was born in Melbourne in 1913 and was

Figure 13: W.N. (Chris) Christiansen (adapted from RAIA B2842-66).

awarded BSc, MSc and DSc degrees by the University of Melbourne. He joined RP during WWII and was involved in radar research. After the War, Christiansen played a key role in the multi-site observations of partial solar eclipses in 1948 and 1949 to pinpoint the locations of the radio-emitting regions (see Orchiston et al., 2006; Wendt et al., 2008a). He then continued with this solar focus through the construction of the E-W grating array, but these activities were interrupted when he was diverted to design and construct a hydrogen line receiver, and then use this and the ex-WWII experimental radar antenna to confirm the existence of the line (see Orchiston and Wendt, 2017). Christiansen then returned to solar work and the construction of the second (N-S) grating array at Potts Hill. Later he combined the concepts of the grating array and the Mills Cross to erect the 'Chris Cross' (Orchiston and Mathewson, 2009) at the Fleurs field station that was set up near Sydney in 1954. Christiansen was one of several leading radio astronomers who left RP in the late 1950s and early 1960s following the decision to focus all research on the Parkes Radio Telescope and Culgoora Radioheliograph and close down the field stations. This was the start of 'Big Science' at RP (see Sullivan, 2017 for details). After RP abandoned Fleurs, Chris inherited his 'Chris Cross' and converted this into the Fleurs Synthesis Telescope, which was used mainly to research discrete sources (Frater et al., 2017). Chris had an international perspective and passion and assisted many nations with their radio astronomical programs (e.g. see Wang, 2017). His book *Radio Telescopes* (Christiansen and Hogbom, 1969) followed the book by Pawsey and Bracewell, and also became a standard reference work throughout the world. Chris was Vice-President of the International Astronomical Union (1964–1970) and President of URSI (1978–1981). He was one of Australia's most famous radio astronomers, and died in 2007. For further biographical details see Frater and Goss (2011), Frater et al. (2017), Swarup (2008) and Wendt et al. (2011a).

Following RP's ambitious 1948 and 1949 solar eclipse programs, Christiansen (1984) wanted to pinpoint the location of radio-active regions in the corona without having to rely on eclipses, and in 1950 he came up with the idea of the solar grating array. The following year saw the construction of the world's first solar grating array along the southern margin of the reservoir at Potts Hill (Davies 2009; Wendt et al. 2008b):

> Designed to track the Sun at 1420 MHz, this novel radio telescope comprised 32 solid metal parabolic dishes each 1.83 m (72 in.) in diameter and spaced at 7 m intervals … (Orchiston and Slee, 2017: 523–524).

This array (see Christiansen and Warburton, 1953a) is shown in Figures 14 and 15, and it

> … provided a series of 3′ fan beams each separated by 1.7°, which meant that the Sun could only be in one beam at any one time. The array was operational from February 1952, and was used daily for ~2 h, centred on midday, to produce E-W scans of the Sun. These showed up the positions of localized active regions situated low in the solar corona and the motion of these as the Sun rotated … (Orchiston and Slee, 2017: 524–525).

For example, Figure 16 shows strip scans obtained between 26 and 30 June 1952, where one major radio plage is visible. Then, by deducting all radio plages and superimposing a succession of strip scans, Christiansen and Warburton (1953b) could determine the level of 'quiet Sun' emission at 1420 MHz (see Figure 17).

When Govind first visited Potts Hill field sta-

Figure 14: View looking west along the E-W grating array soon after it was completed (courtesy: Rod Davies).

Figure 15: Close-up, looking east, showing the E-W grating array and Chris Christiansen (RAIA B2976-1).

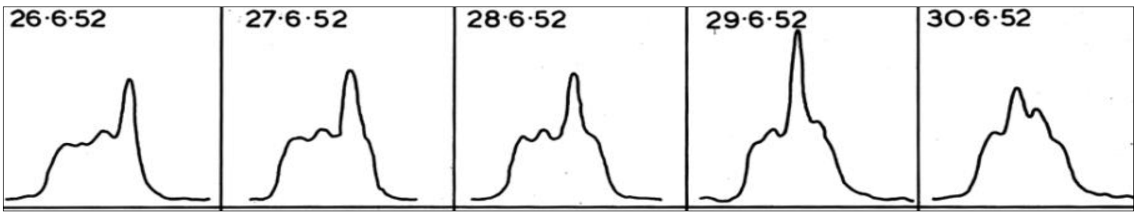

Figure 16: A series of 1420 MHz strip scans of the Sun over a 5-day period in June 1952, showing the existence and motion of a prominent radio plage (adapted from RAIA B2849-1).

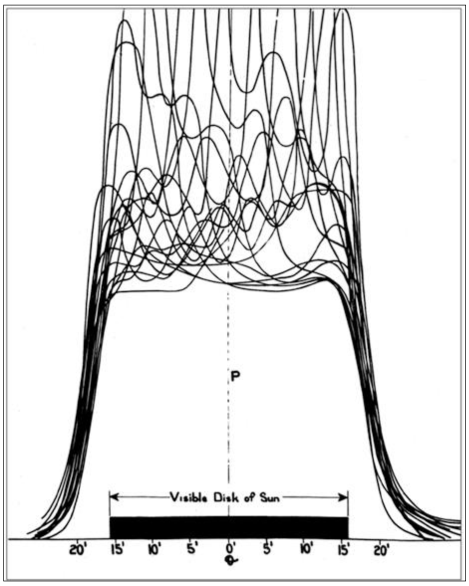

Figure 17: Twenty individual daily one-dimensional brightness distribution scans superimposed. The visual solar disk is indicated by the black bar on the x-axis (after Christiansen and Warburton, 1953a: 200).

tion a second solar grating array was under construction along the eastern margin of the reservoir. This also operated at 1420 MHz, but instead of 32 solid metal dishes there were 16 equatorially mounted 3.4-m (11-ft.) diameter mesh dishes (see Figure 18). This new array was used to obtain N-S scans of the Sun.

Govind's task at Potts Hill was to help Christiansen and Warburton

> … make a two dimensional map of the quiet Sun at a wavelength of 21cm, using strip scans obtained with the east-west and north-south grating interferometers … (Swarup, 2006: 23).

To do this,

> Using an electrical calculator, I first determined the Fourier Transform (FT) of each of the strip scans obtained at various position angles, plotted the values on a large piece of graph paper, made contour plots manually, determined manually strip scans of the two-dimensional plot at various position angles, calculated the FT of each of these and finally determined the two-dimensional distribution of 21 cm radio emission across the solar disk. Ron Bracewell described short cuts to me for faster calculation of the FTs. Nevertheless, it was a very laborious process, but thanks to Chris' gentle guidance it ultimately led to success! (Swarup, 2008: 195).

As Figure 19 illustrates, the 1420 MHz quiet Sun was non-circular, with conspicuous limb-brightening in the near-equatorial regions (Christiansen and Warburton, 1955b), as had been predicted earlier by Steve Smerd (1950), "… who assumed a higher electron density in the solar corona near the equatorial regions". (Swarup, 2008: 195). Christiansen (1976) later told Woody Sullivan that he regard this project as particularly

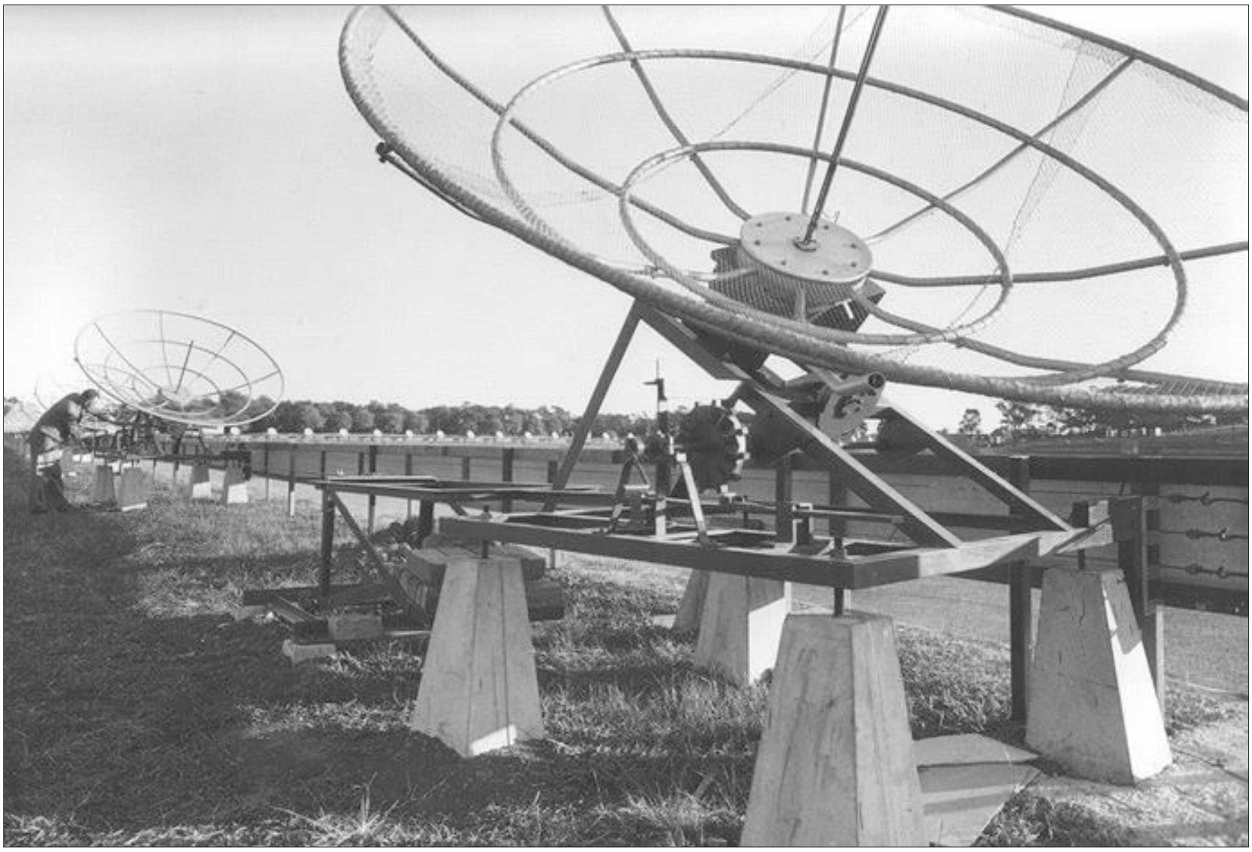

Figure 18: The second 1420 MHz solar grating array, looking south; the antennas of the first solar array are only just visible in the background as a series of small white 'dots' (RAIA 3116-1).

important, since it was the first time that the concept of Earth-rotational synthesis had been used in radio astronomy.

There is an extensive RP historic photographic archive (see Orchiston, 2001; Orchiston et al., 2004), but unfortunately this does not include any images of Govind at Potts Hill. But instead we can enjoy Figure 20, which was published in an Indian newspaper and shows Govind and Parthasarathy posing beside the ex-WWII experimental radar antenna at Potts Hill.

Govind's next 3-monthly assignment was with RP's other leading international solar authority, Paul Wild. British-born John Paul Wild (1923–2008; Figure 21) completed an abridged BA at Cambridge before joining the Royal Navy as a radar officer during WWII. This piqued an interest in radio astronomy, and in 1947 he applied successfully for a position at RP. Soon he

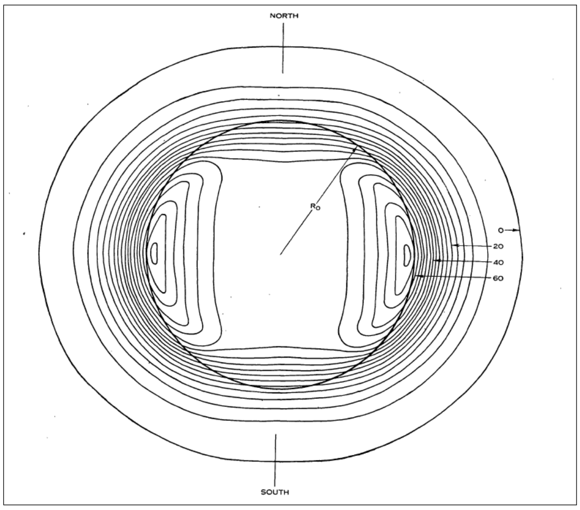

Figure 19: The two-dimensional distribution of radio brightness across the Sun at 1,420 MHz. The central brightness temperature is 4.7×10^4 K and the maximum peak temperature is 6.8×10^4 K (after Christiansen and Warburton, 1955a: 482).

was involved in Pawsey's solar program, and went on to head the Solar Group and built this into the finest team of solar radio astronomers in the world. He developed radio spectrographs at RP's Penrith and Dapto field stations, and a unique instrument, the Culgoora Radioheliograph, which gave real-time images of the movement of solar emission in the corona (McLean and Labrum, 1985). In 1971 Wild took over as Chief of the Division. Then for a time he was Chairman of the CSIRO in the nation's capital, Canberra, before dying in 2008. Back in 2011 Stewart, Orchiston and Slee—who all knew and worked with Paul Wild at RP—wrote:

> His legacy includes amongst other things a list of impressive publications and inventions which established Australia at the forefront of solar radio astronomy from 1949 to 1984, a period that spanned four cycles of solar activity …

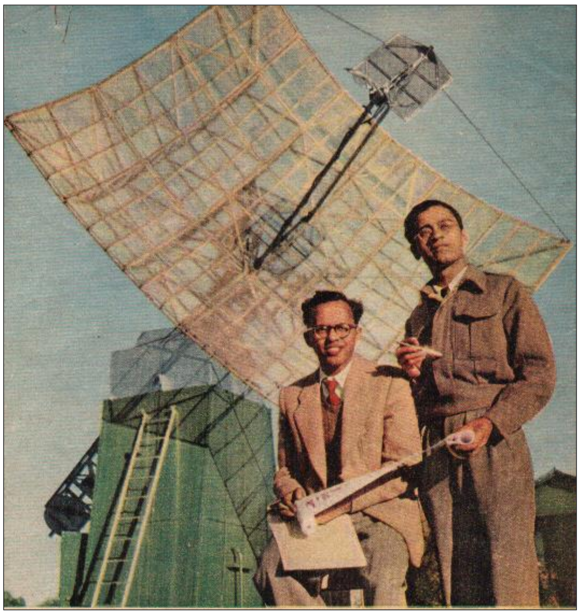

Figure 20: Govind Swarup (left) and R. Parthasarathy (right) at Potts Hill field station in 1954. At the time, this 16 × 18 ft ex-radar antenna was being used to map the distribution of neutral hydrogen in our Galaxy (after *Illustrated Weekly Times of India*, 1954).

> We will always remember how he could light up a room with his wit, intelligence and charm. He loved a party and a few beers, and would amuse the audience with his impressions of Churchill and Hitler at parties … (Stewart et al., 2011b: 539).

For further details of Wild's career and research see Frater and Ekers (2012), Frater et al. (2017); and Stewart et al. (2011a; 2011b).

When Paul Wild joined RP, the analysis of solar bursts was constrained by single-frequency observations. What Wild and his RP colleague Lindsay McCready (1910–1976) did was build the world's first dynamic spectrograph that recorded solar emission over the frequency range of 70–130 MHz, and in 1949 install this at a new PR field station at Penrith, 50 km west of Sydney (see Figure 22). The results were stunning: after just five months observing they were able to identify three very different types of solar bursts. Wild and McCready (1950) named these Types

Figure 21: Paul Wild in 1952 (adapted from a RAIS image).

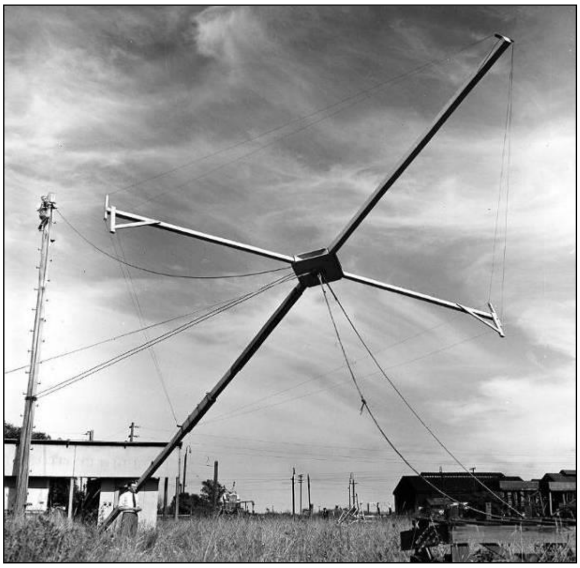

Figure 22: The rhombic aerial of the world's first radio spectrograph, at RP's Penrith field station (RAIA).

I, II and III, and this simple nomenclature was quickly adopted world-wide (Stewart et al., 2010) and became the foundation that then led to the discovery of other types of solar bursts (as Govind knows only too well—but more of this anon).

The challenge then for Wild and his group was to find a new larger radio-quiet site where they could set up further radio spectrographs (and eventually a swept-frequency polarimeter and a swept-frequency position interferometer). After an intensive search they located a suitable site down near Wollongong, to the south of Sydney (see Figure 5), and by the time Govind joined RP three radio spectrographs had been installed. These covered the frequency ranges 40–75, 75–140 and 140–240 MHz, and used crossed rhombic antennas (Figure 23) so that the polarisation of the bursts could be investigated (Stewart et al., 2011a).

But apart from solar bursts, Wild (1953) also was interested in scintillations, and he explains why:

> Although the main long-term programme of work at Dapto is concerned with the sun, it has seemed desirable to find a supplementary line of research to enable the equipment to be put to maximum use during the sunspot minimum. With this in view, exploratory observations of the spectrum of Cygnus fluctuations in the frequency range 40–70 Mc/s have been carried out since September 1952.

The fact that the Cygnus A discrete source showed conspicuous intensity fluctuations that were caused by ionospheric or interplanetary scintillations was well known (e.g. see Stanley and Slee, 1950). At Dapto, three spaced aerials were used to investigate these, and Govind's Dapto project was to work with J.A. (Jim) Roberts (b. 1929) and develop a 45 MHz receiver once it was established that this would be preferable to observing over the full 40–70 MHz fre-

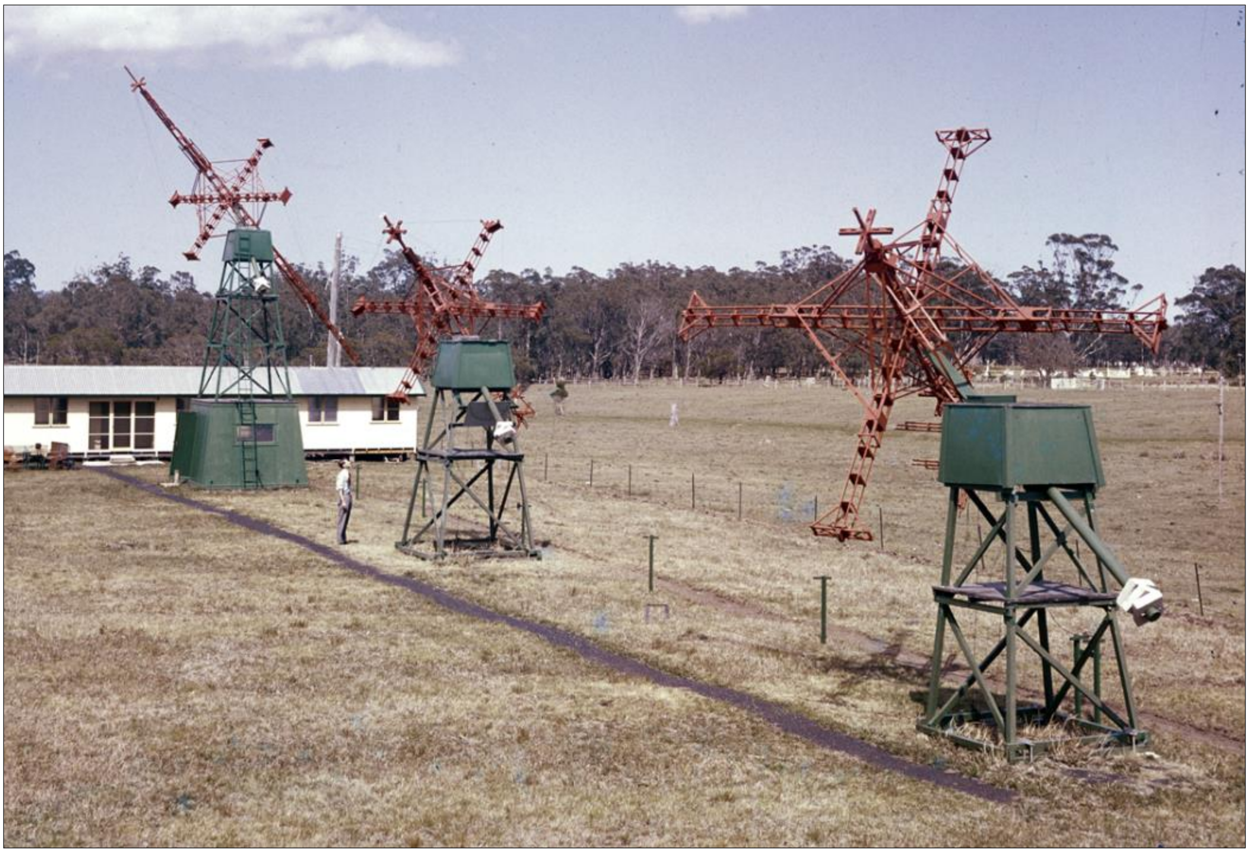

Figure 23: The Dapto field station, showing the three crossed-rhombic antennas and associated buildings (RAIA 12429-1).

quency range (Stewart et al., 2011a). Subsequently, Wild and Roberts (1956a; 1956b) published two papers based on observations made with the 45 MHz receiver.

So Govind's second RP project was about ionospheric research and had nothing to do with solar bursts, but it did give him experience that would prove useful later: designing and constructing a receiver.

After this, Govind returned to the all-too-familiar Potts Hill field station and spent three months working with Bernie Mills and Alec Little who were busy constructing a new radio telescope of novel design.

Bernard Yarnton (Bernie) Mills (Figure 24) is another great Australian name in international radio astronomy (Frater et al., 2013; 2017). Born in Sydney in 1920 and dux of Kings School, he completed a Bachelor of Engineering degree in December 1942 and began working at RP on radar. After the war he was involved in RP's new digital computer before joining Pawsey's radio astronomy group in 1948. His first project was to participate in the 1 November 1948 solar eclipse program, resulting in his first radio astronomy publication, but "… it also was to be his sole foray into solar radio astronomy." (Orchiston, 2014a: 1482). Mills' greatest achievement was to provide one solution to the resolution problem

Figure 24: Bernard Yarnton (Bernie) Mills (adapted from an RAIA image).

plaguing early radio astronomy by inventing the cross type radio telescope (see Mills, 1963), an

> … antenna in the form of a symmetrical cross, where the outputs from the two orthogonal arms were combined electrically so that only the signal received in the overlapping region of the two fan beams was recorded. (Orchiston, 2014a: 1483).

This novel design provided the same resolution as an equivalent circular parabola with a diameter equal to the length of the arms of the cross. To test out the concept Mills and Little constructed a prototype at Potts Hill (see Figure 25) consisting of

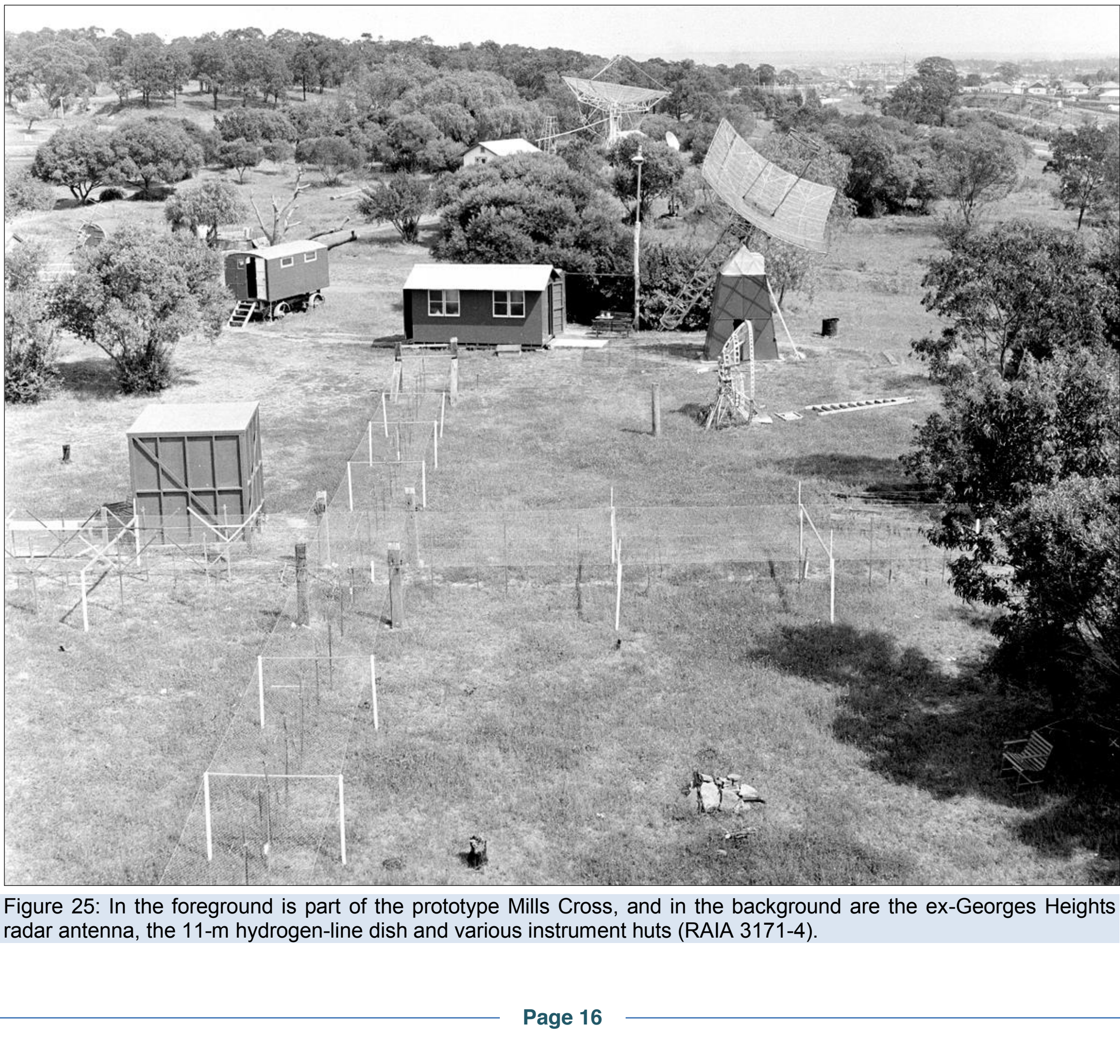

Figure 25: In the foreground is part of the prototype Mills Cross, and in the background are the ex-Georges Heights radar antenna, the 11-m hydrogen-line dish and various instrument huts (RAIA 3171-4).

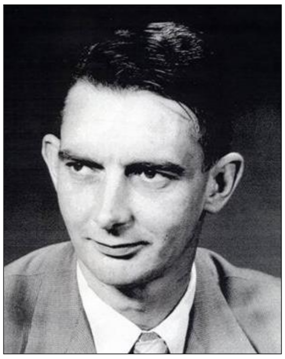

Figure 26: John Bolton at Caltech (courtesy: Edward Waluska).

> … N-S and E-W arms, each 36.6 m (120 ft) in length and containing 24 half-wavelength E-W aligned dipoles backed by a wire mesh reflecting screen (Mills and Little 1953). This novel instrument operated at 97 MHz, and had an 8° pencil beam which could be swung in declination by changing the phases of the dipoles in the N-S arm. (Orchiston and Slee, 2017: 534).

The success of the 'Potts Hill mini-cross' led to construction of a full-scale Mills Cross at RP's new Fleurs field station in 1954 (Mills et al., 1958) and later the Molonglo Cross near Canberra—after Mills joined the exodus from RP following the decision to close down the field stations and he moved to a Readership at the University of Sydney. Over the years Mills received many honours, including a DSc and election as a FRS. He died in 2011, and for further details of his remarkable career see his autobiography (Mills, 2006) and Frater and Goss (2011); and Frater et al. (2017).

Govind's task on this occasion was to help Mills and Little develop a phase shifter for the prototype Mills Cross (Swarup, 2006), experience that would prove to be extremely useful later back in India.

The final project Govind faced during his first year at RP was to work with John Bolton's group at Dover Heights field station and made a highly stable D.C. power supply. John Gatenby Bolton (Figure 26) was born in England in 1922 and by a strange coincidence his early life mirrored closely that of fellow-Briton, Paul Wild: a Cambridge degree, service as a radar officer on a Royal Navy vessel, joining RP following WWII, and marriage to an Australian girl whom he met in Sydney during the war. In 1946 Bolton began working at Dover Heights field station located on the coast just south of the entrance to Sydney Harbour and atop 79-m high cliffs (see Figure 27). In 1953, not long after Govind's arrival, Bolton abandoned radio astronomy and worked on rain-making—RP's other major research field—until 1955 when he moved to Caltech in the USA, set up radio astronomy, and founded the Owens Valley Radio Observatory. In 1961 he returned to Australia as inaugural Director of the Parkes

Figure 27: An aerial view of Dover Heights at the end of WWII, showing the 200 MHz radar antenna (right) used for the earliest radio astronomy observations, with the entrance of Sydney Harbour in the background (RAIA B81-1).

Radio Telescope. After retiring, Bolton and his wife moved north to coastal Buderim in warm sunny Queensland, where he died in 1993. For a summary of Bolton's career see Orchiston and Kellerrnann (2008) and for details of his important contributions to international radio astronomy see Robertson (2017).

So during his first year at RP Govind became familiar with international radio astronomy by reading widely; he gained experience in reducing observations; and he constructed equipment that was used for making observations. All this would prove handy in the second year of his 'apprenticeship' when he and Parthasarathy would carry out a major collaborative project.

As it happened, settling on such a project was not difficult. Christiansen and Warburton had finished their initial research with the two Potts Hill grating arrays and had already published, or were in the process of publishing, their initial results (see Christiansen and Warburton, 1953a; 1953b; 1955a; 1955b). Christiansen was now off to Europe to spend a year working with the French radio astronomers at Paris Observatory, so after discussions with Pawsey

> … Parthasarathy and I decided to convert the Potts Hill EW grating array … from 21cm to 60 cm (500 MHz), in order to investigate whether the quiet Sun exhibited limb brightening at that frequency. This was predicted by Smerd (1950), but was in conflict with measurements made at Cambridge by Stanier (1950). (Swarup, 2006: 25).

Figure 28 shows Smerd's (1950) predicted radial brightness distributions at different frequencies.

Converting the E-W array was an interesting exercise:

> Chris explained the intricacies involved in matching the transmission lines of the 21cm grating array, particularly to ensure that the lengths of the lines from the central point of the array to each of the 32 dipoles was within a few mm. This involved a cumbersome procedure whereby a 21cm signal was transmitted from the junction of each adjacent pair of dishes, the signals were received at the dipole feeds of the adjacent dishes using a movable probe, their phase was then measured using a slotted line, and finally appropriate corrections were made to ensure equality of the lengths of the transmission lines to within a few mm. (Swarup, 2008: 197).

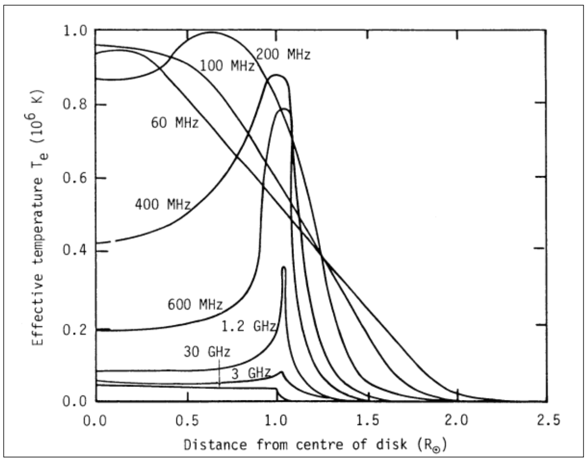

Figure 28: The theoretical distribution of temperature as a function of distance from the centre of the solar disk. Temperatures of 3×10^4 K and 10^6 K are assumed for the chromosphere and corona respectively (after Smerd, 1950: 46).

After modifying the E-W array, Swarup and Parthasarathy carried out solar observations from July 1954 to March 1955, and found strong evidence of limb-brightening (Swarup and Parthasarathy, 1955a; 1955b; 1958). Their results agreed with Smerd's prediction and mimicked the earlier finding by Christiansen and Warburton (see Figure 29). Swarup and Parthasarathy, (1955a: 9) noted that

> Stanier's observations were made near the maximum phase of the solar cycle, while the present observations have been made during the current minimum phase. The dis-

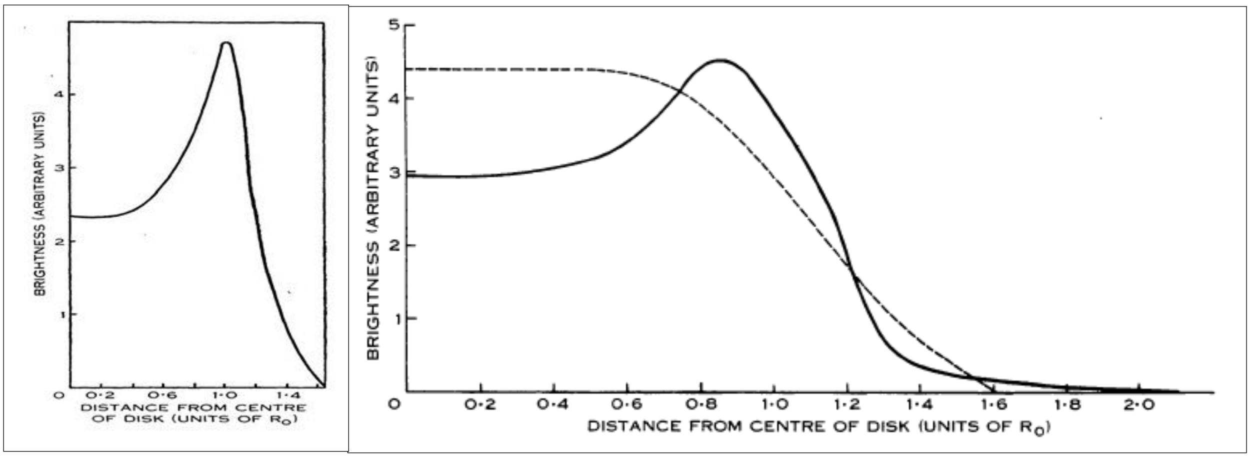

Figure 29: On the left is the radial brightness distribution across the solar disk based on one-dimensional scan observations at 1400 MHz (after Christiansen and Warburton, 1953b: 268). The plot on the right shows the radial brightness distributions at 500 MHz comparing Stanier's result (dashed) and Swarup and Parthasarathy's observations (after Swarup and Parthasarathy, 1955b: 493).

crepancy between the two results could be due either to an actual change in the "quiet" Sun or to errors in Stanier's result, caused by the presence of unrecognized bright areas. Stanier has not given details of the method he used to allow for such bright areas, and without further information it is not possible to decide which alternative is the more likely.

In addition, Govind and Parthasarathy

… also studied localized radio bright regions associated with the slowly varying component and determined their emission polar diagrams by measuring the intensity with the rotation of the Sun (Swarup and Parthasarathy, 1958).

Govind obviously thoroughly enjoyed this ambitious practical project, for he would later reflect:

… this was a great experience: building dipoles, a transmission line network and a receiver system; making the observations; and finally, carrying out data reductions—not to mention saving my dear friend Parthasarathy from drowning in the Potts Hill reservoir! At the time he was using a bucket to draw some water from the Reservoir so that we could make a cup of tea and wash our faces (after a day of hard work), and he accidentally fell into the water. (Swarup, 2006: 25).

Figure 30: Dr K.S. Krishnan, Director of the National Physical Laboratory, who began assembling a fledgling radio astronomy group in 1956 (courtesy: NPL).

When he return from France in early 1955, Christiansen decided to build a new radio telescope combining the concepts of his Potts Hill grating arrays and Mills' cross-type antenna. This would be installed at Fleurs field station, and known as the Chris Cross (Christiansen et al., 1961). Consequently, the two Potts Hill grating arrays became 'surplus to requirements' and were to be scrapped. Govind describes what happened next. During one of Pawsey's visits to Potts Hill

… I asked whether these dishes [from the E-W array] could be gifted to India. He readily agreed to this suggestion, as did E.G. (Taffy) Bowen, Chief of the Division of Radiophysics … On 23 January 1955, I wrote to K.S. Krishnan about the possibility of transferring the thirty-two dishes from Sydney to the NPL in New Delhi (Swarup, 1955). I proposed simultaneous dual frequency observations with a 2,100-feet long grating interferometer using the thirty-two dishes at 60 cm and 1.8m. On 22 February Krishnan (1955) replied: "I agree with you that we should be able to do some radio astronomy work even with the meager resources available." (Swarup, 2006: 25).

CSIRO authorities in Canberra agreed to donate the dishes to India through the Colombo Plan scheme, but they insisted that India must pay for their transportation.

4 RETURN TO THE NATIONAL PHYSICAL LABORATORY IN INDIA:

In July 1955 Govind returned to the National Physical Laboratory (NPL) in New Delhi and began building a 500 MHz receiver for the ex-Potts Hill array, as Dr K.S. Krishnan, Director of the NPL (Figure 30) was keen to start a radio astronomy program. This soon attracted others. In 1956 his namesake T. Krishnan (but no relation) joined the NPL after studying physics at Cambridge University and working with Martin Ryle for a year. Parthasarathy also left Kodaikanal Observatory in 1956 and came to the NPL. M.N. Joshi and N.V.G. Sarma also joined the NPL in 1956, soon after completing their MSc degrees in India, and in 1958 they were joined by Mukul Kundu, who had just completed a solar radio astronomy DSc in France.

However, all was not well. Notwithstanding his enthusiasm, commitment and political acumen, Krishnan could not get the CSIR authorities in New Delhi to agree to fund the transportation of the Potts Hill dishes to India. Instead, they "… suggested that the Australian authorities should bear the cost of transportation, considering the shortage of foreign exchange in India at the time." (Swarup, 2006: 25). The Australians refused, and over the next few years this led to a mass exodus of NPL radio astronomers: Parthasarthy went to Alaska; T. Krishnan to RP in Sydney; Joshi to France (for a PhD); Sarma to Leiden Observatory (to build receivers); Kundu to the USA, not long after joining the NPL; and in August 1956 Govind also decided to go to the USA. In just two short years Krishnan's promising young radio astronomy group had all but disappeared, just as quickly as it had emerged!

Finally, the Australians agreed to pay for the transfer of the 32 dishes to New Delhi, but by then it was too little too late. The Indians may have won the diplomatic battle, but in the interim they lost their fledgling radio astronomy group!

Govind (2006: 25) is somewhat more charitable (and diplomatic): "Thus, it may be said that the NPL acted as a foster mother for the subsequent development of radio astronomy in India …"

5 FORT DAVIS, THEN STANFORD UNIVERSITY AND DOCTORAL RESEARCH

When Govind decided to leave the NPL in late 1956 and travel overseas with his new wife, Bina, he had a challenging decision to make. Where should he go for the next couple of years that would be in the best interest of his future career in radio astronomy and provide a suitable family environment?

All his experience had been in solar radio astronomy, and this is what India would offer when it eventually received the Potts hill dishes and mounted them, but there were various options, since

> The success of the Division of Radiophysics' solar research program in the late 1940s and throughout the 1950s inspired other groups in America, Japan, France, Holland and elsewhere to build similar instruments for solar radio-frequency investigations. (Stewart et al., 2011c: 623).

Some of these facilities are summarized earlier in the afore-mentioned Stewart et al. paper and in Ishiguro et al. (2012), and (apart from RP's Solar Group in Australia) the French and the Japanese were particular active in developing instrumentation and carrying out inspiring research (see ibid.; Orchiston and Ishiguro, 2017; Orchiston et al., 2009; Pick et al., 2011).

When it came to the USA there really was no choice because the Ft Davis field station of Harvard College Observatory was the only major solar radio astronomy facility that was operational at that time (although several other groups would very soon 'join the club'). Consequently, Govind

> … decided to join the Harvard College Observatory as a Research Associate in order to study dynamic spectra of solar bursts using the 100-600 MHz swept frequency radio spectrograph that had just been installed at Fort Davis … (Swarup, 2008: 197).

He would spend just one year there.

Leading this small team was the New Zealander Alan Maxwell (b. 1926), who completed an MSc at Auckland University College (as it then was) back in 1948 (see Orchiston, 2016: 645–646). His thesis was titled "Enhanced Solar Radiation at 3 Metre Wavelengths", but

> Despite this being one of the first postgraduate theses on solar radio astronomy ever written anywhere in the world, Maxwell failed to publish his work—it simply was not the custom at this time—and soon after completing his Auckland studies he moved to the dynamic astronomical environment of Jodrell Bank (at the University of Manchester) where he was quickly immersed in new research for a Ph.D. (Orchiston, 2017b: 683).

Figure 31 shows Maxwell adjusting his 100 MHz twin Yagi antennas mounted on the roof of one of the Auckland University College buildings.

Maxwell carried out further solar work for his Manchester doctorate and in 1955 was appointed to lead Harvard College Observatory's new solar radio astronomy program, inspired in part of the International Geophysical Year (1957–1958) and funded (initially, at least) by the U.S. Air Force.

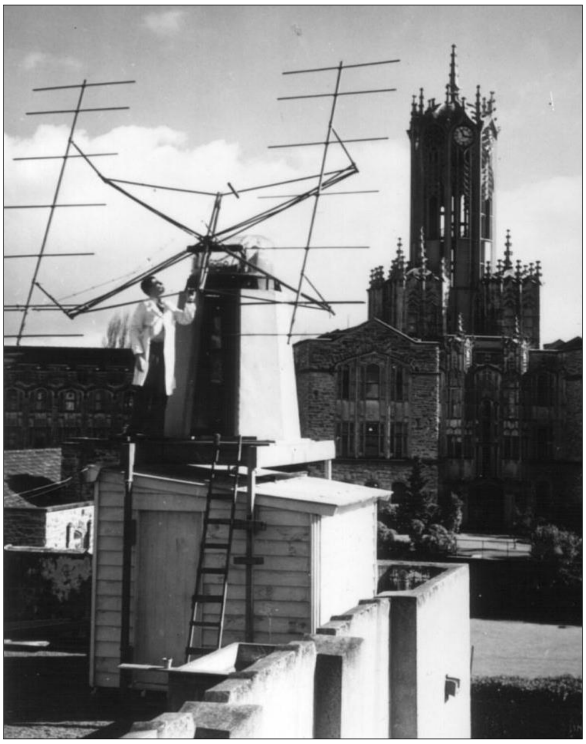

Figure 31: Alan Maxwell and his 100 MHz twin Yagi antenna used for his Auckland University College MSc project (courtesy: Alan Maxwell).

Harvard Professor and respected (optical) solar astronomer Donald H. Menzel (1901–1976) was instrumental in establishing the Harvard solar radio astronomy program, and

> When Maxwell took up his position … orders had already been placed for a 28-ft. diameter equatorially-mounted antenna from D.S. Kennedy Co. of Cohasset, MA, a feed system covering 100–600 MHz from Jasik Labs. of Westbury, NY, and receivers from Airborne Instruments Laboratory Inc. (A.I.L.) of Mineola, NY. (Thompson, 2010: 18)

All that was missing was a site for this equipment and with help from Sacramento Peak and McDonald Observatory colleagues Maxwell found Cook Flat, a small radio-quiet valley near Ft Davis in west Texas, and at the foot of Mt

Figure 32: Alan Maxwell, Govind Swarup and Sam Goldstein (left to right) posing in front of the 28-ft dish at Harvard Observatory's Fort Davis field station in Texas (courtesy: Govind Swarup).

Locke (where McDonald Observatory was located).

Given Maxwell's New Zealand pedigree and the considerable local fame of the British explorer Captain James Cook (1728–1779) in New Zealand, not to mention Cook's preoccupation with Queen Charlotte Sound on all three voyages to the Pacific (see Orchiston, 2016: 107–226), his observations of the 1769 transit of Venus (Orchiston, 2017a) and his role as expedition commander *and* astronomer on the First and Third Voyages (Orchiston, 2016: op. cit.), we are bound to wonder if the name 'Cook Flat' resonated in any way with Alan Maxwell and played a part in his decision to site his field station there! Or was this just a happy coincidence?

Be that as it may, when Govind first visited the Ft Davis field station (alias Cook Flat) in August 1956 he found the radiospectrograph already attached to the 28-ft Kennedy Dish and functioning (Thompson, 1961). Figure 32 shows Alan Maxwell, Govind and Sam Goldstein posing in front of the dish.

By mid-1956 Wild's nomenclature of three basic spectral types of bursts (Types I, II and III) was well-known internationally, and the fact that Type II bursts sometimes exhibited harmonic structure, so the quest at Ft Davis (and elsewhere) was to categorize all newly-arriving bursts, identify any new types of bursts, and investigate if radio bursts were associated with flares, prominences and other optical activity (Maxwell, 1957; 1958). While Govind was at Ft Davis, André Boischot (1957) discovered a new variety of burst, the Type IV, and then Wild et al. (1959) added the Type V burst to the list. Typical examples of all of these are shown in Figure 33.

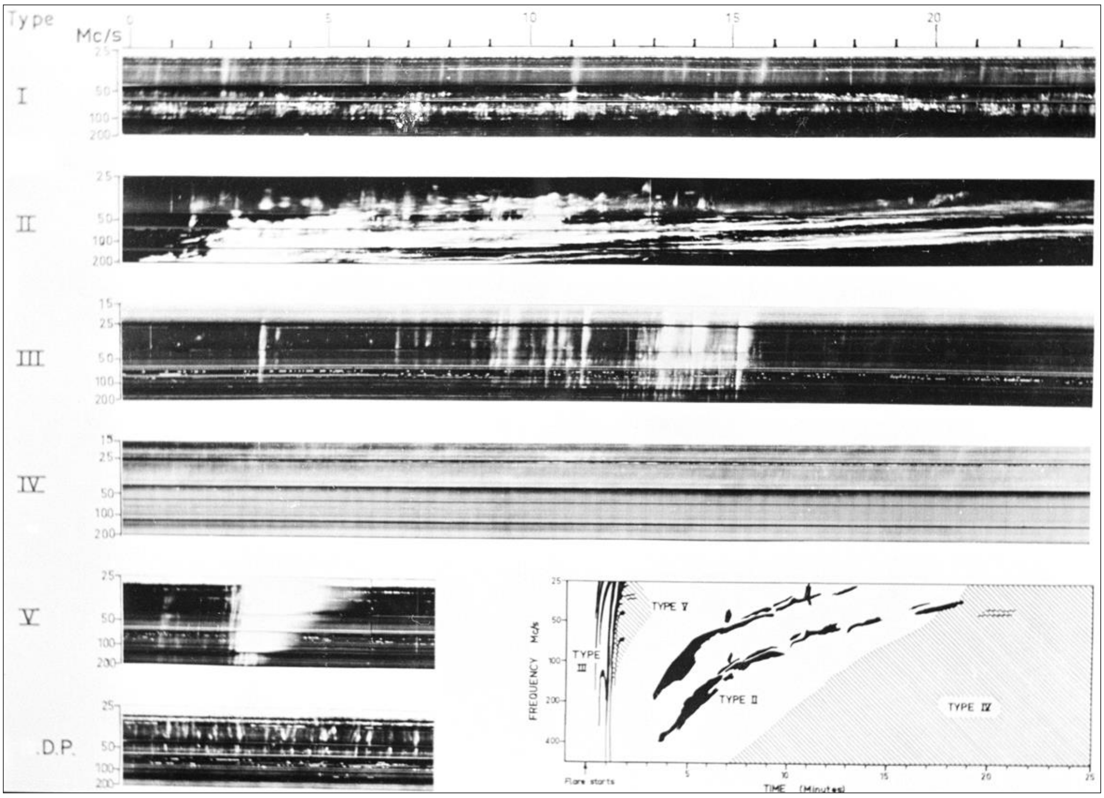

Figure 33: Typical examples of the six different spectral types of solar bursts recorded at Dapto (Types I-V and Drifting Pairs – DPs), with a schematic (bottom right) that summarizes their relative features (RAIA 6317).

For his part, Govind participated in this research at Ft Davis and published several papers (e.g. see Maxwell et al., 1958; Swarup et al., 1960), but his major success was in discovering a new type of solar burst, the U-burst: "In December 1956 I discovered the Type U burst while Maxwell was on a holiday in New Zealand …" This was subsequently reported in *Nature* (Maxwell and Swarup, 1958), and is described by Thompson (2010: 20):

> A type of fast-drift burst, in which the spectrum initially drifts downward in frequency and then turns upward again, was discovered at Fort Davis by Swarup. These appear on the Fort Davis records as an inverted letter U, and are known as 'U-bursts' (Maxwell and Swarup 1958). U-bursts are believed to be generated by excitations that begin to move outward through the solar corona, but are guided by loops in the solar magnetic fields causing them to turn and move down toward the solar surface. They occur much less frequently than the usual Type III bursts.

For a slightly later more detailed account of U-bursts, assembled by two RP radio astronomers, see Labrum and Stewart (1970). For an example of a typical U-burst see Figure 34.

In the course of carrying out this solar research at Ft Davis, Govind and Bina also gave thought to their future, and decided it would be their long-term interests if Govind could obtain a PhD Thus

> In early 1957, I decided to work for a Ph.D. degree in the USA and received favourable responses from Harvard, Caltech and Stanford, all of which were already active in radio astronomy … Pawsey (1957) wrote: "Stanford is famous for radio engineering, Caltech for its physics and, of course, its astronomy research, and Harvard for its training in astronomy … If you are returning to India, I should recommend to you to place great emphasis in electronics. It is a key to open many doors." (Swarup, 2006: 25 – 26).

With this advice echoing in his mind, Govind chose Stanford, and in September 1957 he began his PhD under the watchful eye of Professor Ron Bracewell. Given his previous Sydney apprenticeship, is it any wonder that Govind chose to be guided by a former Sydney radio astronomer, one of Joe Pawsey's protégés, and a solar radio astronomer to boot! So who was Ron Bracewell?

Ronald Newbold Bracewell (Figure 35) was born in Sydney (Australia) in 1921 and received BSc, BE and ME degrees from the University of Sydney, and a PhD from the University of Cambridge (with a thesis on ionospheric research). In 1949 he joined RP and through sharing a room with Chris Christiansen and Harry Minnett was soon involved in radio astronomy, with interests in interferometry, signal processing and imaging, data analysis and the role of Fourier transforms in radio astronomy (which would later lead to a book: Bracewell, 1965). Pawsey also invited Bracewell to join him in co-authoring a text book, and in 1955 *Radio Astronomy* (by Pawsey and Bracewell) was published by Oxford's Clarendon Press. This was quickly accepted worldwide as *the* standard work on radio astronomy—and many of us find it illuminating reading today, more than half a century later! Bracewell "… later surmised that this [book] was partly a device to get him more involved in the subject." (Thompson and Frater, 2010: 172).

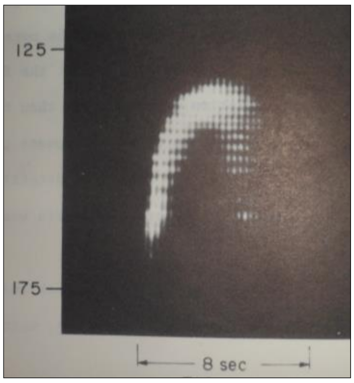

Figure 34: An example of a U-burst recorded with the University of Michigan radiospectrograph on 29 November 1956; time is shown on the x axis and frequency (in MHz) on the y axis (after Kundu, 1964: 408).

During the 1954 – 1955 US academic year

> Bracewell was invited by Otto Struve (1897–1963) to give a series of lectures on radio astronomy at the University of California, Berkeley. He also lectured at Stanford University, which led to his joining the Electrical Engineering Department at Stanford in December 1955. (ibid.).

Struve also asked Bracewell to suggest a new

Figure 35: A caricature of Ron Bracewell drawn by cartoonist Emile Mercier (after Bracewell, 1984: 187).

Figure 36: The completed Stanford 9.2 cm cross-antenna interferometer (courtesy: TIFR Archives).

radio telescope that Stanford could build to launch its radio astronomy research program. After due deliberation, Bracewell recommended a microwave spectroheliograph, and he notes that at the same time

> … I mailed the plan to Joseph L. Pawsey … proposing to build this radio telescope in Sydney [upon his return to Australia]. It comprised NS and EW arms in a cross configuration, each containing sixteen solid metal 10-ft parabolic 'dishes' spaced at 25-ft intervals. It was designed to operate at a wavelength of 9.2 cm, with a pencil beam of 3.1 arcminutes. (Bracewell, 2005: 75).

However, Pawsey advised that Christiansen already planned to build a similar solar grating array near Sydney. Appropriately dubbed the 'Chris Cross', this 1420 MHz radio telescope was completed in 1957 (see Christiansen and Mathewson, 1958; Christiansen et al., 1961; Orchiston, 2004), and its design and research accomplishments are summarised in Orchiston and Mathewson (2009).

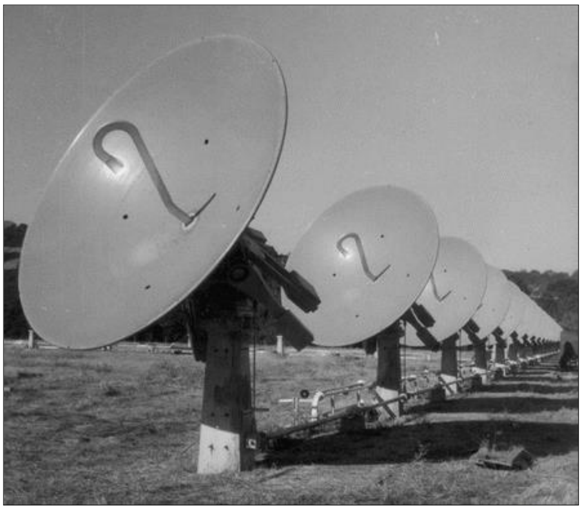

Figure 37: A close-up showing the design of the metal dishes, feeds and mountings (courtesy: TIFR Archives).

Instead, Bracewell chose to build his solar grating array in the USA, and in December 1955 he joined Stanford University's Department of Electrical Engineering. He would later become the Lewis M. Terman Professor of Electrical Engineering and one of the world's most innovative radio astronomers (see Bracewell, 2005; Frater et al., 2017; Thompson and Frater, 2010).[5]

By the time Govind Swarup moved from Fort Davis to Stanford in September 1957, Bracewell was in the process of constructing his 'Solar Radioheliograph' at the 'Heliopolis' radio astronomy precinct on the outskirts of the Stanford University campus (Figure 36), and it became operational in April 1960 (Bracewell, 2005). As indicated above, the radioheliograph comprised two orthogonal arrays, each with

> … 16 parabolic dishes 10 feet diameter, spaced at 25 feet intervals (Bracewell and Swarup, 1961). The voltage outputs of the two arrays were multiplied giving a pencil beam of 3.1 arc minutes. (Swarup, 2008; 197).

Figure 37 provides a close-up of some of the dishes. The array was designed to produce daily maps of solar radio emitting regions at 3.259 GHz (e.g. see Figure 38).

The solar array was first described in Bracewell (1957), but this was later followed by a detailed account, penned by Bracewell and Swarup (1961). Govind's co-authorship of this important paper was fully justified because of his input to the design: the waveguide path to each antenna feed horn had to be kept constant to within one millimeter, but

> … the phase length to individual antenna feeds was found to vary from month to month, largely as a result of activity of spiders and birds. To measure these shifts a novel scheme was developed that became the forerunner for adjustment of interferometer arrays elsewhere. At each feed horn a very small fluorescent tube developed by Govind Swarup was inserted across the waveguide. A signal injected into the NS waveguide terminal in the control room would undergo successive subdivisions at the seven tee junctions and radiate into space. But if one discharge tube was switched on, it caused almost total reflection from its feed horn. A slotted waveguide section between the signal generator and the transmission wave-guide terminal indicated, for each feed horn in turn, the location of a standing wave minimum and the amount of the necessary adjustment, if any. Phase compensation was carried out with calibrated half-wavelength slivers of copper inserted on the waveguide floor at a junction. (Bracewell, 2005: 77; cf. Swarup and Yang, 1961).

Govind elaborates on the background to this innovative idea:

> After more than six months of hard work we [i.e. Govind and fellow graduate student K.S. Yang] were able to make maps of the Sun but we found huge spurious sidelobes. Bracewell asked us to make fresh phase measurements. Again we found large sidelobes and we concluded that the spacing and physical location of the antennas could be in error. Bracewell decided to survey their positions himself and to make corrections as required but asked us to make the phase measurements again. How strenuous and boring, getting up early in the morning in order to make phase measurements before the length of the probes was affected by temperature changes caused by sunlight, not to mention having to attend classes at 9a.m.! (Swarup, 2008: 197–198).

This is why Govind came up with the idea of inserting small fluorescent tubes across the waveguide and injecting a signal into the N-S waveguide terminal! Furthermore,

> The idea was conceived while I was a graduate student, when time was of the essence, so prior experience (at Potts Hill) and necessity became the mother of invention! (Swarup, 2008: 198).

After Pawsey heard about this he wrote Govind:

> I had already heard of your phase measurement technique and think that you have made a real break-through in this technique. Congratulations! Chris regards the idea as the key to really large Mills Crosses. Without a good checking technique, they could not operate. (Pawsey, 1960).

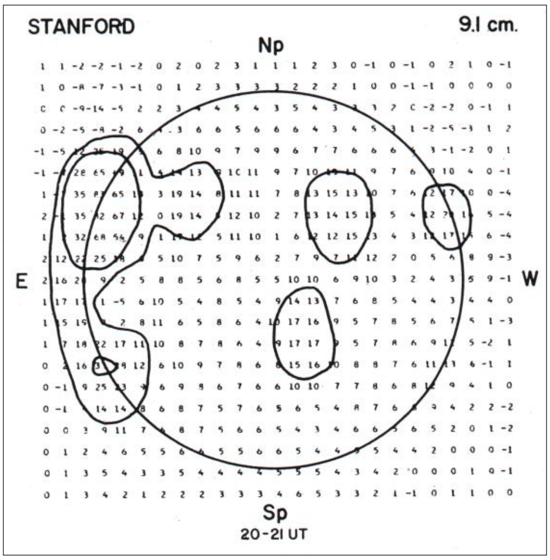

Figure 38: A map of 3.224 GHz solar radio emission on 3 January 1969 (after Bracewell, 2005: 76).

Upon looking through the list assembled by Ron Bracewell (2005: 85–86) of research publications based on observations made with the Stanford radioheliograph it is—at first sight—strange to see no papers by Govind, given that the array "… was astronomically productive in the field of solar physics." (Bracewell, 2005: 77). But we must remember that Govind was busy helping design, construct and test the array for his PhD (see Figure 39), which he completed in 1960[6] just a few months after the array became operational in April 1960.

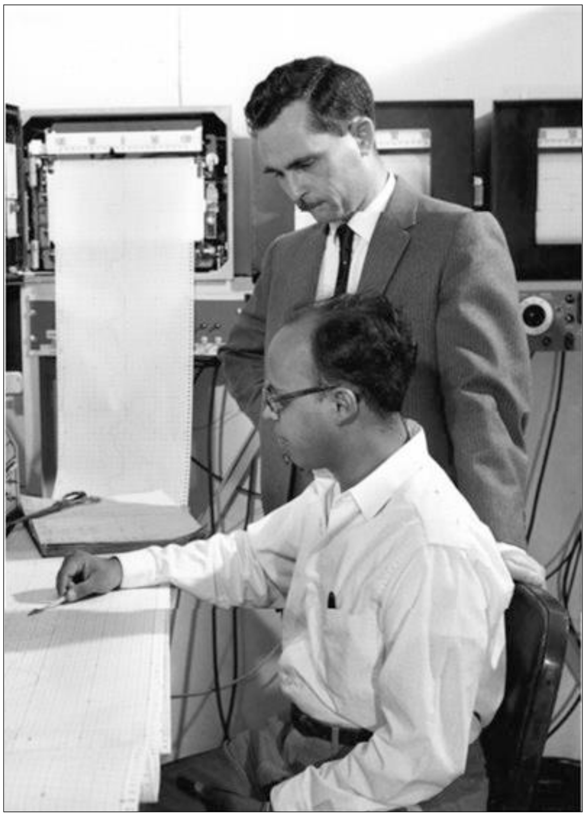

Figure 39: Ron Bracewell and Govind Swarup examining solar records (courtesy: Stanford University News Service).

We do know that Govind later suggested a new way of converting the strip scans into two-dimensional maps of quiet Sun emission. Writing about his Potts Hill days, he reveals that

> … a decade later that painstaking experience gave me an idea of a simpler scheme to make maps from one-dimensional scans without taking Fourier transforms. The new concept was described by me to R.N. Bracewell in late 1962, just before I returned to India from Stanford. In this method, a 2-dimensional map can be readily obtained by multiplying amplitudes of each of the one-dimensional strip scans by appropriate weights and then plotting the resulting modified scans along corresponding scan-angles, in order to obtain a 2-dimensional map. (Swarup, 2006: 23).

Govind remarks (2008) that since he was about to return to India he did not pursue the idea, but later it was developed and published by Bracewell and Riddle (1967).

Figure 40: T.K. Menon (left) and M.R. Kundu (right) at the Berkeley IAU General Assembly in 1961 (Menon Collection).

One interesting solar radio astronomy project that Govind did initiate while at Stanford was a collaboration involving colleagues from Canada, Japan and Australia. Inspired by an earlier successful project published by Christiansen et al. (1960), Govind's study focused on the sizes, heights in the solar atmosphere, and brightness temperatures of radio plages observed at 3.2, 7.5, 9.1, 10.7 and 21 cm, and their association with photospheric features (see Swarup et al., 1963b).

Once the grating array was operational, what Ron Bracewell's team did was to look at modifying the design so that for the first time in his comparatively short astronomical career Govind could research discrete radio sources—rather than continue to focus solely on solar radio emission. This was achieved by adding two further antennas to the E-W arm of the array so that it could function as a compound interferometer.[7] This produced fan beams with widths of 52 arcsec, and east-west scans of several strong radio sources were obtained with this angular resolution (Swarup et al., 1963a; Thompson and Krishnan, 1965).

The aforementioned Swarup et al. 1963a paper was Govind's first research publication on a non-solar topic. Little could he have imagined at the time that this paper would set the pattern for much of his subsequent career, after he returned to India.

One other paper Govind would co-author while at Stanford, also would fore-shadow his later interest in designing and constructing novel radio telescopes. During the 1960s, apart from the solar array there were two equatorially-mounted 30-ft parabolic dishes at Heliopolis that were used as a two-element variable baseline interferometer, but they were only useful for observations of the strongest discrete sources. Therefore

> Bracewell considered building an instrument with a much larger collecting area, using several long cylindrical reflectors. He envisaged an instrument that would grow with time, by the addition of more elements as funding allowed (Bracewell, Swarup, and Seeger, 1962). However, funds for a large instrument proved to be unavailable, and the development of Earth-rotation synthesis by Martin Ryle (1918–1984) showed the advantage of fully steerable antennas.

Obviously Govind also was captivated by the concept of a large cylindrical antenna for this would feature prominently in his later plans—as we shall see in Sections 8 and 9, below.

6 PLANNING A POSSIBLE RETURN TO INDIA

Although Govind accepted an Assistant Professorship in Electrical Engineering at Stanford on 1 January 1961, soon after being awarded his doctorate, from time to time he had contemplated returning to India and launching a radio astronomy program there.

At several meetings of the American Astronomical Society and the American chapter of URSI Govind proceeded to discuss these ideas with M.R. Kundu and T.K. Menon, two Indian colleagues then working in the USA. Mukul Kundu (1930–2010; Figure 40) had completed a doctorate in radio astronomy in France (see Orchiston et al., 2009) before joining Fred Haddock's group at the University of Michigan in 1958, while T.K. Menon (Figure 40) completed MS and PhD degrees at Harvard University and worked in the Astronomy Department there until 1959 when he joined the (U.S.) National Radio Astronomy Observatory. Kundu was interested in solar radio emission, while Menon's field was galactic HI clouds and HII regions.

As Govind remarks (2006), in 1960 and 1961, he raised the idea of the three of them returning to India in letters he wrote to Pawsey, Christiansen and fellow-Australian Frank Kerr.

They were supportive, but suggested adding T. Krishnan (Figure 41), to the group. At that time Krishnan was at RP in Sydney, and was involved in solar work with the Chris Cross (see Orchiston and Mathewson, 2009).

Christiansen wrote Govind on 22 September 1960:

> … you two [i.e. Swarup and Krishnan] and Menon and Kundu should get together for a united attack on the monolith of Indian bureaucracy – separately I can't see you getting anywhere in radioastronomy very fast … I know you all, and feel that [the four of you] would make a very fine team.

Meanwhile, in his letter penned one month later Pawsey (1960) was equally supportive, but he also was concerned about group dynamics and the types of research the group might pursue:

> It will probably happen that different ones want different things. You must all try to sink your personal preferences in favour of the whole project and judge objectively. Remember that strength lies in unity … keep off fashionable stuff as far as possible. Be original. Try, if possible, to develop ideas which one or more of you have originated. The small groups bring in the radical new thoughts. They are not tied up with inherited large programmes. The other point for me to emphasize is the importance of good experimental technique.

In commenting on the dynamism of small groups Pawsey was clearly reflecting on the successes of those at the RP field stations in and near Sydney.

It is also clear that issues of group dynamics and leadership continued to worry Pawsey, as on 18 April 1961 he wrote:

> If the scheme comes off, you are a key person. Your practical ability and direct approach will be most important ... A real difficulty is the question of leadership of the group. It could well lead to jealousies and failure. The position is that there are several of you, each with something different to contribute, and no one alone is likely to be able to make things go by himself ... [The] problem ... can be met if the individuals of the group are each willing to subordinate their individual interests to some extent … (Pawsey, 1961a).

Pawsey returned to the leadership question in his next letter, dated 29 June 1961:

> ... you, I think stand out in practical experience and ability. Menon has the astronomical knowledge. Who then will be the leader? This is the sort of situation which can be made to work if the members have a real urge to make the project a success and are willing to subjugate their individualities to a reasonable extent. Not all men can do this and you do not want to pick up members who won't fit in. On the other hand, you must get a few key people. My own feeling is that there are only two essential key men: (1) a good practical physicist combining radio skill and common sense (you are my choice here); and (2) an organizer with drive and good external contacts (Krishnan stands out here). (Pawsey, 1961b).

Govind finally responded to Pawsey's concerns in a letter dated 25 July 1961:

> It would be desirable for me to devote all my limited energies to the construction and development of the apparatus. I personally would not care who would be the leader. But the overall scientific program should be mutually decided so as to make everybody in the group feel his importance. (Swarup, 1961).

It is not clear how widely Govind discussed the issues Pawsey raised with the other Indian radio astronomers, but in August 1961 all four of them met during the Berkeley General Assembly of the IAU. On 23 September 1961 they completed a 3.5-page proposal titled "Proposal for the Formation of a Radio Astronomy Group in India" (Krishnan et al., 1961) and they wrote about at first setting up a solar radio astronomy program using the thirty-two ex-Potts Hill dishes, and then

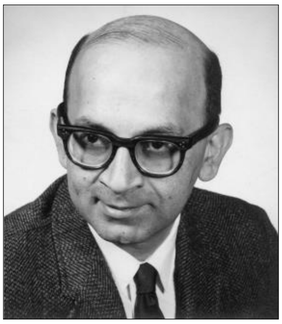

Figure 41: T Krishnan in India in 1970 (Krishnan Collection).

> … a very high resolution radio telescope of a novel design would be the next step in our programme ... certain types of radio telescopes would be cheaper to build in India due to lower labour cost … such as a Mills Cross operating at low frequencies ... (ibid.).

The proposal was then send to five major scientific organizations and agencies in India, "… indicating our desire and willingness to return to India and form a radio astronomy group and also to attract others in due course." (Swarup, 2006: 26). Goss (2014: 12) lists the five recipients:

(1) The Atomic Energy Commission (through the Tata Institute of Fundamental Research)
(2) The Council of Scientific and Industrial Research
(3) The Ministry of Natural Resources and Scien-

tific Research, Director General of Observatories
(4) The University Grants Commission
(5) The Physical Research Laboratory

Copies of the proposal also were sent to Bart Bok (Director of Mt Stromlo Observatory in Australia and Professor of Astronomy at the Australian National University in Canberra), J.-F. Denisse (leader of the Paris Observatory radio astronomy group), Jan Oort (Professor of Astronomy at Leiden University in the Netherlands), Joe Pawsey and Harlow Shapley (Director of Harvard College Observatory and Professor of Astronomy at Harvard). All were asked to send confidential assessments to the Indian authorities. Govind (ibid). notes that copies of the supporting letters from Bok, Oort and Pawsey to Dr Homi Bhabha, Director of the Tata Institute of Fundamental Research in Mumbai are available in the TIFR archives. He also mentions that Bok's (1961) recommendation was very supportive:

Figure 42: Dr Homi Bhabha (1911–1966), founding Director of the Tata Institute of Fundamental Research, Mumbai (courtesy: TIFR Archives).

> It seems to me that their offer to return to India as a group is a unique one, and that should by all means be accepted and acted upon promptly. An offer like the present one comes only rarely in the history of scientific development of a nation, which scientifically, is obviously coming of age.

Pawsey (1961c) was equally flattering:

> I have a very high opinion of the scientific talent in this group ... a group chosen from among them should have an excellent chance of building up a first class scientific institution ... I regard this spontaneous movement among the young Indians who have initiated this proposal as a most encouraging sign and strongly urge you, in the interests of science in India, to try to assist them in their efforts to work out something worthwhile.

What is a little surprising is that there is no letter of support on file from J.-F. Dennise (though this does not automatically mean that he did not send one). Like Pawsey, he was an internationally respected solar radio astronomer, and he certainly knew Mukul Kundu who had carried out his DSc research using facilities located at Paris Observatory's Nançay field station (see Orchiston et al., 2009).

Nonetheless, according to Govind,

> We got replies from all the concerned authorities from India, but the most encouraging and highly supportive was from the great visionary scientist and a dynamic organizer, Dr Homi J. Bhabha … (Swarup, 2006: 27).

Born in 1909, Homi Bhaba (Figure 42) was particularly interested in cosmic rays, so it is easy to understand his support for radio astronomy. But it goes deeper than that: he was quick to recognise research opportunities that could consolidate India's place on the world stage. In 1935 he had completed a PhD at the Cavendish Laboratory in Cambridge at the same time that Pawsey was there; his thesis was titled: "On Cosmic Radiation and the Creation and Annihilation of Positrons and Electrons". Four years later he joined the Physics Department at the Indian Institute of Science, but he left in 1945 in order to found the Tata Institute of Fundamental Research in Bombay, which he built into a major international centre for cosmic ray research (see Sreekantan, 1998). Homi Bhabha died unexpectedly in an Air India crash in the Alps on 24 January 1966, and apart from his cosmic ray research he is known today as 'The Father of India's Atomic Energy Programme'. For further biographical details of this remarkable man, who strongly supported early Indian radio astronomy, see Chowdhury and Dasgupta (2010) and Venkataraman (1994).

On 20 January 1962 Homi Bhabha sent a cable to the four radio astronomers: "We have decided to form a radio astronomy group stop letter follows with offer …" (Bhabha, 1962a). Over the next two months Homi Bhabha somehow was able to formalize the establishment of the new radio astronomy group at the Tata Institute of Fundamental Research, and on 3 April 1962 he wrote Govind:

> If your group fulfills the expectations we have of it, this could lead to some very much bigger equipment and work in radio astronomy in India than we can foresee at present. (Bhabha, 1962b).

7 TATA INSTITUTE OF FUNDAMENTAL RESEARCH AND THE KALYAN RADIO TELESCOPE

Govind then resigned from Stanford, and he and Bina headed for India, via Europe. In Leiden (Holland) Govind visited Professor Jan Oort (1900–1992), one of the world's leading

Figure 43: View of part of the east-west grating array, consisting of twenty-four 1.8-m diameter dishes and built at Kalyan, near Mumbai, in 1965 (courtesy: TIFR Archives).

authorities on galactic and extragalactic astronomy, who

> … showed him was a model of a 25 m diameter parabolic dish antenna that they were in the process of building. The great Jan Oort suggested to Swarup that he might build one such dish and use it to study the distribution of neutral hydrogen gas in the southern part of the sky, which is not accessible from Europe but would be easily accessible from the southern latitudes. Such a study would complement the survey they had done of the northern sky. Since Oort knew Bhabha, he was willing to provide TIFR with all the engineering drawings. The 21 cm line radiation from hydrogen atoms had been discovered only a few years earlier – one of the most momentous discoveries in the entire history of astronomy – and mapping the distribution of hydrogen was the hottest problem in astronomy. (Srinivasan, 2015: 621).

But Swarup recalled Pawsey's warning to keep away from the "… fashionable stuff … [and] Be original." So he diplomatically chose not to accept Oort's tantalizing offer, and it was left to Pawsey's group at Radiophysics to pick up the collaboration (see Wendt et al., 2011b).

On 31 March 1963 he returned to India. Shortly afterwards the ex-Potts Hill dishes were transferred to the TIFR, and Govind was joined by two recent graduates, J.D. Isloor and V.K. Kapahi. The following year, two more recent graduates, D.S. Bagri and R.P. Sinha, joined the group, along with N.V.G. Sarma and M.N. Joshi (both of whom transferred from the NPL in New Delhi). Collectively, they constructed India's first radio telescope, which was completed in April 1965 (see *Nature*, 1966). This solar grating array was sited at Kalyan, near Mumbai, and consisted of the thirty-two 1.8-m diameter ex-Potts Hill parabolas:

> … 24 of them were placed along a 630-m east-west baseline and 8 along a 256-m north-south baseline, giving an angular resolution of 2.3 × 5.2 arcmin … (Swarup et al., 1991b: 79).

Part of the E-W arm is shown in Figure 43 and in Figure 44 one of the radio astronomers is adjusting the transmission line.

The idea of using a T-array rather than a cross (as at Stanford) was something that Govind

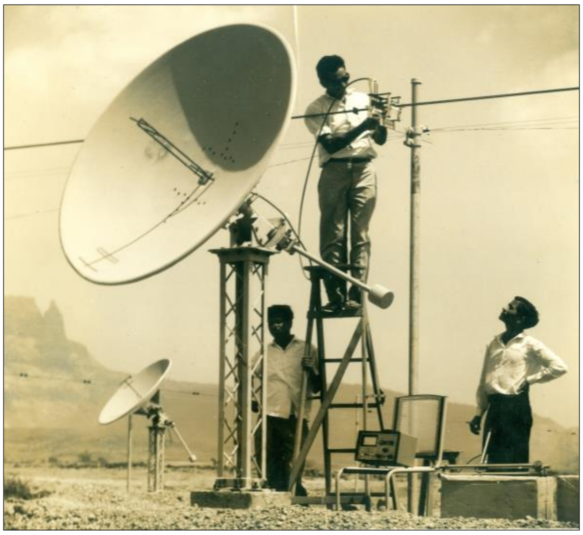

Figure 44: A close-up of two of the Kalyan array antennas, with R.T. Kapahi adjusting the transmission line (courtesy: TIFR Archives).

already decided on years earlier, when the Kalyan array was all but a distant dream:

> In September 1957, soon after joining Stanford, I made a detailed study of a Cross antenna versus a T-shaped antenna and showed that both provided the same resolution but that the latter, although more economical, was much more sensitive to phase errors, which resulted in spurious sidelobes. (Swarup, 2008: 197).

Over the next three years Govind's group used the Kalyan Radio Telescope "… to investigate properties of the quiet and active radio Sun at 610 MHz …" (Swarup, 2006: 27). Even though this period extended from sunspot minimum towards what would prove to be a relatively weak maximum (see Figure 45), the young TIFR radio astronomy group "… found that the Sun showed considerable limb brightening, and that the solar corona had a temperature of around one million degrees." (ibid.). These findings, and others, were discussed in a series of

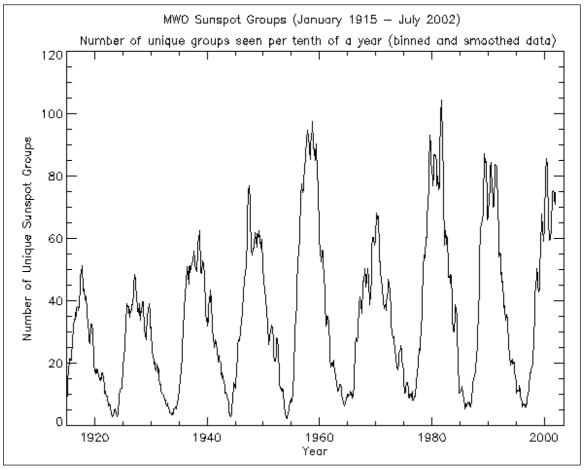

Figure 45: A plot showing sunspot numbers from about 1912 to 2003. The Kalyan solar observations were carried out at, and soon after, sunspot minimum (courtesy: Mt Wilson Observatory).

research papers (see Sinha and Swarup, 1967; Swarup et al., 1966a; 1966b; 1968) that built on or confirmed the results published by Govind and Parthasarathy during their Potts Hill sojourn. Meanwhile, technical details of the Kalyan array were provided in Swarup and Kapahi (1970: 404–406). Collectively, these publications—and particularly the *Nature* paper (Swarup et al., 1966b)—marked the start of India's attempt to place its name of the world stage as a serious radio astronomical nation.

Govind noted that Mukul Kundu joined the TIFR radio astronomy group in early 1965, but returned to the USA three years later. In the interim, he "… contributed a great deal to the growth of the group during its critical formative years." (Swarup, 2006: 29). He also featured as a co-author of one of the Kalyan papers (Swarup et al., 1968).

8 THE OOTY RADIO TELESCOPE (ORT)

With a functioning solar grating array (shades of Potts Hill and 'Heliopolis'), we could be forgiven for thinking that Govind's next move would be to expand his solar observatory by adding one or more radiospectrographs (shades of Cook Flat, alias Ft Davis), but no. Admittedly, he did briefly consider adding 20-ft dishes to the E-W grating array in order to have access to a compound interferometer, and discrete radio sources (Swarup, 2006). But as early as June 1963—immediately after starting construction of the Kalyan array—he was already thinking seriously about the second phase of Indian radio astronomy mentioned in the 1961 proposal document that was sent to the TIFR and other agencies, namely, after a solar array the group would construct "... a very high resolution radio telescope of a novel design …" (Krishnan et al., 1961).

This is when Govind

> … came across a paper by Cyril Hazard in a recent issue of *Nature* describing observations of a lunar occultation of the radio source 3C273 made with the 64 m Parkes Radio Telescope, as well as a companion paper by Marteen Schmidt, concluding that the enigmatic spectrum of the blue stellar object identified with 3C273—which had been a great puzzle for several years—was easily explained for an object with a redshift of 0.17. (Swarup, 2006: 27).

As we know, this marked the discovery of quasars (see Kellermann, 2014) and opened up a whole new way of viewing the Universe.

Govind describes what happened next:

> While reading the two papers, a thought flashed through my mind: that the lunar occultation method could provide accurate positions and angular size measurements of a large number of radio sources, much weaker than those in the 3C [Cambridge] catalogue, and thus distinguish between competing cosmological models. At that time there was a raging controversy between the Steady State and Big Bang cosmologies. A quick calculation showed that in order to obtain occultation observations of a sizable sample of distant weak radio sources, say ~200 per year, one would need a telescope with a collecting area of more than four times that of the 64 m Parkes or the 76 m Jodrell Bank Radio Telescopes, which was not practical to build, even in advanced countries. It occurred to me that the solution would be to *construct a large cylindrical radio telescope on a suitably-inclined hill in southern India so as to make its axis parallel to the Earth's axis,* and thus taking advantage of India's close proximity to the Equator. (Swarup, 2006: 27; our italics).

This was an ingenious idea (Srinivasan, 2015: 621 calls it "Exceedingly clever!"), and it certain-

Figure 46: The Ooty Radio Telescope, consisting of the 530 m long and 30 m wide cylindrical parabolic antenna placed along a north-south sloping hillside at an angle of 11.3° so that its axis of rotation is parallel to that of the Earth (courtesy: TIFR Archives).

ly qualified as a high resolution radio telescope of novel design. Not surprisingly, Govind quickly 'sold' the idea to Homi Bhabha.

Actually, initially Govind wanted to set up a synthesis radio telescope in India, and in late 1963 he discussed this option with Chris Christiansen who visited the TIFR while *en route* to the Netherlands. But

> An even less ambitious synthesis radio telescope [than the Westerbork Shynthesis Radio Telescope] operating in India at a longer wavelength would have required access to considerably more expertise and technology than was then available in India. Many components would have to be imported, but there was a serious foreign exchange constraint in India at that time. Hence we continued to pursue the cylindrical radio telescope project … (Swarup, 2008: 199).

Govind and Ramesh Sinha then went in search of a suitable site, and in early 1965 they found one, at Ooty in the Nilgiri Hills (see Figure 2). In late 1965 Dr Bhabha enthusiastically approved the establishment of the Ooty Radio Telescope (Swarup, 1991), and through Prime Minister Nehru accessed funding science education funding; the Tamil Nadu State Government provided the land. Sadly, Homi Bhabha died in an air crash in January 1966, before the ORT could be built, but his successor at the TIFR continued to provide strong support for the project.

The Ooty Radio Telescope (ORT) was completed at the end of 1969 (Swarup, 1986), and it is still in operation today. Back then it consisted of

> … a parabolic cylindrical 530 m long × 30 m wide antenna … The reflecting surface is made of 1100 stainless steel wires, each 530 m long and 0.38 mm in diameter. This surface is supported by 24 parabolic frames … placed 23 m apart. The unique feature of the telescope is that its long axis is aligned in the north-south direction along a hill with a natural slope of about 11°, which is equal to the latitude of the observatory. This enables ORT to track a celestial object for about 9.5 hours every day by rotation of the telescope mechanically in the east-west direction about its long axis. The pointing in the north-south direction is achieved by electronic phasing of the 1056 dipoles placed along the 53-m-long focal line of the parabolic reflector. A useful declination range of ±40° can thus be covered.
>
> The telescope operates in a band centred on 326.5 MHz (λ = 92 cm). (Swarup et al., 1991b: 79).

With a total collecting area of 8,700 m^2, the ORT was one of the largest steerable radio telescopes in the world at the time, and could detect sources down to 0.2 jansky. Two different views of the ORT are shown in Figures 46 and 47, and further technical details are provided in Swarup et al. (1991a).

Although the ORT was completed in December 1969, the first occultation was only observed on 18 February 1970 (see Swarup et al., 1971a). By the time the research paper "Lunar occultation observations of 25 radio sources made with the Oooty Radio Telescope: List 1" (Swarup et al., 1971b) was published, Govind's team had already used the occultation method to observe more than 300 sources. At this time (i.e. early

Figure 47: Another view of the Ooty Radio Telescope; reflections of sunlight by 1,100 stainless steel wires are seen on the right. The inset bottom left shows an Indian stamp featuring the ORT (courtesy: TIFR Archives).

1971), the TIFR radio astronomy group comprised 16 researchers, plus several engineers and technicians. One of the researchers was Dr T.K. Menon (but he would return to the USA in 1974). Later, Govind would pay tribute to his team:

> The design and construction of the ORT was a great challenge to the above team, as the development of technology in India was still in its infancy in those years, and foreign exchange for importing components was very limited … (Swarup, 2006: 29).

Srinivasan (2015: 622) elaborates:

> A telescope like that was not easy to build in the late 1960s. The technological capabilities were still primitive in India. While the Tata Consulting Engineers (known then as Tata Ebasco) did the structural and mechanical design, and the Calcutta Firm Bridge and Roof were identified to do the mechanical construction, the group itself lacked experienced engineers. Since foreign exchange was virtually impossible those days, the entire electronics had to be fabricated in India. The indigenous manufacture of critical components like coaxial cables, ultra-high frequency connectors, etc. was just starting. So it was a challenge to build a large telescope like that. The remote location of the site was an added complication.
>
> Nonetheless,
>
> It must be noted that our success was solely due to a close teamwork of all the staff, whose median age in 1971 was about 27 years. (Swarup, 2006: 30).

Srinivasan (2015: 622–623) would go further, and he contrasts Govind's students who worked on construction of the ORT with present-day graduate students:

> The entire electronics had to be built in-house by the handful of students, guided by Sarma and Joshi. This included the phase shifters, the 1024 dipoles along the focal line, the control system and the back end electronics. The students … worked incredibly hard, often 18 hours a day. Contrast this with the present-day trend where students refuse to dirty their hands ... The 'publish or perish' syndrome has overtaken science. One can only be nostalgic about the days when students had a pioneering spirit; they were not obsessed with getting a 'quick Ph D'. Of course, they needed to be motivated and inspired by an inspired leader. Govind Swarup was certainly one of them!

The ORT was very productive as a research instrument:

> During the 1970s, lunar occultation observations of more than 1,000 radio sources were made … The median flux density of these sources is about 0.6 Jy at 327 MHz, being about ten times lower than that of the 3C catalogue. The occultation survey was able to provide accurate positions of the sources, and to reveal their angular structure with arc-second resolution. The data provided inde-

pendent support to the Big Bang model (Kapahi, 1975; Swarup, 1975). Detailed physical properties of many Galactic and extragalactic sources were also derived. In addition, interplanetary scintillation (IPS) observations of selected samples of radio galaxies and quasars provided information on their compact structure with a resolution of 0.05 to 0.5 arc-second at 327 MHz. Valuable contributions were also made in the new field of pulsar astronomy. (Swarup, 2006: 30).

By 1984 the Ooty radio astronomers had

> … made many pioneering contributions and gained world-wide recognition for themselves and for Indian radio astronomy, thus paving the way for the future growth of radio astronomy in India. (ibid.).

It was now time to move on, and the Ooty Radio Telescope evolved into the Ooty Synthesis Radio Telescope (OSRT), which was designed to provide 2-D images of radio sources. The OSRT consisted of the original ORT, plus

> … seven small and inexpensive parabolic cylinders of size 22 m × 9 m at distances of up to 4 km from the ORT. The pointing of these cylinders in both east-west and north-south directions was controlled from the central observatory by means of radio telemetry. In order to achieve a wide field of view of 2° by 40′ arc, ORT was itself divided into five sections and the signals received from the 12 antennas were mutually combined to form a total of 66 interferometer pairs. The resulting image had a resolution of about 1 arcmin at 327 MHz. (Swarup et al., 1991b: 80).

The configuration of the ORT and the 'satellite antennas' is shown in Figure 48.

The OSRT operated at a much lower frequency than any of the other synthesis radio telescopes in existence in 1984, and it also had the advantage of accessing both the northern and southern skies (see Sukumar et al., 1988).

Initially. the OSRT was used to search for new galactic supernova remnants; and to map galactic sources, edge-on and face-on spiral galaxies, including the nearby radio galaxy Fornax A, giant radio galaxies and selected very-steep-spectrum sources in clusters of galaxies (Swarup, 1984). Sukumar et al. 1988: 108) elaborate on the importance of the galaxy clusters research program:

> The OSRT with its high sensitivity and resolution, large field of view and operation at meter wavelength is well suited for a survey of clusters of galaxies which are known to contain very steep spectrum (VSS) radio sources with spectral indices α > 1.2 and head-tail radio galaxies with extended diffuse steep spectrum tails. The VSS sources are remnants of old radio galaxies confined by hot thermal gas. The head-tail sources owe their morphology to the motion of their parent galaxies through the intra-cluster medium leaving behind a trail of relativistic electrons which are confined by the hot ICM gas. Such sources can be used as probes to study the dynamics of ICM.

Further details are provided in Swarup (1991).

Srinivasan (2015: 625) is in an excellent position to make an unbiased assessment of the ORT and OSRT. Here is his 'report card':

> The 'balance sheet' after the exercise to build the Ooty radio telescope read[s] something like this.
>
> - A large number of talented young people were attracted to Swarup's 'crazy idea' (to quote one of his illustrious students) to build a novel world class telescope in the middle of no-where. This included both students of science as well as engineering. The cream of the TIFR/ Atomic Energy Training School wanted to work with Swarup.

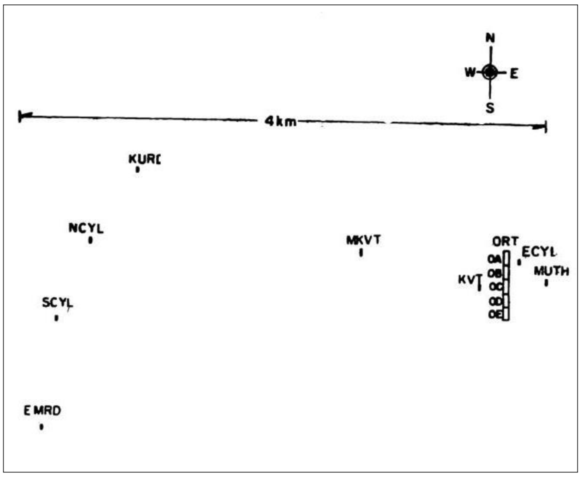

Figure 48: An OSRT map showing the location of the ORT and the satellite antennas (after Sukumar et al., 1987: 97).

> - The project helped several engineering firms – such as Tata Consulting Engineers – to reach the next plateau in their capability and sophistication.
> - The successful indigenous design and construction of the Ooty Radio Telescope led to the development of a large microwave antenna industry in India, starting with the construction of the ARVI satellite earth station north of Pune in 1971.
> - The Ooty telescope produced not only good science; it produced a number of outstanding astronomers and engineers, endowed with leadership qualities.
> - There was tremendous cohesion and camaraderie within the group.
> - This group was to stay together and design and build the GMRT – the world's largest low frequency telescope.

More on the aforementioned GMRT later, in Section 10.

9 INTERNATIONAL SCIENCE AND THE PROPOSED GIANT EQUATORIAL RADIO TELESCOPE (GERT)

Flushed with success experienced with the Oorty Radio Telescope, in 1976 Govind began thinking about constructing a radio telescope of similar design but about four times the length of the ORT, and sited on the Earth's equator—where flat terrain would facilitate rapid construction of the antenna and make it relatively easy to operate (and track sources for up to 12 hours per day).

In 1978 this formally became known as the 'Giant Equatorial Radio Telescope' (GERT), and would consist of a single cylindrical antenna 2 km long and 50 m wide, and operating "… at a few discrete [protected] bands in the range of about 38 and 328 MHz." (Swarup, 1981: 269).

As part of his overall proposal, Govind also envisioned a second phase:

> … to construct an aperture synthesis interferometer around GERT at a relatively small additional cost by adding 14 parabolic cylinders of smaller dimensions (say 50 m × 15 m) on a baseline measuring 14 km east-west and 12 km north-south. (Swarup, 1981: 272).

The GERT Synthesis Telescope was thought to be ideal for the investigation of steep-spectrum sources with low surface brightness, and as the largest and most powerful low frequency radio telescope in the world would improve our understanding of the evolution of galactic and extragalactic radio sources. Furthermore, by including the GERT Synthesis Telescope in existing VLBI networks, it would be useful in studying galactic nuclei, compound components in galactic objects and proper motions of pulsars.

The science case for a fully-developed GERT was overwhelming, but more than this, Govind (1981) pointed to the inevitable technology spin-offs for countries involved in this venture.

In April 1979 a workshop attended by scientists from Egypt, India, Indonesia, Iraq, Kenya and Nigeria, and Professors W.N. Christiansen from Australia and T. Hewish from England (representing UNESCO) was held on India to "… consider the technical feasibility and scientific merits of the project." (Swarup, 1981: 276). There was over-whelming support for the proposal, and for the establishment of the International Centre for Space Sciences and Electronics (INISSE), with the GERT as its flagship research facility (see Swarup et al., 1979).

Finding a suitable site for the GERT was not difficult. Although the Earth's Equator traverses various nations in South America (Ecuador, Colombia and Brazil), Africa (Gabon, Congo, the Democratic Republic of Congo, Uganda, Kenya and Somalia) and Asia (Indonesia) as shown in Figure 49, potential sites in Kenya and Indonesia were quickly settled on. The Kenyan site was then selected, but although the Kenyan Government was supportive and the Indian Government agreed to fund half of the all-up cost of US$20 million, the project fell through after President Kenyatta died (in August 1978) and Kenyan scientists were not able to follow up on the project.

Attention then switched to Indonesia, and

> … two suitable sites were identified in West Sumatra (Indonesia) very close to the Equator, but progress was slow because of a lack of astronomical interest in most of the developing countries [which needed to provide fin-

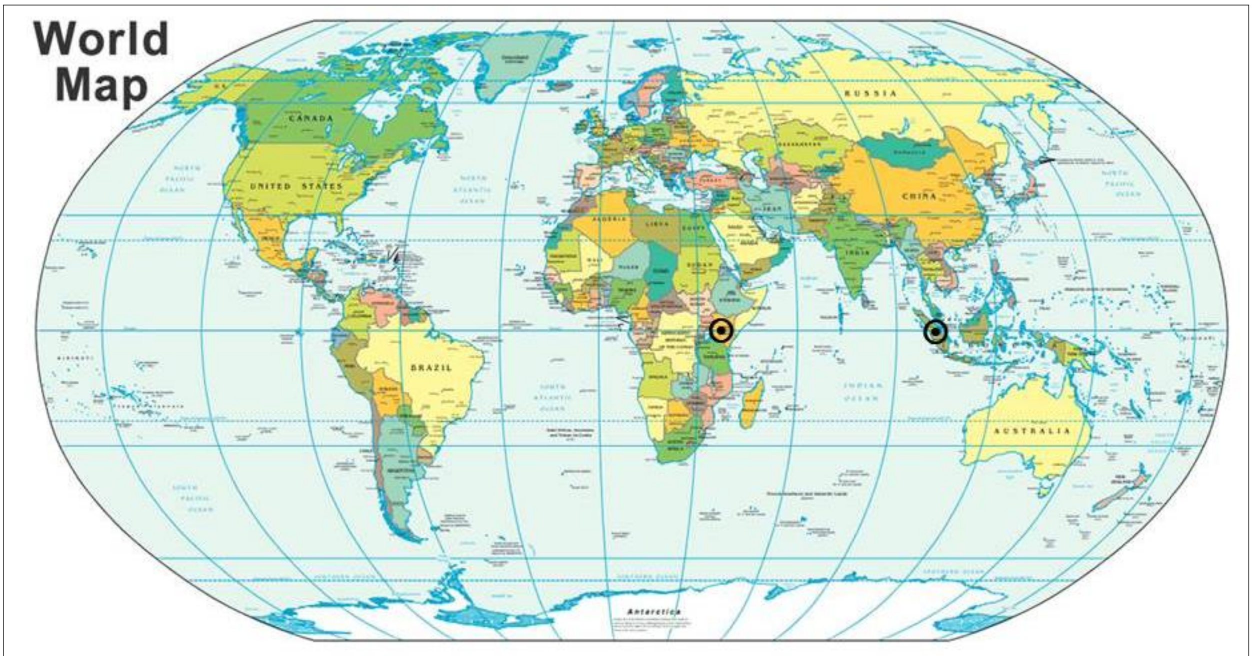

Figure 49: Map showing the equator and sites selected for the GERT in Kenya (left) and Indonesia (right) (map: Wayne Orchiston).

> ancial or other support for the project]. In 1983 President Suharto of Indonesia pledged support for half the cost of the GERT. However, concerns were expressed about the high levels of seismic activity in West Sumatra, even though our engineers indicated that a suitable antenna could be built there without much cost penalty.

Notwithstanding President Suharto's invaluable support and a financial commitment from the Indian Government, the seismic concerns sent shock waves through the project. Apparently they were 'the last straw', for by the end of 1983 Govind had decided to abandon the GERT altogether and champion another major project in its place. Thus, the GMRT was born.

10 THE GIANT METREWAVE RADIO TELESCOPE (GMRT)

By early 1982 Govind was already aware that

> … revolutionary methods of phase and amplitude closures and self-calibration allowed radio astronomers to obtain radio maps of celestial sources of high quality even in the presence of phase and amplitude variations caused by electronics, the ionosphere or the atmosphere. It also seemed feasible to connect the antennas of a radio interferometer of a relatively large separation by using lasers and optical fibres.

It was apparent that the TIFR radio astronomers would not be able to use the GERT to study proto-clusters, "… the postulated condensates of neutral hydrogen existing at very high redshifts prior to the formation of galaxies in the Universe." (Swarup, 2006: 30). What was needed was a major new low frequency radio telescope … and once again Govind had a brainwave:

> Initially, in a flash, I divided the 2 km long and 50 m wide GERT into 34 smaller parabolic cylindrical antennas, joined by optical fibres, to form a synthesis radio telescope of about 25 km in extent. Since the operation over a wide frequency range seemed problematic using parabolic cylinders, we finally invented the concept of SMART (Stretched Mesh Attached to Rope Trusses) in order to build parabolic dishes of 45 m diameter economically and affordably: in this case necessity was the mother of invention … (Swarup, 2006: 30).

Re the SMART concept, Srinivasan (2015: 626) explains:

> The reflecting surface – a stainless steel mesh – is attached to these rope trusses. This is what gives the 'see-through-look' to the dish. This ingenious invention by Swarup greatly reduced the cost of the dish, by reducing the wind load, and has been acclaimed internationally.

Srinivasan (2015: 627) notes that when Govind first came up with this clever design "… he called it '*The Great Indian Rope Trick*'! Later he nicknamed it SMART."

Govind's research objective, plus

> … experience gained in designing and building the ORT, and the dynamism of the younger members of our group propelled me to propose the Giant Metre-wave Radio Telescope on 1 January 1984. (Swarup, 2006: 30).

Chris Christiansen also believed this was the right path for Govind (and India) to follow. On 30 July 1984 he wrote:

> I think that you are doing the right thing in continuing your work at the lower end of the radio frequency spectrum. This part of the spectrum has been relatively neglected. India is a good place to do such work because of its relative radio "quietness" and you have developed good techniques for such work ... (Christiansen, 1984).

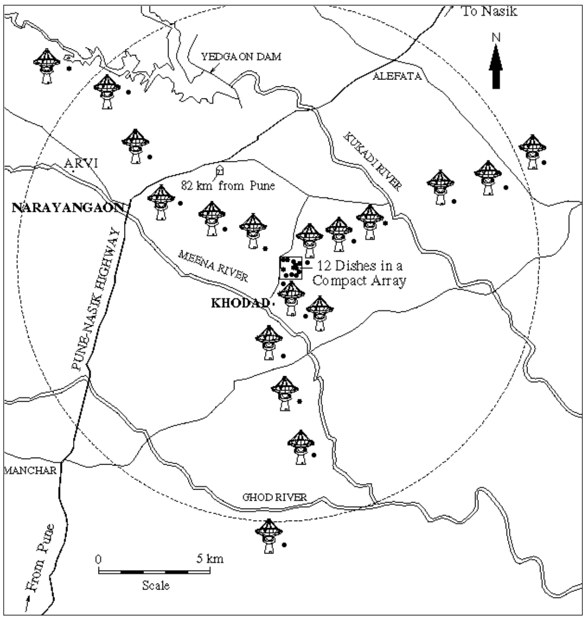

Figure 50: Map showing the location of the thirty 45-m fully steerable parabolic dishes of the GMRT, located near Khodad in western India (courtesy: TIFR Archives).

The Government of India gave its approval in March 1987, "… after the Prime Minister, Rajiv Gandhi—who was an active radio ham—was satisfied after asking three penetrating questions." (Swarup, 2008: 200). The GMRT was no longer a dream, and Govind's group moved from Mumbai to Pune and formed the National Centre for Radio Astrophysics (NCRA), but still under the TIFR umbrella.

The GMRT is a synthesis radio telescope consisting of thirty parabolic dishes each 45 m in diameter each, spread in an approximate Y-shaped configuration across a region of about 25 km diameter (see Figure 50). There are fourteen antennas in a central array of about 1 km × 1 km (Figures 51 and 52), while the remaining

Figure 51: Some of the GMRT dishes in the central array (courtesy: TIFR Archives).

Figure 52: A close up of one of the 45-m antennas, with six others in the background (courtesy: TIFR Archives).

sixteen dishes—as Figure 50 indicates—are situated along the three 14 km long arms (Swarup et al., 1991a). The GMRT operated at the following radio frequency bands: 120–180, 225–245, 300–360, 580–650, and 1000–1430 MHz. It takes about 10 hours of observations to build up an image of a discrete source. The GMRT became fully operational in 2000.

Country	Nos
Argentina	13
Austria	5
Australia	75
Belgium	7
Brazil	11
Canada	50
China	19
Chile	1
Denmark	6
France	66
Germany	40
India	847
Iran	2
Italy	49
Ireland	7
Japan	21
Korea	6
Malaysia	3
Mauritius	3
Mexico	7
Netherlands	75
Nigeria	1
Poland	55
Portugal	3
Russia	13
Spain	14
South Africa	16
Sweden	2
Taiwan	20
UK	163
USA	169
Total	1769

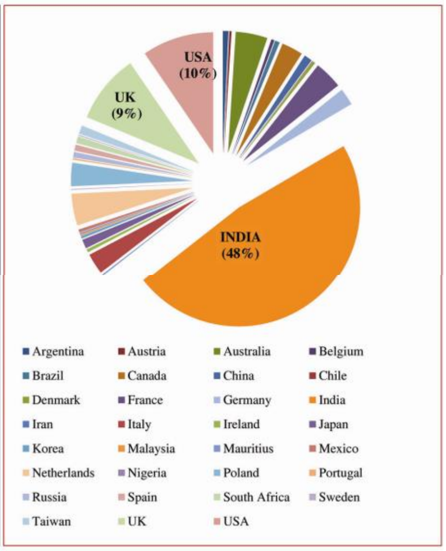

Figure 53: A pie diagram showing successful GMRT observing proposals 2002–2015 by country (after Srinivasan, 2015: 628).

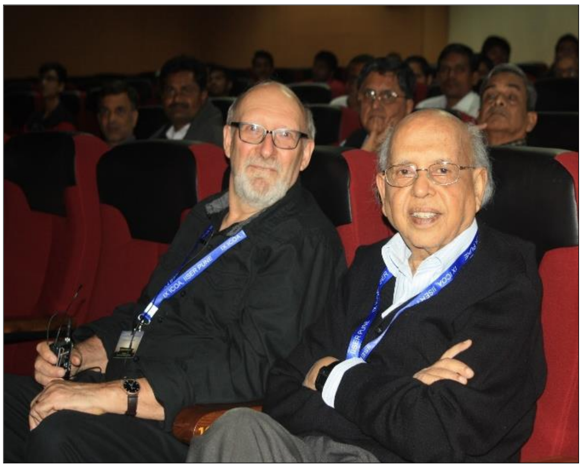

Figure 54: The November 2016 ICOA-9 Conference featured one Public Lecture, which was presented by Professors Wayne Orchiston (Thailand) and Govind Swarup (India), who are shown in the foreground. Their topic was the early development of radio astronomy in Asia, with emphasis on Australia, China, India, Japan and New Zealand (after Orchiston et al., 2018: xxii).

The GMRT is the world's largest and most powerful low frequency array and has been popular with Indian and overseas radio astronomers from the time it became operational. As Figure 53 illustrated, between January 2002 and September 2015 there were 1769 successful research proposals submitted by astronomers from 31 different countries. Just under half of all proposal came from India.

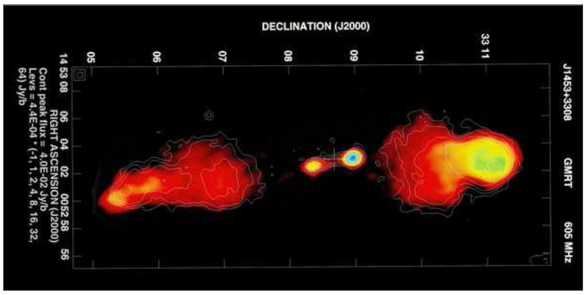

Figure 55: A false-colour image of the unusual radio galaxy J1453+3304 (courtesy: TIFR Archives).

During the November 2016 Ninth International Conference on Oriental Astronomy, which was held in Pune, Govind Swarup and the first author of this paper stepped in at the last-minute (Figure 54) to present a Public Lecture when the scheduled speaker could not attend. In their review of the historical development of Asian radio astronomy, Govind discussed the many research accomplishments of the GMRT and singled out three of special interest (Orchiston and Swarup, 2018: 204–205). They were (but with revised figure numbers for this paper):

> (1) Observations made with the GMRT have have led to the discovery of the new and interesting double-double radio galaxy (J1453+3304) (Saikia et al. 2006), which is shown in [Figure 55]. The outer-most lobes are remnants of an earlier epoch of the radio source when the supply from the central engine was stopped; millions of years later the central engine was activated again, giving rise to another double radio source.
>
> (2) The GMRT is being used to search for giant radio galaxies and probe the intergalactic medium. The giant radio galaxy J1420-054 [shown in Figure 56] is identified

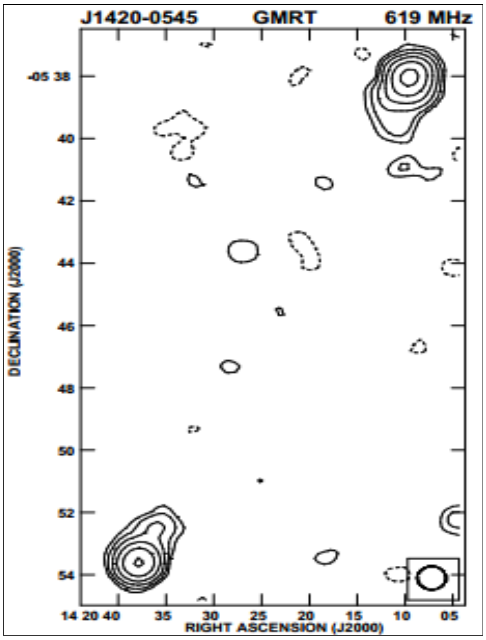

Figure 56: The radio source J1420-054, bottom left, is currently the largest-known giant radio galaxy (courtesy. TIFR Archives).

with an optical galaxy at z = 0.3067, and has a projected linear size of 4.69 Mpc (15 million light years). This is currently the largest known radio galaxy (see Machalski et al., 2007).

(3) A recent outstanding result relates to the formation of structure in the Universe by the merging of galaxies and clusters of galaxies, and is the discovery of a giant double radio relic in the Planck Sunyaev-Zel'dovich Cluster [Figure 57].

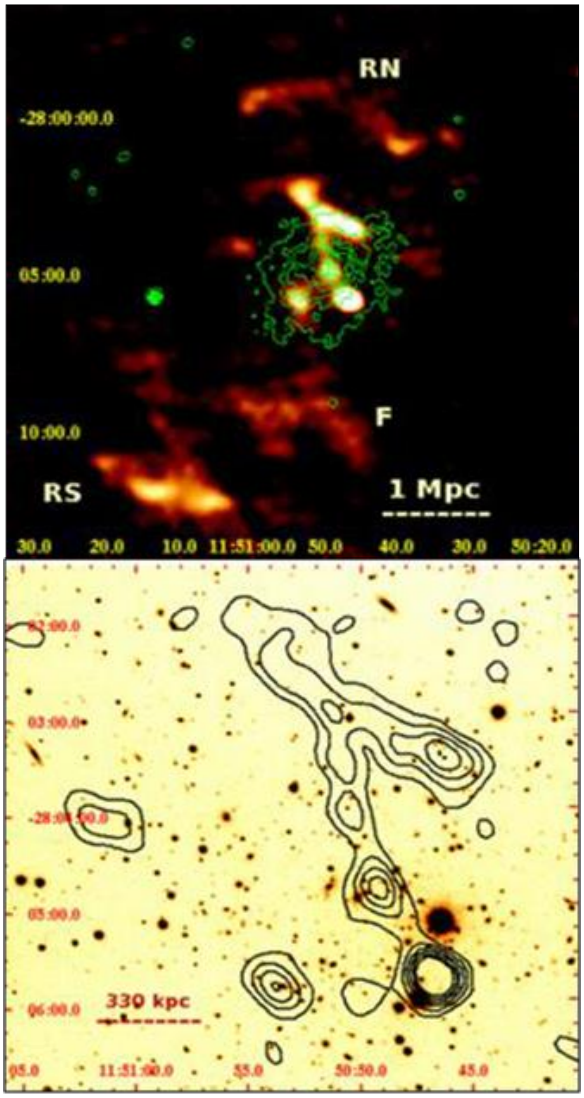

Figure 57, Top: XMM-Newton contours in X-rays (green) superimposed on the 150 MHz GMRT radio map of the cluster (orange and yellow). Bottom: The 150 MHz GMRT radio map near the cluster centre, superimposed on the R-band optical image (after Bagchi et al., 2011: 3).

Professor Srinivasan (2015: 627) has the last word about the GMRT:

> The GMRT should become the benchmark for many things in Indian science. It demonstrates that self-reliance in instrumentation is possible. It is true that far more complicated things, such as Fast Breeder Reactors, advanced satellites, giant rockets like the PSLV and GSLV, have been made. But they were made by large organizations with large budgets. GMRT was made with a shoestring budget, at a fraction of what it would have cost elsewhere in the world. And it was made by a small team of scientists and engineers working in unison.

11 DISCUSSION

11.1 Unique Educational Initiatives

Govind and the Indian physicist and educationist Professor V.G. Bhide promoted an all-inclusive approach to teaching science. Their proposal led to a 5 year integrated program for intensive education in science and the setting up of the Indian Institute of Science Education and Research (IISER) in Pune and Kolkata in 2005 and later in other places in India. Govind considers this as one of this important achievements (Srinivasan, 2015).

In addition, with the assistance of villagers Govind was able to form the Khodad Rural Science Center (Figure 58). This was another of his dreams: to encourage rural students to study science by offering them hands-on experiments. This is a wonderful example of how a world-famous scientist can influence Indian education at the grass-roots level and help change society (Phakatkar, 2015).

11.2 Recognition and Rewards

Over the years, Govind has received many national and international prizes and awards, and we can do no better than to once again quote Srinivasan (2015: 629), a personal friend and self-proclaimed admirer:

> I would be doing an injustice to him [to Govind] if I were to dwell on these at any length, for he never aspired for any awards. Nevertheless, I would like to mention a few of them.
>
> Govind Swarup is immensely proud of the fact that C. V. Raman elected him to the Fellowship of the Indian Academy of Sciences in 1967. Subsequently, he was elected to the Royal Society of London, and to the Pontifical Academy in the Vatican.
>
> The astronomical community bestowed on him the Grote Reber Medal, the most coveted award for achievement in radio astronomy.

11.3 Other Indian Radio Astronomy Initiatives

In science, often the outstanding achievements of one group serve as a catalyst that leads to the emergence of other like-minded groups, and this is precisely what happened in India once Govind Swarup's group at the TIFR became prominent internationally. Eventually, this led to radio astronomy research being launched at the Raman Research Institute and the Indian Institute of Astrophysics (in Bengalaru) and the Physical Research Institute (in Ahmedabad).

Figure 58: The Khodad Rural Science Center is located in the village of Khodad, close to the central cluster of GMRT radio telescopes. With a population of about 5,000, Khodad is mainly an agricultural centre, but because of the GMRT it has also become a tourist destination (photograph: Sudhir Phakatkar).

Scientists at some of these facilities (especially at the Raman Research Institute) established close collaborations with Govind's group at the TIFR.

12 CONCLUDING REMARKS

Govind Swarup is a child of modern India but a man of two worlds. He was born and part-educated in colonial India, but grew up as India gained its independence. He remembers hearing Mahatma Gandhi's scintillating speeches when he was still an impressionable school boy, and this instilled in him a patriotic spark that has lasted a lifetime. Govind could so easily have built an international career as a radio astronomer in Australia or in the USA—indeed in any country —but he chose India (to its eternal gain and their loss).

Jawahar Lal Nehru was a great visionary Prime Minister, and in the early years of independence he saw the newly-established scientific laboratories as the 'temples' of modern India. One such temple was the Tata Institute of Fundamental Research in Bombay/Mumbai, but all temples are useless and internationally invisible unless sustained by suitable 'high priests'. There is no doubt that Govind Swarup has filled that role admirably for more than half a century, and in the process he has built the Institute's radio astronomy group into one of its flagship accomplishments (see Sreekantan, 2006).

In this regard, we wholeheartedly agree with Srinivasan (2015: 630) that Govind Swarup's career "… personifies the stuff legends are made of." It has been our pleasure and privilege to know Govind, and we applaud his intellect, his inspirational leadership, his remarkable inventtions that have helped reshape astronomical instrumentation—and the role that India has been able to play—and lastly, his countless achievements as a scientist and a researcher.

In the 'Concluding Remarks' in their 2016 Asian history of radio astronomy review paper, Orchiston and Swarup (2018: 207) noted that

> Over the last sixty years, there has been a succession of remarkable scientific discoveries made by radio astronomers in the USA, in European countries and in three different Asian nations: Australia, India and Japan. (Orchiston and Swarup, 2018: 207).

What is particularly remarkable is that most of the Indian scientific discoveries were the direct or indirect result of the achievements of just one remarkable man: Govind Swarup. What is more, he never tires—even though he is supposedly retired he continues to contribute to science and technology and build India's international reputation in radio astronomy.

Govind, we salute you for all that you have accomplished for Indian astronomy, and we hope that you will enjoy and cherish this little memento. We had hoped to formally present this paper to you on your birthday, during 'The Metre Wavelength Sky II' conference" (Figure 59), but—as you know—unfortunate last minute visa problems prevented the first author of this paper from visiting India. We hope, nonetheless, that you will enjoy reading this belated birthday present and that it will bring back many fond memories.

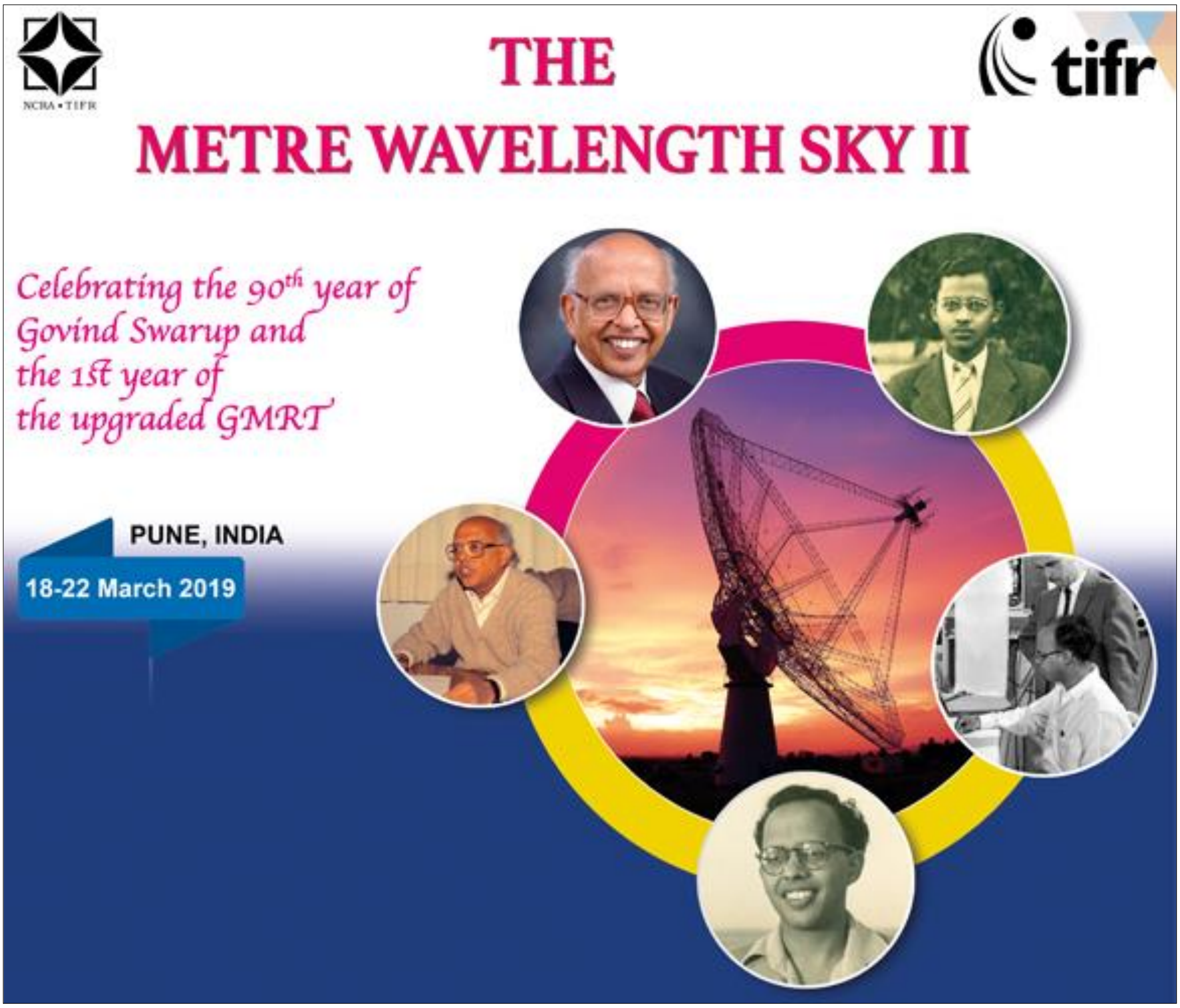

Figure 59: The attractive poster about 'The Metre Wavelength Sky II' conference.

13 NOTES

1. At that time, Kodaikanal had a vibrant optical solar astronomy program (see Kochhar and Orchiston, 2017), but was keen to expand and include radio astronomy. This would be Parthasarathy's responsibility upon his return to India.
2. RP began as a Division of the Government's Council for Scientific and Industrial Research (CSIR), which in 1949 was reconstituted as a new organisation with a similar name, the Commonwealth Scientific and Industrial Research Organisation (CSIRO).
3. For an example of the use of this 'discarded' equipment see Wendt and Orchiston (2018).
4. But this was a 'two-way street' for at first most optical astronomers viewed radio astronomers with suspicion, and it would take time before they were accepted as part of the international astronomy community (e.g. see Jarrell, 2005).
5. Bracewell retired from teaching in 1991, but continued his research, and by the time he died in 2007 he was an acknowledged authority not only on radio astronomy but also on Fourier transforms and medical imaging (e.g. see Bracewell, 1984; 2005; Frater et al., 2017; Thompson and Frater, 2010). In the twilight years of his life Ron also cultivated an interest in astronomical history, and he published two papers in this journal (Bracewell, 2002; 2005).
6. Govind was only the second student to complete a Stanford radio astronomy PhD under Ron Bracewell. His degree was awarded in 1961 for a thesis titled "Studies of Solar Micro-wave Emission Using a Highly Directional Antenna".
7. Note that Christiansen's 'Chris Cross' also was modified by the addition of the 60-ft (18-m) 'Kennedy Dish' near the eastern end of the E-W arm of the array so that it too could be used as a compound interferometer. The Kennedy Dish was relocated to Parkes in 1963, but between

> … August 1961 and October 1962 … the FCI [Fleurs Compound Interferometer] was used to determine the right

ascensions and angular sizes of eight well-known discrete sources. (Orchiston and Mathewson, 2009: 25).

As at Stanford, two papers were published on this work (Labrum et al., 1963; 1964).

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Professor Wayne Orchiston was born in New Zealand in 1943. He works at the National Astronomical Research Institute of Thailand in Chiang Mai, and is also an Adjunct Professor of Astronomy at the University of Southern Queensland in Toowoomba, Australia. In the 1960s Wayne worked as a Technical Assistant in the CSIRO's Division of Radiophysics in Sydney, and forty years later joined its successor, the Australia Telescope National Facility, as its Archivist and Historian. He has a special interest in the history of radio astronomy, and in 2003 was founding Chairman of the IAU Working Group on Historic Radio Astronomy. Through James Cook University and the University of Southern Queensland he has supervised six PhD or Masters theses on historic radio astronomy, and has published papers on early radio astronomy in Australia, England, France, India, Japan, New Zealand and the USA. He also has published extensively on ethnoastronomy, the history of meteoritics, historic transits of Venus and solar eclipses, historic telescopes and observatories, and the history of cometary and asteroidal astronomy. In 2016 and 2017 Springer published his books, *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits* and *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe* (co-editored by Tsuko Nakamura), both of which contain various chapters on early radio astronomy. At the moment, Wayne is working on a book about early Australian radio astronomy, co-authored by Peter Robertson and Woody Sullivan, and this will be published by Springer in 2020. Currently, Wayne is the President of IAU Commission C3 (History of Astronomy), and he is a co-founder and the current Editor of the *Journal of Astronomical History and Heritage*. He also is the Series Editor for Springer's books on Historical and Cultural Astronomy. In 2013 the IAU named minor planet 48471 Orchiston after him.

Sudhir Phakatkar worked at the GMRT from 29 years as a Technical Assistant in Electronics for Telescope Receiver system. Simultaneously he worked on popularizing science among students and laypersons. In the process, he wrote two books in the vernacular language (i.e. Marathi), one about the GMRT and the other a biography of Professor Govind Swarup. Sudhir writes on science and technology for Marathi newspapers, magazines and radio stations, and he works as a guide at the Khodad Rural Science Center.

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DELLA PORTA, COLONNA, AND FONTANA: THE ROLE OF NEAPOLITAN SCIENTISTS AT THE BEGINNING OF THE TELESCOPE ERA

Mauro Gargano
INAF-Astronomical Observatory of Capodimonte,
Salita Moiariello, 16, 80131 Napoli NA, Italy.
Email: mauro.gargano@inaf.it

Abstract: Giovan Battista Della Porta is best known for his theory of experimental science; Fabio Colonna is well-known for his botanical studies; and Francesco Fontana for his powerful telescopes and the exact observations of the Moon and planets, particularly of Mars. All three were interested in astronomy. But when were the first observations in Naples? And what did they observe? And by whom? This paper, based on the correspondence of the protagonists, attempts to retrace the events of the first Neapolitan astronomical observations.

Keywords: telescopes, astronomical observations, Giovan Battista Della Porta, Fabio Colonna, Francesco Fontana

1 INTRODUCTION

The role of Galileo Galilei in the technological development of lenses and telescopes, along with his primary role in defining a method to explain and decode natural phenomena, has been studied and analyzed by many authors over the past four hundred years. Just as Galileo's astronomical observations of planets, satellites, sunspots and stars opened new frontiers in the study of the cosmos, the multitalented figure of Giovan Battista della Porta played a central role in many fields of scientific, alchemical and literary knowledge. The charisma of Galileo and della Porta went beyond national borders and helped to give great prestige to the Accademia dei Lincei. Moreover, the optical studies of Della Porta contributed to, if not anticipated, the development of technologies for the construction of the first optical devices, leading up to the telescope, as he stated in a letter to Federico Cesi. Although primarily interested in botany, Fabio Colonna had an experimental approach to the sciences and natural phenomena, so much so that he was also interested in optics and astronomy. Finally, Francesco Fontana, a much discussed scientist who made telescopes and astronomical observations, aroused great interest and some envy.

The scientific debate in Naples in the first half of the seventeenth century appeared Manichaean and vain in its extreme contrast between modernity and obedience to the scholastic tradition. The presence in Naples of Della Porta, Colonna, and Fontana as well as Campanella, Imparato and Stelliola, revived the Neapolitan panorama of cultural and philosophical discussion. The collaboration between the elderly 'Della Porta Mago' and the young botanist Colonna produced interesting developments in the construction of both Galilean telescopes and those of a new optical design, the so-called 'Keplerians'. Studies and the advancements presented by Della Porta and Colonna merged with the great skills of Fontana, an obscure Neapolitan personality who has been talked about for decades because of his instruments and scientific results.

Based on the original documents and correspondence of the Neapolitan scientists, this paper traces the first steps in the development of astronomy and optical technology in Naples, a short but exciting period characterised by great enthusiasm and interesting scientific results.

2 THE TELESCOPE OF GALILEO GALILEI

"Mister Galileo of Galilei family, true mentor of the mathematical sciences, and highest professor of his studies for students in the University of Padua." (Gagliardi, 1608).[1] This is the heading of a dedication written by the jovial Padua poet and painter Giuseppe Gagliardi in March 1608. At this time Galilei (1564–1642; Figure 1) was undoubtedly a revered Professor at the University of Padua and an excellent manufacturer of mathematical instruments. He knew ancient and modern astronomical theories, confiding to Kepler that he had "… embraced Copernicus' opinion already for many years …" (Galilei, 1597), and he corresponded with Tycho Brahe about different cosmological hypotheses (Brahe, 1600). Galilei began practicing astronomy towards the end of October 1604, following the appearance of Kepler's Supernova in Serpens.

This extraordinary event, the second after the supernova of 1572 observed by Tycho Brahe in Cassiopeia, marked the beginning of Galilei's great interest in the study of the cosmos. He delivered three passionate lectures at the University of Padua about this unusual astronomical event (Rosino, 1995: 16–17) in the presence of very large audiences:

> On 10 October 1604 a certain strange light was first observed in the heavens ... ooh guys! Many of you rushed here to listen to my dissertation, you are witnesses of this marvellous appearance, [you stay here] with

> great care and unanimous interest to learn the substance, the motion, the place and the reason for that appearance. Desire amazing and worthy of your minds, my goodness! (Galilei, 1604).

With his instruments and observations, the Tuscan scholar would transform the ancient science of the heavens into the 'new astronomy'.

The tale of the first telescope made by Galilei is told in a letter that Galilei wrote to his brother-in-law Benedetto Landucci (1569–?) on 29 August 1609, four days before he presented this instrument to the Doge and the Venetian Senate:

> I haven't written to you after receiving the wine you shipped to me because of the lack of arguments, I write to you now ... Therefore you must know that about two months ago the fame of a spyglass presented in Flanders to Count Maurice has here spread, it is made in such a way that very distant things appear quite close, so that a man can be distinctly seen two miles away ... It seemed to me that having to rely on the perspective science, I began thinking how to make it, finally I found the manner, and I have made one so perfectly that it far exceeds the reputation of the Flanders one. (Galilei, 1609).

Figure 1: A painting of Galileo Galilei by Justus Sustermans in 1636, now in the National Maritime Museum, London (https://commons.wikimedia.org/wiki/File:Justus_Sustermans_-_Portrait_of_Galileo_Galilei,_1636.jpg).

Commenting on the news of the spyglass, Paolo Sarpi (1552–1623) wrote to Francesco Castrino (ca.1560–1630) that he considered it uninteresting and not really useful:

> In Italy we haven't news, except the appearance of the eyepiece showing things far away, I admire it very much for the beauty of the invention and for the dignity of art, but I do not consider it useable both in terrestrial or maritime war. (Sarpi, 1609).

In scientific literature there were many well-known examples about the idea and the concept of using lenses that magnified distant objects. Almost certainly the oldest text describing the magnifying effects of 'refracted light' was the *Opus Majus* by Roger Bacon written in 1267, in which the English philosopher and scientist says:

> Thus from an incredible distance we may read the smallest letters, and count the smallest grains of dust and sand owing to the magnitude of the angle under which we viewed them ... So also we might cause the Sun, Moon and stars in appearance to descend here below, and similarly to appear above the head of our enemies. (Bacon, 1733: 357).

In the sixteenth century, Girolamo Fracastoro (1538: 58) dealt with the topic of reflected and refracted light in the volume *Homocentrica* published in 1538, where he wrote that the use of lenses would make the Moon and the stars appear very near and not farther off than the tops of towers. Leonardo da Vinci argued in his studies on optics about some devices that allowed him "… to see the Moon enlarged …" (Da Vinci: 518r). Finally, Francesco Sizzi, a bitter opponent of Galilei, wrote that Pope Leo X held an excellent telescope, allowing him to clearly observe from Florence the birds flying in the mountains of Fiesole (Sizzi, 1611: 57r).

The first document attesting the use of a telescope is a report to Prince Maurice of Nassau (1567–1625), Stadtholder of the States General of the Hague, of a visit in 1608 by a Siamese diplomatic delegation.[2] In the presence of Ambrogio Spinola Doria (1569–1630), a Genoan General, the optician Hans Lippershey (1570–1619) showed how his 'optical tube' allowed one to see objects 12–16 km away as though they were in the foreground. In mid-September 1608, Lippershey applied for the patent for his device,[3] and fifteen days later Jacob Metius (ca.1571–1628), another Dutch instrument-maker, did the same (*Minute Book …*, 1608a: 169r; *Minute Book …*, 1608b: 178v). Although Lippershey's request was not approved—the Commission asked him to improve the spyglass to make it suitable for binocular observation—the States General of the Hague ordered three samples of the 'Dutch perspective glass'. News of the device spread rapidly throughout Europe, and in April 1609 some French magazines, such as *Le Mercure François* and the *Journal du Regne de Henry IV*, reported that many Parisians were interested, with the glasses, "… allowing people to see distant objects clearly." (*Le Mercure …*, 1611: 338v–339r; cf. De L'Etoile, 1741: 513– 514).

The telescope also became a stylish element for distinguished men in paintings done at this time, such as General Spinola at the Breda fortress in the canvas of Diego Velasquez (ca. 1624), and Archduke Albert VII of Habsburg in the painting by Pieter Bruegel the Elder (ca. 1609). The telescope seemed to be a status symbol that was flaunted, as in *The Allegory of the Vision* by Bruegel (1617) and Paul Rubens (1617). In these paintings, the spyglasses appear to be decorative objects to show off in society, or a new garden 'divertissement'. Even the first known astronomical observation, made by Thomas Harriot (1560–1621) seemed more like a logbook note to remember a night spent with the "… silvery face of the beautiful Cynthia." (Capocci, 1857: 11). In the London house of the Earl of Northumberland, this prolific mathematician and shrewd astronomer who studied Halley's Comet in 1607, observed the Moon on 26 July 1609 and made a small portrait of it. Although the sketch was very simple, it was interesting to understand the real capabilities of the lenses. It showed that the terminator and the contours of the main craters were somewhat uncertain. It would be Galileo's observations, made in the last weeks of 1609, that showed the 'true' face of the Moon, the irregularities of its surface, the craters, mountains and valleys:

> When I gave up observation of terrestrial objects, I turned my attention to the celestial bodies; and first I saw the Moon so close as if it was barely two terrestrial diameters distant. After that, with incredible delight I observed several times the stars fixed as well as wandering; and when I saw their very great number, I began to study the method by which I might be able to measure their distances, and I finally found it. (Galilei, 1610: 6r–v).

Galilei's observations were not only phenomenal but they immediately created incredible enjoyment for the soul. Galilei analyzed the observational data, studied the physical aspects, and refined his investigation techniques. The scientific method applied to the analysis of the cosmos was born. Modern astronomy was born!

3 THE EARLIEST ASTRONOMICAL OBSERVATIONS MADE IN NAPLES

Who invented the telescope? Galileo? Lippershey? Or was the telescope invented 'ex nihilo', as van Helden (1977) writes? In Naples, Giovan Battista Della Porta and Francesco Fontana both claimed to have conceived and built telescopes. Did the city of the mermaid Parthenope provide a fruitful background to stimulate such scientific and technological developments?

Throughout the sixteenth and seventeenth centuries Naples and its Kingdom were under viceroy control from Austria and Spain and the cultural and academic fabric was conditioned by imperial rule, transforming the 'very noble Naples' into the 'very loyal Naples', as the historian Giuseppe Galasso (1996) defines these sweeping changes in an insightful analysis of that era. Scholastic doctrine was the beacon of cultural debate, including the scientific one. The tradition of the great academies of Giovanni Pontano and Jacopo Sannazaro appeared blurred by sectarian meetings more inclined to "… vain pompous rumours … [than to] useful and elevated readings." (Cesi, 1616). The fertile ground to promote a scientific debate in Naples, like the rest of Europe, could be found in some private circles and academies such as the Oziosi of Giovan Battista Manso (1567–1645), the Secrets of Della Porta, and the Lincei.

Figure 2: The frontispiece of *Magiae Naturalis* (Lugduni Batavorum, 1650) with a portrait of Giovan Battista della Porta.

Among the personalities who animated these assemblies, men like Giovan Battista Della Porta, Fabio Colonna, Ferrante Imperato, Marco Aurelio Severino and Niccolò Stelliola were known beyond Neapolitan borders. They imposed themselves as representatives of the physical, medical and botanical sciences. To the circles of these prestigious scientists, we can add Francesco Fontana, who attracted the worthy consideration of most astronomers of the time because of his telescopes and observations.

Giovan Battista Della Porta (ca.1535–1615; Figure 2) was a scientist who "… with the fast wings of the mind …" (Crasso, 1666: 170) investigated various aspects of physics: alchemy, astrology, physiognomy and optics. He engaged in many philosophical and scientific discussions with Tommaso Campanella, until they held a public debate in 1589 in the monastery of San Domenico, in the room where Thomas Aquinas con-

Figure 3: An etching of Fontana's portrait printed in his *Novae Colestium Terrestriumque Observationes ...*

ducted his lessons. In his best known volume, *Magiae Naturalis*, published first in 1558 and reprinted in 1589,[4] Della Porta deepened his studies of optics, including the configuration of different kinds of lenses, both concave and convex, and exhorted: "… if you know how to use them correctly together, you will see things, both nearby and in the distance, clearly and enlarged." (Della Porta, 1611: 647).

We do not know if Della Porta had access to the Dutch optical tube, but when he was aware of Galilei's telescope, he wrote to Federico Cesi reminding him that the 'eyeglass secret' refered to his insight, described in *Magiae Naturalis*, to combine two different lenses and obtain a great advantage in telescopic observation. However, he recognized that Galilei had improved the instrument and obtained astonishing results:

> The invention of eyeglasses in the tube was mine. Galileo, professor of Padua, adapted it, and with it he found 4 new planets in the sky and thousands of fixed stars, and just as many, never seen in the Milky Way, and great things on the orb of the Moon. They fill the world with astonishment. (Della Porta, n.d.).

Della Porta's argument seemed to satisfy everyone. In reality, Giovan Battista Manso provided further and different details on Della Porta's feelings. In a letter addressed to Galilei, Manso (1610a) expressed admiration for the 'new Columbus', because the "… discoveries of the new skies …", indicated he was "… a person of such rare virtues and singular doctrine." But in a letter to Paolo Beni (1552–1625), a Reader in Padua, Manso (1610b) pointed out that "Mr. Galileo has provoked no small jealousy in our Mr. Porta for making the invention of glasses so perfectly." In his *Dissertatio cum Nuncio Sidereo* that confirmed the validity of the Galilean discoveries, Kepler also highlighted his thoughts on this controversy:

> So powerful a *telescope* seems an incredible undertaking to many people, yet it is neither impossible nor new. Nor was it recently produced by the Dutch, but many years ago it was announced by Giovan Battista della Porta in chap. X, on the properties of lenses, in book XVII of *Magiae Naturalis* [Second Edition, published in 1586]. (Kepler, 1610).

The dispute seemed to end with the publication of *Il Saggiatore* in 1623. This text is introduced with the poem 'Ad Galilæum Galilæi' by Johann Faber (1574–1629), the German scientist who in 1608 stayed for some months in Naples, and said: "Della Porta holds the first, the German has the second, [but you], Galileo, shine before others." (Galilei, 1623: a1r). A few years later, another claim would reopen the quarrel: that the Neapolitan Francesco Fontana in his *Novæ Cœlestium Terrestriumque Observationes* claimed to have built a telescope as early as 1608.

Francesco Fontana (Figure 3) studied law at the University of Naples and then he became a lawyer in the court at the Capuano Castel. But failing to always find truth in the Court, he began to study mathematics and astronomy. During his studies Fontana made a long series of observations of the Moon, creating the first selenographic 'atlas', and of the planets, noting the rotation of Mars, drawing the 'bands' on the surface of Jupiter and hypothesizing on the structure of Saturn's rings (Molaro, 2017). Father Giovan Battista Zupi (1590–1650), a Professor of Mathematics at the Jesuit College in Naples and a good friend of Fontana, observed Mercury and its phases for the first time on 23 May 1639 with Fontana's telescope. This was clear evidence that even Mercury revolved round the Sun.[5] But when did Fontana begin his observations? With which instruments, and where did he observe from? The biographical accounts of Fontana are very fragmentary, starting from the date of his birth, which could be between 1585 and 1589, as referenced in the portrait published in his book (see Figure 3).[6] Crasso (1666: 296–300) instead, informs us that Fontana and his whole family died in July 1656 when the plague descended on Naples. Records of where Fontana lived and made his observations are even more obscure, but a report on the damage produced by the 1688 earthquake gives us an important piece of information:

> On San Biagio dei Librari street, parts of the stairs collapsed belonging to our late distinguished mathematician Francesco Fontana, of which there were 121 steps in total. They fell onto the Palace of Duke of Marzano, crushing two horses. Due to this collapse, the upper apartment in the palace of the late Dr. Luigi Caracciolo also collapsed. (Bulifon, 1698: 80).

Therefore, Fontana lived in the historical heart of Naples, in the Decumanus Inferiore (see Figure 4), now known as Spaccanapoli, close to the church of San Gennaro all'Olmo, the palaces of Diomede Carafa and Marigliano, and not far from the Jesuit College where Girolamo Sirsale (1584–1654) taught theology. The Jesuit testified that in 1625 he saw a telescope with two convex lenses, and a microscope, built by Fontana. Meanwhile, the Mathematics Professors from the College, Zupi and Giovanni Giacomo Staserio (1565–1635), both claim to have observ-

Figure 4: A detailed drawing of Naples, engraved by Joachim von Sandrart and published in *Itinerarium Italiae Nov-Antiquae* (1640).

ed from Fontana's house in 1614 using a telescope composed of two convex lenses, and "… not without the admiration and joy of both of us." (Fontana, 1646: 5). Zupi certified that Fontana had achieved this perfection in polishing lenses and building telescopes after many years of study and persistent work. Zupi pointed out that he and his confrere advised Fontana to mount in the optical tube two convex lenses. Instead, Fontana claimed that he made a telescope with a double convex lens as early as 1608. Furthermore, he wrote that Kepler had reached the same optical hypothesis in an independent way, they having no knowledge of each other's ongoing studies.

Fontana's first known astronomical observation was only made on 31 October 1629. His drawing of the Moon was full of detail, and has been well analyzed by Molaro (2017). Fontana's reputation for his 'exquisite' lenses and observations only began to spread in 1637. A letter from that year by Benedetto Castelli (1578–1643) to Galilei testified that Neapolitan lenses were already circulating in Rome, and Raffaello Magiotti (1597–1656) asserted that "… the lens gives great enjoyment in observing the Medicean Stars." (Magiotti, 1637). To the skeptics, Magiotti (ibid.) suggested a strong therapy based on hellebore! In a letter of 1638 to Vincenzo de' Medici, agent of the Grand Duchy of Tuscany in Naples, Fontana tells us that

> I give perfectly the spherical shape to any glass … the art of polishing glass has never been my profession, hence the idea that all the glasses I composed are marked. (Fontana, 1638a).

In the same letter Fontana added that he had donated some telescopes

> … to the late Duke of Alcalà, to the most eminent the Cardinal Boncompagni, and to the most illustrious the Monsignor Nuncio of His reigning Holiness; furthermore he has sold some instruments to the Jesuit Father Girolamo Sersale and to the most Reverend Father Lord Benedetto Castelli. (Fontana, 1638a).[7]

In October 1639 Fontana sent the Grand Duke "… a convex lens of 22 palms surpassing any other by far." To testify as to the goodness of his lenses, Fontana enclosed with the letter a drawing of Jupiter with the horizontal bands of its atmosphere well traced: "… these stripes that I see on Jupiter are new things from what anybody else has ever observed." (Fontana, 1638b). Finally, in a letter to Antonio Santini, Giovanni Camillo Gloriosi (1572–1643), Galilei's successor at the University of Padua, described the Neapolitan telescope:

> … we see the objects clearly and very close, although upside down, it is amazing for the celestial things, especially for the Moon making it seem so close to say that you can touch it with your hand. (Gloriosi, 1638a).

In a subsequent letter Gloriosi sent Santini a drawing of Saturn, that sometimes appeared 'ovate' and at other times 'circular', due to the "… different positions of the Sun." Moreover, Gloriosi (1638b) pointed out that the 'vacuum' between the 'handles' was sky.

The known correspondence does not allow us to fully understand if Fontana was really the inventor of the telescope. However, in 1644 the physicist Evangelista Torricelli (1608–1647) wrote to Magiotti saying he had made an excellent lens comparable to the perfect one produced by Fontana and owned by the Grand Duke. Torricelli (1644) emphasized how his lens was the best compared to the many made by Fontana over a period of about 30 years. This indicates that Fontana had began making telescopes by 1614, at very least. Therefore, Galilei's comments below about "... the Telescopes and the new observations by Fontana of Naples …", appear quite biting:

> It is really true that they magnify objects more than our telescopes that are shorter; about the blow-up the Moon, showing it greater than the Naples market square, this is an ordinary phrase indicating the little competence of the Neapolitan craftsman ... He does not observe new and different objects compared to the first discoveries made by me and confirmed by many others. (Galilei, 1639).

The diffusion of Neapolitan telescopes continued to create debate, as did skepticism about the quality of the lenses made by Fontana. Studies of the technological improvements and scientific analyses that Fontana carried out on his own, combined with his liberal arts background, do not strengthen his case.

The scientist Carlo Antonio Manzini (1600–1677) was a pupil of Magini, and he maintained good relationships with famous scientists from Bologna such as Marsili and Riccioli. Manzini carried out a long series of astronomical observations with telescopes of the highest quality, including those made by Torricelli, Divini and Fontana. In 1660 Manzini published the book *L'occhiale all'occhio*, in which he appreciated the "… perfection …" of the Neapolitan telesscopes. Much earlier, in 1641 Manzini had arrived in Naples, looking forward to meeting Fontana and enhancing his knowledge of "… the admirable applied Dioptric Art." In the preface of his book, which was published four years after Fontana's death, Manzini described the Neapolitan's telescope as "… a fragile tube with lenses at each end …", which he used for the first time in the garden of the palace of Francesco I d'Este, the Duke of Modena (known locally as the 'Mars of Lombardy'). Manzini really regret-ed the loss of the "… wonderful secrets …" that Fontana conceived in Naples (Bellé, 2009).

After the observations that he made for his 1646 book, we are not told of any other astronomical observations made by Fontana. Another strange feature of his book is that it was published in February 1646, according to what the printer, Giacomo Gaffaro, wrote in the frontispiece, yet the last astronomical observation made by Fontana was dated 14 March 1646. Two hours after sunset he observed 'Venus corniculata', which means horned Venus. At this time the planet was in the decreasing phase, with about 35% of the disk illuminated.

In May 1647 Torricelli made a telling comment about Fontana in a letter that he sent to the astronomer and mathematician Vincenzo Renieri, who was a friend of Galilei. Torricelli (1647) poked fun at Fontana's observations and his book:

> I hold the book of idiocies observed in the sky, or rather dreamed of by Fontana. If you want to see crazy things namely over-kills, fiction, insolences, and a thousand similar invectives, I could send you the book: perhaps you can extract laughter for your own work.

Yet this jaundiced viewpoint does not tally with Fontana's claims. For example, he wrote that he and Father Zupi had observed Jupiter many times and with different telescopes, all of which were made by himself. They noted up to three bands on the surface and four satellites on the equatorial plane of the giant planet. Note that Father Zupi confirmed these observations in two letters to Riccioli dated 23 January and 4 February 1644 (Riccioli, 1651: 489).

According to Colangelo (1833: 246–268), in addition to Riccioli, Huygens, Hevelius and Bailly, other astronomers appreciated and studied Fontana's astronomical observations

4 TELESCOPIC OBSERVATIONS BY COLONNA AND DELLA PORTA

At the Cesi-Gaddi Palace on Maschera d'Oro Street in Rome, Federico Cesi established the Accademia dei Lincei on 17 August 1603 together with three other young peers, the scientist Francesco Stelluti (1577–1653), the physician Johannes van Heeck (1574–1616), and the astronomer Attanasio de Filiis (1577–1608), to replicate the lynx's eye in the examination of natural phenomena. Cesi wanted to set up Academy branches throughout Europe, but apart from the Rome branch, only in Naples would another branch be established. The 'Neapolitan Linceo' was linked personally to Della Porta, who had enrolled as a Linceo as early as 8 July 1610.[8] The partnership between the young 'Lincean Prince' and the old Neapolitan scientist—who was very famous throughout Europe—was fruitful both for Cesi, who saw his institution growing in importance, and for Della Porta, who succeeded in readily publishing his books *De Aeris Transmutationibus* (1608), *Elementorum Curvilineorum* (1610) and *De Distillazione* (1610) due to Cesi's influence with the Roman censors. All three books were dedicated to Federico Cesi.

In 1612 Della Porta established the Neapolitan seat of Lincei, and he asked Cesi for funds to give the Academy a suitable home.[9] Della Porta (1612) also provided a list of "… very excellent men, since the Neapolitan stables are full of philosophers, doctors and ordinary men." He also proposed as members:

> Mr. Nicola Antonio Stelliola, philosopher and mathematician of a high culture, and an uncommon inventor in architecture ... Mr. Fabio Colonna, a scholar in fine Greek and Latin literature, and of excellent judgment on the natural things ... Mr. Filesio Costanzo Della Porta, the 18 year old grandson of Mr. Giobatta, talented and of great character ... and also Mr. Diego D'Urrea, a noble knight with extraordinary knowledge since he is fluent in the Arabic, Persian and Turkish languages, in addition to philosophy and has a vast knowledge of other sciences. (Cesi, 1612).

During 1612 Della Porta became ill, but he did not relinquish his role as Vice-Prince of the Neapolitan Linceo, suggesting to Cesi the creation of a new Academy seat in Palermo to be led by the scholar Mariano Valguarnera (1564–1634) (Paolella, 2002). In August, Della Porta had "… almost recovered …", and Cesi and Galilei rejoiced upon hearing this news:

> … our Mr. Porta, who at an elderly age, has a sharp and tireless talent; he does not stop working hard and studying, and he will put many things into practice. (Cesi, 1613).

Thus, Della Porta would continue to produce new scientific and technological advances until shortly before his death on 4 February 1615.

Fabio Colonna (1567–1640; Figure 5) was one of Fontana's closest collaborators. Nephew of Cardinal Pompeo, he was a lawyer "… for he needed a living". But because of faltering health, Colonna approached the study of medicine and pharmacological methods, convincing himself of the usefulness of botanical gardens. He became a friend of Ferrante Imperato and was a regular at the garden of Giovanni Vincenzo Spinelli. More broadly, Colonna was interested in any kind of investigation of nature without being "… a slave to either Aristotle or another Philosopher …", in full agreement with Della Porta's unitary conception of nature and the scientific methodologies followed by Cesi and Galilei. The aims of Lincean scientists were

Figure 5: A portrait of Fabio Colonna, published in *La Sambuca Lincea* (1618) (https://it.wikipedia.org/wiki/Fabio_Colonna).

> … to get the most comprehensive knowledge of the sciences ... after observation, and experimentation ... and also to extend the sciences, to communicate and transmit knowledge to the public. Cesi, 1616).

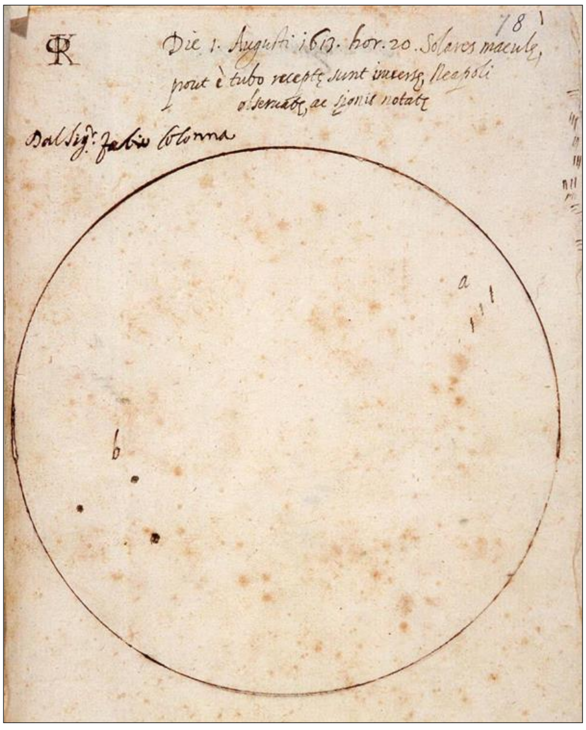

Figure 6: Sunspots observed by Fabio Colonna on 1 August 1613 at about 3 p.m. (after Colonna, 1613a).

This statement anticipates the modern concepts of public outreach activities and 'third mission' projects.

The partnership with Della Porta led Colonna to also be interested in the construction of telescopes, and astronomical observations. In March 1613 Galilei published his *Istoria e Dimostrazioni Intorno alle Macchie Solari e Loro Accidenti* with a long series of observations made from 21 October to 14 December 1611 and then from 2 June to 21 August 1612. In this volume Galilei argued that sunspots were "… clouds … [like the] smokiness around the Earth". Colonna also conducted a similar survey, taking 57 observations of sunspots that he illustrated and noted. To our knowledge, his drawing of 1 August 1613 (see Figure 6) was the first telescopic astronomical observation carried out in Naples. Colonna's mention also of 'clouds' is hard to interpret due to his lacking of observing experience and the 'bad' telescope that he used, as he pointed out in a letter to Galilei:

> I observed sunspots for two months, if Your Lordship will have pleasure to see what I have done, I could send all drawings even if they are not as well observed, as in your book where they are painted with light and shade. They are similar in size, using a sheet of paper placed at the distance of two palms length from the telescope I made by myself. (Colonna, 1613a).

Galilei, however, appreciated Colonna's enthusiasm and interest, for which Colonna was grateful:

> I have gladly surmised that you appreciate the sunspot [drawings] I made, although I am a beginner and without help; here nobody takes delight in nor makes such observations with whom I can learn to observe, nevertheless I will gladly make them in the future. (Colonna, 1613b).

In this letter Colonna regretted that "… in Naples there is no one who knows how to make perfect telescopes …", which contrasts markedly with Fontana's claim that he was building telescopes from 1608. Colonna was a tenacious person and he told Galilei he was working at making a telescope himself. He pointed out all the difficulties that he encountered in polishing the lens:

> For three days I worked to make some lenses by myself and to obtain, if I'm able, a good convex that allows me to see clearly without any little cloud; I find many defects both in the glass and in the work; I'm going to produce one with a length of eight and ten palms to magnify things without the tube being too long; I find that when the convex lens has a greater circumference, there will be greater magnification in the observations; but the difficulty is to work it in a good way, the bad ones show objects as double or shady. (Colonna, 1613a).

We do not have Galilei's reply to this letter, but he must have sensed something promising because he offered the young Neapolitan astronomer some of his lenses, which Colonna willingly accepted: "

> When you send me the lenses, put them in a well-checked, sealed box so that there is no chance they will be stolen during the journey … (Colonna, 1613a).

Colonna improved his technique of polishing lenses, and informed Galilei that he used one to observe Saturn, and the Sun, Moon and stars.

In mid-1614 Della Porta fell ill again but he continued to support Colonna's initiative by advising him on observing techniques and improvements in lens production. Colonna excitedly continued his planetary observations and writing to Galilei. Between 15 and 18 June 1614 Colonna observed the Medicean satellites:

> … with great joy of mine, and with great admiration of your knowledge and wisdom, I observed what you have forecasted and calculated with great accuracy, and recently again corrected some small details. (Colonna, 1614a).

Back in good health, Della Porta returned to take an interest in some of his own optical studies (e.g. see Figure 7) that he began in 1610 and

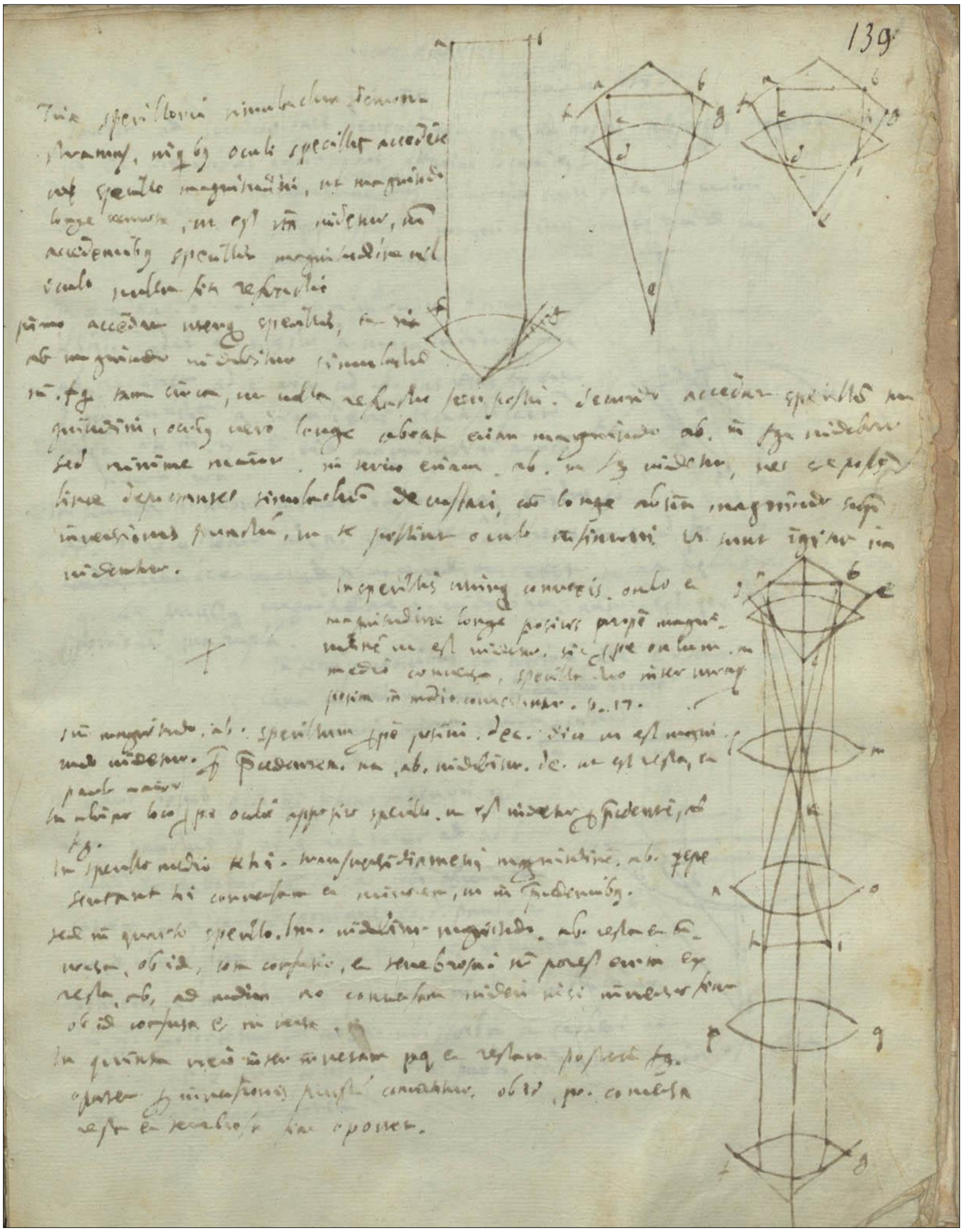

Figure 7: Part of the manuscript of *De Telescopio* by Della Porta, dating to about 1610 (c. 139r, Library of the Accademia dei Lincei e Corsiniana. Archivio Linceo 14).

wanted to bring together in a new book titled *De Telescopio*, "… a most difficult and complicated challenging undertaking and the most difficult of all he had ever taken." (Stelliola, 1615). The manuscript, which remained unpublished until 1962,[10] enhanced the studies on optics already evaluated in the *Magiae Naturalis* and *De Refractione* and anticipated some concepts that Kepler analyzed in his *Dioptrice* (Borrelli, 2017). Della Porta's new studies on convex and plano-convex lenses and Colonna's scientific progress, spurred Della Porta to get back to work. The enthusiasm of the 'Lincean Vice-Prince' is evident in the following letter to Galileo of 26 September 1614, showing the great expectations that the two Neapolitan astronomers held for the new telescope they were making:

> I am working with Mr. Fabio Colonna, who is very ingenious and a mechanic, to realize a new kind of telescope, which will multiply the effect more than usual; if we see until the eighth sphere with the usual one, we will be able to the highest heaven with this new one; God willing, we will investigate what is above, and we will publish the Empyrean Messenger. (Della Porta, 1614).

This new Neapolitan telescope was used to observe the solar eclipse of 3 October 1614. On that day, Colonna ignored commitments in court and he returned home in time to follow the astronomical event that he observed "… as best I could." Immediately afterwards, he wrote a long letter to Galilei:

> I send you six images of today's eclipse … marking both the path of the Moon, or better to say of the Sun, which moved rapidly, and the precise sunspots and their size; due to the rush and the little thought I could not do better … Your Lordship will see a very rough sketch; you will be able to recognize the accurate parts, taking what is possible, and you will invert them ... I know that Your Lordship and other scholars would have done likewise, I would like to see any of those learn how to make a good one next times. (Colonna, 1614b).

Upon reading this letter it is evident that Colonna used a telescope and not a Galilean spyglass. Therefore, this was the first astronomical observation made from Naples using a Keplerian-like refractor. The new optical config--ration did not derive from Kepler's studies or those of Fontana, but was the result of the combined theoretical and practical skills of Della Porta and Colonna. The lines in the drawings are rough, however the six images taken between 12:32 and 1:40 pm offer adequate detail of the astronomical event and of the sunspots present (see Figure 8), thus providing a basis from which to improve lens polishing techniques and to enhance the astronomical studies. Unfortunately, at the beginning of 1615 Della

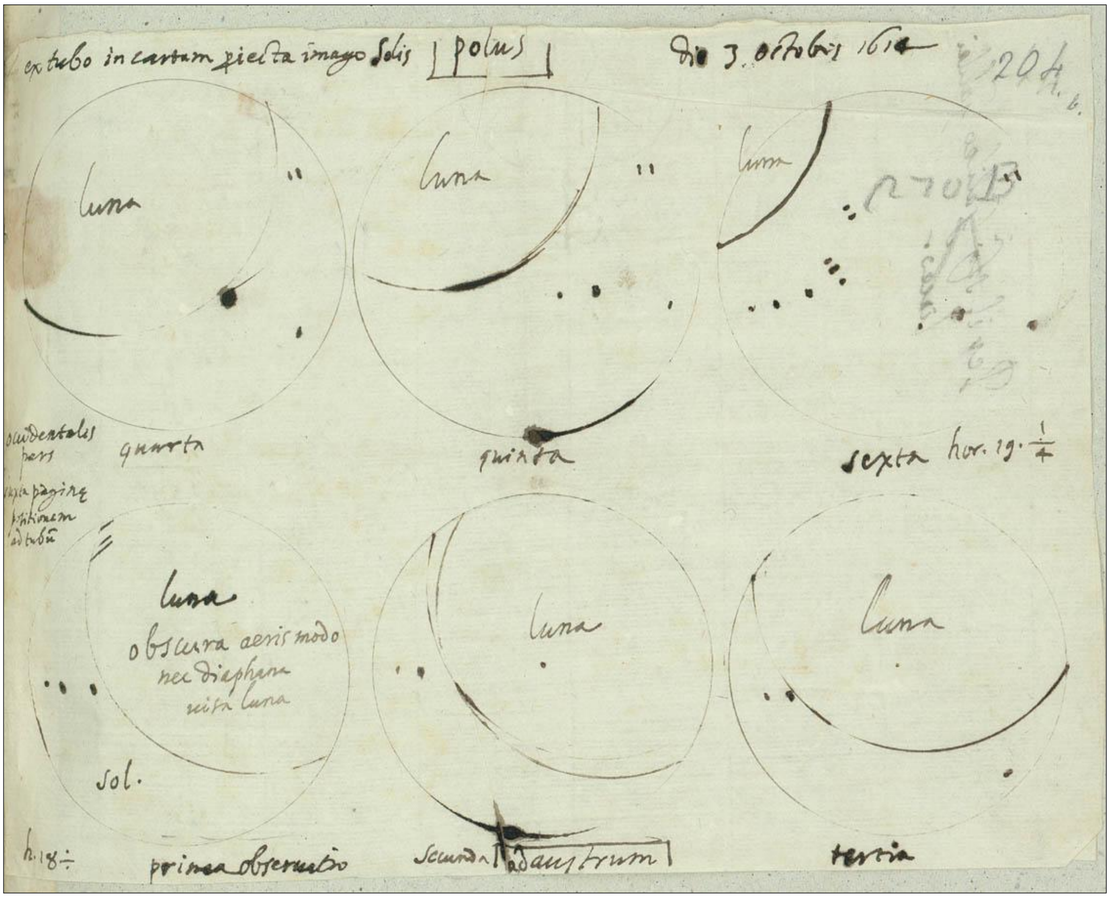

Figure 8: Sketches of solar eclipse phases observed by Colonna on 3 October 1614 (after Colonna, 1614b).

Porta fell ill again, and on 4 February he passed away.

Colonna (1617) was left without an experienced mentor, and he quickly lost his original enthusiasm for astronomy: "… here they is no one with whom I can discuss cosmic concerns, because there is no one who really knows, just our Stelliola." In August 1615 Colonna told Galilei he had observed Jupiter and its satellites for two months, just for fun, thereby confirming his unscientific approach to astronomical observations. Meanwhile, a sudden gust of wind caused the lens, which he has received through Galilei's "… particular courtesy …" to shatter and prompt "… a great pain." (ibid.). Colonna then told Galilei that he had good intentions of producing a new plano-convex lens, but he ran into many technical difficulties to find good-quality glass, to make a uniformly circular copper cup, and to obtain a proper lathe. All these hindrances did not allow him to make perfect lenses, as he would have liked (Colonna, 1615). Consequently, in Naples there were few remaining accomplishments from the incentive of the two Lincean's activities, only the diligent research by Stelliola.

Fourteen years then passed before Colonna again praised Fontana's telescopes and observations, telling Cesi about the

> … eight-palms telescope which, although giving a reverse image, shows closely the Moon, the stars, and everything with much greater magnification than the usual telescopes of the same length, and it makes the objects clearer than usual. (Colonna, 1629).

It is likely that the meeting between the two Neapolitans took place around the end of 1625, when Colonna followed Cesi's studies of nature, as published in his *Apiarum*.

5 FRANCESCO FONTANA AND THE INVENTION OF THE MICROSCOPE

In 1621 Jakob Kuffler (1600–1622) arrived in Rome and presented a new instrument designed to magnify miniature objects. He demonstrated how this instrument could recognize the compound eyes of insects, including that of fleas. He was the brother of Johannes Sibertus (1595–1677), Aegidius (1596–1658), Abraham (1598–1657), and Isaak (1605–1632), and the son of Jakob, a Dutch merchant residing in Cologne. Johannes and Aegidius became sons-in-law and business partners of Cornelis Jacobszoon Drebbel (1572–1633), the supposed inventor of the microscope that used two convex lenses (De Waard, 1912). The Dutch engineer and inventor lived in England from 1605 to 1610, then three years at the court of Rudolf II (1552–1612) in Prague before returning to England in 1613, where he made microscopes with two convex lenses. In May 1622 Jakob was in Paris to present the new instrument to Queen Maria de' Medici (1575–1642). The French astronomer and savant Nicolas-Claude Fabri de Peiresc (1580–1637) participated in the demonstration. De Peiresc wrote to Girolamo Aleandro (1574–1629), who was the Secretary of Cardinals Bandini and Barberini, informing him about the instrument and asking him to introduce Jakob Kuffler to Scipione Cobelluzzi (1564–1626), the Cardinal-Priest of Santa Susanna, and Maffeo Vincenzo Barberini (1568–1644), the Cardinal-Priest of Sant'Onofrio and from 1623 Pope Urban VIII. Unfortunately, due to the plague, Jakob died in Rome in November 1622, before he could explain to the Cardinals how the microscope worked. Galilei, who was in Rome at the time, saw the microscope and taught Cobelluzzi how to use it. However, Galilei remarked that he had created such an instrument some years earlier, using a lens configuration similar to his telescope (Freedberg, 2003: 151–154). In 1625, after Jakob's death, Aegidius and Johannes Kuffler arrived in Italy to present and sell some new inventions, "… a clock moving for a year without regulation … [and] four extra-ordinarily good telescopes …", as Aegidius wrote in letters to Johannes Faber (Kuffler, 1625).

In June 1625, one of the Kuffler brothers was in Naples at the Dominican monastery of Santa Caterina a Formiello to present a telescope to Friar Donato d'Eremita[11] and his confreres. However, Colonna was there to admire the microscope and understand its working principles:

> Since Your Lordship wrote to me that he has seen such an instrument, I wanted to see what it was like, although its operations were not known, I knew the characteristics of the lenses of different shapes, I tried and today I made it with the same proportion without disassembling the instrument because of haste, the lenses do not possess the clarity they must have, but as soon as I have some free time I will do it. I call it an enghiscopio, which means eye-wear up close. I believe that the Fathers would have become inventors if they had succeeded immediately, as they are used to engaging in such successful activities, but I believe they will labor for a long time if they do not know how to use them, since lenses cannot be produced in an ordinary way. (Colonna, 1625).

The microscope and the study of bees then became Colonna's new scientific goal. He was not satisfied with his microscope and, as usual, he set out to manufacture a new one. In July 1626 he was making

> … the foot and the tube, like a screw, that will be no more than four fingers for an eyepiece; using it you can observe a whole day without straining your eyes, it gives an upright image; it is an invention of a friend that I'm helping to publish; by intending to create

> one similar to that of the Cologne people, but he did not know how, and studied to find a better way. (Colonna, 1626a).

Who was this friend? Colonna's letters do not disclose this. Then one month later Colonna regretted the delay in producing the bee sketches, due to his friend's shock at recently having lost a daughter. In September "… the bee's friend was a little unwell, since he suffers a bloody cough." Nevertheless, the friend was completing a new microscope commissioned by Cesi, and

> Although it does not enlarge as much, it multiplies sufficiently so that we can see the follicles of the bee's hairs close up, without the eye suffering any glare like that of the Cologne craftsman. This friend has also crafted another small one inch eye-piece, which shows in reverse but magnifies the object significantly. (Colonna, 1626b).

By the end of 1626, this anonymous friend had sent Cesi a drawing of the bees, observed with great detail, to be engraved by Matthäus Greuter (ca.1564–1638). Only when Francesco Stelluti published his *Persio* in 1630 was the name of Francesco Fontana revealed as the anonymous 'friend'. He was identified by Stelluti as the person who recorded the observations of bees with Fabio Colonna:

> After Mr. Francesco Fontana observed and carefully drew everything, I had three bees engraved on copper, here in Rome, representing the arms of Our Lord the Pope Urban VIII. They are great in that form as displayed by the microscope lenses; and I had them engraved in three different positions. (Stelluti, 1630: 47).

Comparing the table of *Melissografia* published in 1625 with the bee observations of Stelluti and that of Fontana in the *Persio*, the Neapolitan images show remarkable detail, both in the paws and in the eyes of the bees.

In his *Novæ Cœlestium Terrestriumque Observationes*, Fontana wrote that his invention of the microscope in Naples occurred in 1618. He claimed that the microscope was never invented before that year. Because the microscope used an optical configuration like the telescope —he continued—it was possible that other scientists could have make it. Once again the Jesuit Father Sersale testified to having also seen and used the microscope at Fontana's house in 1625. This comment is similar to his other one about the invention of the telescope. As Fontana's statement concerning the telescope was confirmed by witnesses or via observations only a few years later, likewise his observations with the microscope were only known eight years later. Fontana also described his microscopic observations of dust, fleas, ants, flies, spiders, and even sand, but there was nothing about his observations of bees.

The protagonists of this scientific adventure disappeared within a few years but the secret of the Neapolitan eyepiece, which was the result of a very insightful enterprise, atones for Manzini's fear that "… men die and with them the technology, which is so necessary for humanity, is also buried." (Manzini, 1660: 2).

6 NOTES

1. Unless indicated otherwise, all translations into English were made by the author.
2. The diplomatic mission of King Ekathotsarot (?–1610) of Siam comprised sixteen people who arrived in Holland at the beginning of September 1608 on board the *Orange*, which was skippered by the Admiral Cornelis Matelief de Jonge (1570–1632) (De Renneville, 1725: 243).
3. The recommendation letter of the Zeeland authorities to the States General of the Netherlands to issue a patent for Lippershey's invention is dated 25 September 1608 (Zuidervaart, 2010: 11).
4. The first edition of *Magiae Naturalis*, published in 1558 when Della Porta was only fifteen, was indexed by the Spanish Inquisition. The revised and augmented edition of 1589 provides a comprehensive representation of the experimental activities of the Neapolitan scientist (Valente, 1999).
5. In his *Almagestu*m Riccioli (1651: 484) is skeptical about these observations, considering them optical illusions produced by Fontana's telescope, but Molaro (2017) shows a really good overlap between Fontana's drawings and a modern simulation of the sky as observed by the Neapolitan astronomers.
6. The portrait caption reads: "The Neapolitan Francesco Fontana inventor of the new astronomical optical tube in the year 1608, *Ætatis Suæ* 61 …", but this number could also be read as 19. Excluding that in 1608 Fontana was 61 years old, then if the age refers to the year 1608, Fontana was 19 and must have been born in 1589. If, instead, the date refers to the year of publication of the book (1646), we must accept that Fontana was 61 and was born in 1585.

   Although the book was published in only one edition, there are at least two versons of the volume, with the scientist's portraits prepared by two different engravers, and an additional item in the list of errata. The text appears to be printed and bound hurriedly: in addition to the variations described above, there are different collations of both the index, inserted after c. A4v, or after c. B4v, or even after c. T4v, and the portrait. Other copies report a double c. B3 with different headings. In the second version of the portrait the date of the invention of the telescope is shown in Arabic numerals (Olostro Cirella, 2016: 146–147). Also, in this latter case, the second number [19 or 61] is not evident. However, the portraits do not seem to represent a young man, let alone an adult gentleman. Crasso (1666: 298) refers to the "... unclear Fate of a famous man."

7. The cited persons are: Fernando Enriquez d'Afán de Ribera (1583–1637), the Duke of Alcalá and Viceroy of Naples from 1629 to 1631; Francesco III Boncompagni (1592–1641), the Metropolitan Archbishop of Naples from 1623 to 1641; and Niccolò Enriquez de Herrera, the Apostolic Nuncio to Naples from 1630 to 1639.
8. In the spring of 1604 Della Porta contacted the Lincei members and had a close friendship and scientific correspondence with Cesi. The 'Lincean Prince' stayed in Naples for some days that year meeting Della Porta and Imperato, "… very good friends of Lincei and miracles of nature …", as he wrote to Stelluti, and he described the city as "… the paradise of delights … dwelling of the very fertile Ceres, the most abundant Neptune, and the very courteous and pleasant Venus." So much so, that Della Porta can be considered a member of the Academy from that time. In 1610 Della Porta wrote his name in his own hand in the Academic register (Galluzzi, 2017).
9. Three different buildings were proposed: the first was in the working area of Montesanto near Porta Medina, usually called *Porta Pertuso* by Neapolitans; the second palace, suggested by Colonna and visited by Stelluti in 1613, was near the Porta di Chiaia, the most elegant and popular street of Naples for princes and knights, but this elegant palace was already inhabited by a minister; the last one was suggested by Stelliola, a place owned by the D'Anna family near Porta Regale (now Piazza Dante) where astronomical observations could be made and scholars at the nearby new University building (now the archaeological museum) could be received. However, due to lack of sufficient funds the project did not proceed (Colonna, [1612]; Stelliola, 1615).
10. With the death of Della Porta in 1615 the manuscript remained unpublished and its traces were lost, along with other scientific and literary works of the Neapolitan scientist. The original text of *De Telescopio* was found in the Archives of the Accademia dei Lincei in 1940 by Giuseppe Gabrieli and was published by Olschki in 1962 and edited by Maria Amalia Naldoni and Vasco Ronchi.
11. Fra Donato d'Eremita was born in Rocca d'Evandro, in the Campania region, at the end of the sixteenth century. He was among the greatest connoisseurs of descriptive and taxonomic botany in the first decades of the seventeenth century. In Florence he was a chemist of Cosimo II de' Medici. After his return to Naples, in 1611 he was a pharmacy apothecary of the Dominican convent of Santa Caterina in Formiello, where he used alchemical knowledge to produce spagyric medicines based on minerals and metals. He was also a peripheral figure in the Accademia dei Lincei, as he counted among his friends Della Porta, Imperato and Stelliola. In 1624 Fra Donato published *Dell'elixir Vitae*, a treatise on distillation, alchemical equipment and experiments, including a description of his pursuit of the 'elixir vitae', thought to grant eternal youth and immortality. He died in Naples around 1629, as evidenced by a letter from Colonna to Stelluti (Genticore, 1998: 41–42; 78–79).

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Dr Mauro Gargano graduated in Astronomy from the University of Padua, and is a researcher at the Astronomical Observatory of Capodimonte in Naples. He is the scientific manager of the MuSA (Museum of Astronomical Instruments) in Naples and is responsible of the digital web platform 'Polvere di Stelle – Stardust' of the National Institute for Astrophysics to recognize Italian astronomical heritage made up of rare volumes, historical archives and museum collections, and to disseminate astronomical knowledge in society. Among his scientific activities he has a special interest in the history of Neapolitan astronomers and their astronomical studies. He is also a member of the board of the Italian Society for the History of Physics and Astronomy. The author of books, research papers and popular articles on the history of astronomy (and not only Neapolitan), since 2012 he has co-edited the "Cielo d'Inchiostro ("Cosmic Ink") column in the *Giornale di Astronomia*.

PETRUS APIANUS' VOLVELLE FOR FINDING THE EQUINOXES

Lars Gislén
Department of Theoretical Physics, University of Lund, Dala 7163, 242 97, Sweden.
E-mail: LarsG@vasterstad.se

Abstract: In this paper the mathematics behind the equinox volvelle in Petrus Apianus' *Astronomicum Cæsareum* is investigated.

Keywords: Petrus Apianus, *Astronomicum Cæsareum*, equinox volvelle

1 INTRODUCTION

This is the fifth and final paper (see Gislén, 2016; 2017a; 2017b; 2018) in a series on the volvelles in Petrus Apianus' *Astronomicum Cæsareum* (1540),

> … a magnificent book with more than thirty volvelles or equatoria, a kind of paper computer, that, using the detailed instructions and examples in the text, allowed readers to calculate astronomical, chronological and also astrological phenomena. (Gislén, 2018: 135).

The *Astronomicum Cæsareum* has been described as "… undoubtedly one of the most extraordinary books in the world." (Gislén, 2018: 199). Gislén (2018: 135) also notes that such "… computing devices were quite popular during the fifteenth and sixteenth centuries."

Petrus Apianus (Figure 1) was born Peter Bienewitz on 16 April 1495 in Leisnig in Saxony, Germany, and after studying astronomy and mathematics he joined the University of Ingolstadt as a mathematician and printer. He remained in Ingolstadt until his death on 21 April 1552. For further biographical details of Apianus see Draxler and Lippitsch, (2012), Galle (2007) and Gingerich (1971).

This paper examines the equinox volvelle in Apianus' *Astronomicum Cæsareum*.

2 DESCRIPTION OF THE EQUINOX VOLVELLE

For this paper I have used the digital copy of the *Astronomicum Cæsareum* in the Astronomy Library at the Vienna University. This copy has a high resolution and the scanned pages are almost free of distortions. The equinox volvelle, (Figure 2) is the penultimate volvelle in the first part of the *Astronomicum Cæsareum*. It consists of a bottom plate, the mater, and a moveable top disk that can be rotated around a central axis. The mater is graduated by the fourteen days on which the equinox can occur in the selected time interval CE 1300–3000. Each day is sub-graduated by 24 hours from midnight to noon to midnight. Night and day portions are indicated by an outer circular band with white and black partitions. In the middle of the night part are the words MEDIA NOX or just NOX, and in the middle of the day part the words DIES or MERI(DIES) or just M. The letters R and C stand for sunset and sunrise respectively (see Figure 3). In the innermost circular band of the volvelle are eighteen fixed century indexes marked 1300 to 3000 for years after Christ. The index for the index 1500 is marked with M. When the specified year is a leap year, the February dates at the top of the mater should be 28 and 29 instead of 27 and 28.

Figure 1: Petrus Apianus

The moveable top disk has five equally spaced tabs marked B, C, D, E, and F. Each of the tabs represents twenty years of the century, grouped in five concentric circular bands, each band having a sequence of four years. In a circular band immediately below the tab there is a scale from 12 hours midnight over noon to 12 hours midnight. To the right of this scale are the letters OC (occident, west) and to the right OR (orient, east). This scale is used for geographical time difference corrections for locations west or east of Ingoldstadt, the meridian used for the *Astronomicum Cæsareum*. Finally, there is a

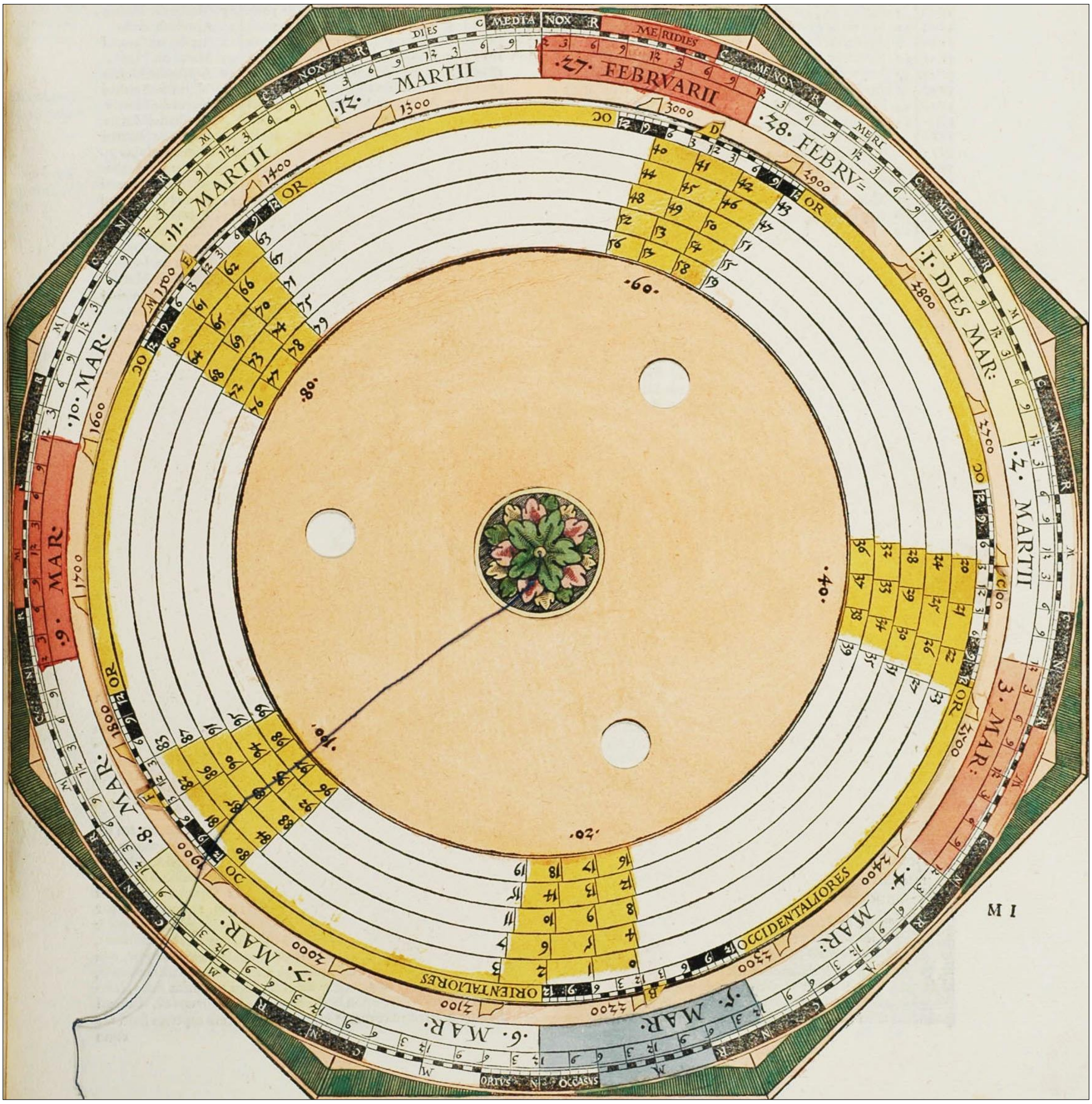

Figure 2: The equinox volvelle.

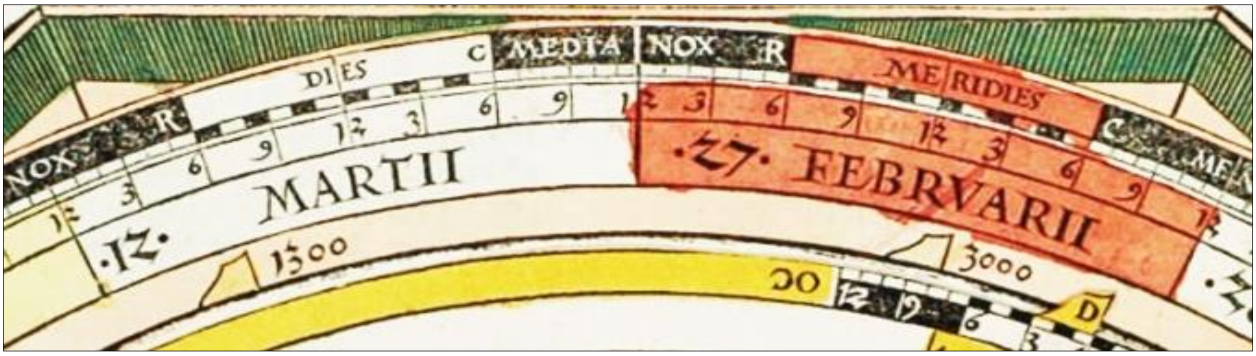

Figure 3: Detail of the mater.

thread from the centre of the volvelle to be used for reading off the time of the equinox.

The instrument uses the Julian calendar with a mean year length of 365.25 days.

3 HOW TO USE THE VOLVELLE

The working of the volvelle is very simple. The tab of the top disk with the 20-year group containing the specified year in the century is placed on top of the index of the chosen century. The thread from the centre is aligned with the line representing the specified year in the 20-year group and the time and day of the spring equinox are read out from the mater scale. If necessary, the time is corrected for east-west longitude time difference using the time scale below the top disk tab. To find the corresponding autumn equinox you add six months, three days, and 42 minutes. Due to the difficulty of reading the time scale the result has an effective precision of about 10 minutes. In the examples given by Apianus in the *Astronomicum Cæsareum*, he states the times with a precision of minutes, and he clearly got his results by some other means of computation.

4 THEORY

The volvelle in principle only uses the mean motion of the Sun but what is wanted is the true equinox when the true Sun has longitude 0˚. The volvelle is based on the assumption that the correction added to the solar mean longitude in order to get the true solar longitude, the equation of centre, is fixed during the time interval covered by the volvelle. The equation of centre is determined by the anomaly, the difference between the mean solar longitude and the solar apogee. In the Ptolemaic model used by Apianus the apogee is fixed relative to the fixed stars but moves with the precession of the equinox. In the Alfonsine and Apianus models the precession has two components, one steady motion that takes the equinox a full turn of 360° in 49,000 years, and a periodic oscillation, the trepidation, with an amplitude of 9° and a period of 7,000 years. The trepidation is a false hypothesis brought along by medieval astronomers who found that their measurements of the precession differed from Ptolemy's value of precession and then assumed that the value of precession varied (see Dreyer,1953; Neugebauer, 1962). The precession means that the solar apogee moves and that the solar equation of centre is not constant. However, it turns out that by coincidence, for the centuries CE 1300 to CE 1700, in the model of precession above, the equation of centre is maximum and almost constant (see Figure 4). I used the scheme of the Alfonsine Tables (Gislén, Poulle) to compute the equinoxes and added 1 hour 29 minutes as given in the *Astronomicum Cæsareum* as the longitude time difference between Toledo and Ingolstadt. The result agrees very well with the volvelle values for century years 1300 to 1700 but then diverges progressively from the volvelle values to make a difference of about 15 minutes for CE 3000. The mean solar tables in the *Astronomicum Cæsareum* are based on the Alfonsine tables but with a correction to the mean solar longitude at the epoch that corresponds to the geographical longitude time difference between Toledo and Ingoldstadt.

It is very tedious to compute the time of the true equinoxes by hand using tables and I speculate that Apianus computed the time for one century by tables and then used the extrapolation shown below for the others, assuming a constant equation of centre. It turns out that such an assumption agrees very well with the layout of the volvelle.

In the following I use the notation a, b, c, d … where 'a' is the zodiacal sign with Aries = 0, 'b' the degrees within the sign, and 'c', 'd' and so on representing each 1/60 of the preceding unit. For time I use the notation hour: minute. In the present investigation there is no need to retain the seconds, although I have used them in the internal calculations.

As there are fourteen days along the periphery of the volvelle, each day represents an angle of 360°/14 or 25.714° of the circumference. In the *Astronomicum Cæsareum* the Sun's mean daily motion is v_S = 0;59,08,19,37, 19,13,56 = 0.985646398°. This gives a year length of 360 / v_S = 365.2425461 days. Now, 100 Julian calendar years contain 36525 days

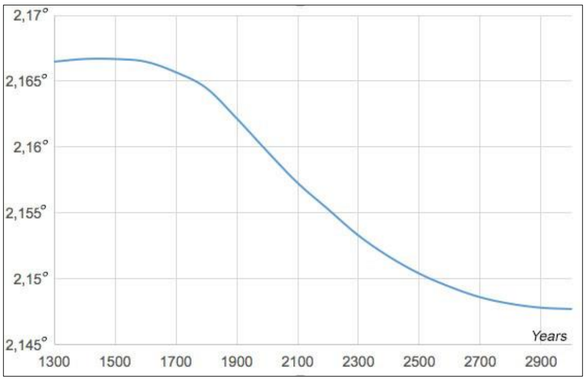

Figure 4: The equinox equation of centre.

while 100 solar years have 36524.25461 days. The difference is 0.74539 days and this corresponds to an angle of 25.714 · 0.74539 = 19.167° between the centuries. In Figure 5 I have added 18 computer-generated century lines, starting with the year 1300 using this fact. As can be seen the agreement is excellent.

In a 20-year Julian period there are 7305 calendar days, but 20 tropical years have 7304.850922 days. The difference is 0.149078 days or 3:35 hours. In the top disk of the volvelle, the years within a century are divided into 5 groups each with 20 years. Within each group of 20 years there are 5 leap year cycles, each with 4 years. On the top disk these five groups are placed with the index tabs equally spaced along the edge of the disk. The index tab B with years 0–19 is aligned with year 0. The index tab C of the years 20–39 is displaced

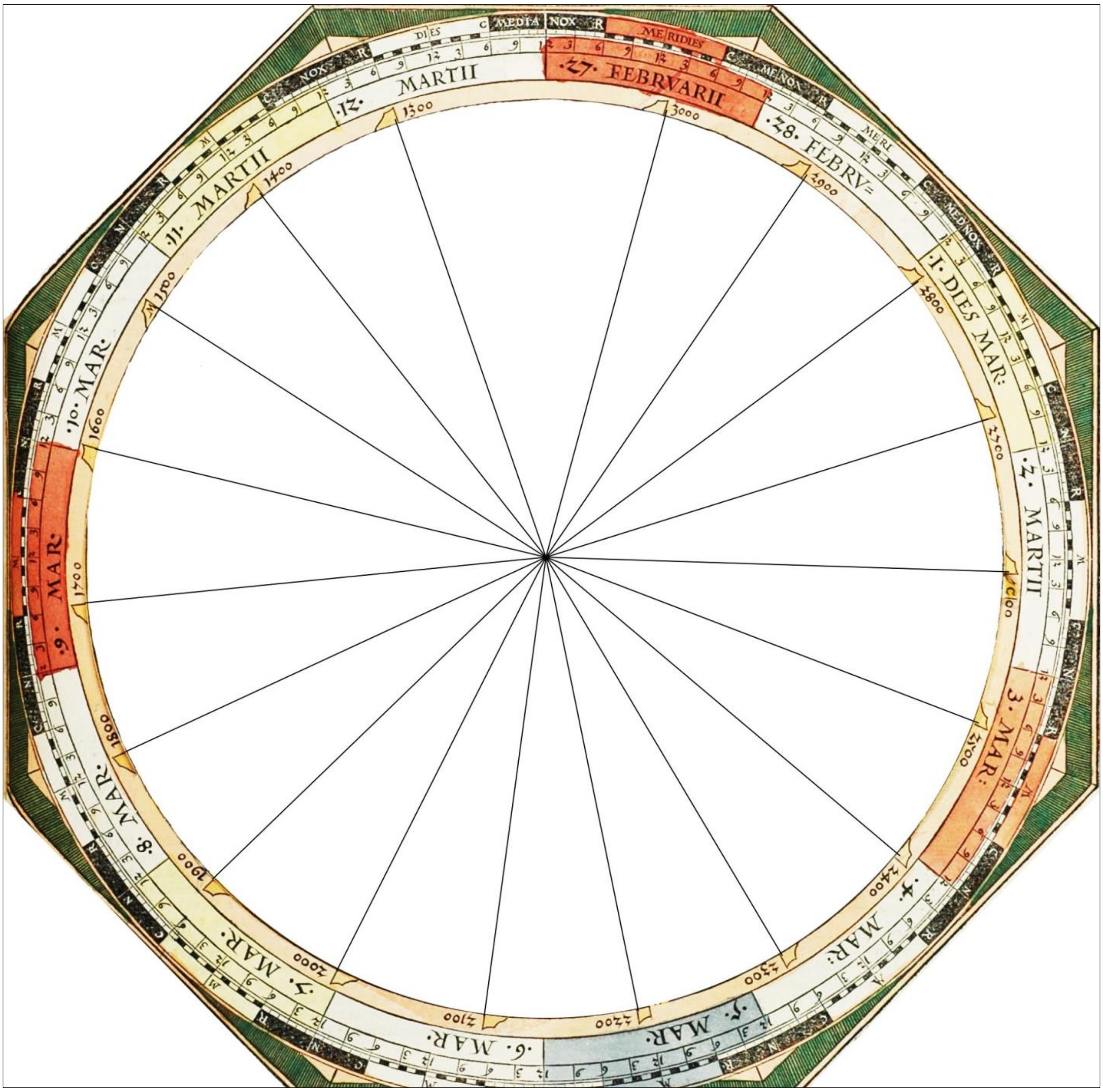

Figure 5: Predicted locations of the index tabs.

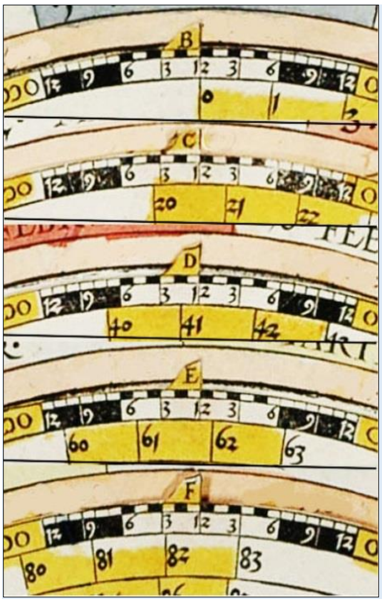

Figure 6: The tab displacements.

3:35 hours clockwise with respect to year 20 and similarly further forwards in turn by 2 · 3:35 = 7:09 hours for the tabs D for year 40, by 3 · 3:35 = 10:43 in E for year 60, and by 4· 3:35 = 14:18 in F for year 80. Figure 6 show this progressive displacement.

In a 4-year period there are 1461 calendar days and 1460.970184 solar days. The difference is 0.029816 days or 0:43 hours. In one ordinary year the difference between the civil days and the solar days is 0.2425461 = 5:49 hours. In each group of four years the equinox time is moved forward by this amount for each year. At the end of the fourth year it would have moved in total 4 · 5:49 = 23:17 hours but because of the leap day it is also moved back 24 hours and starts the next 4-year period 0:43 hours earlier than the previous 4-year group. This is illustrated in Figure 7 by the green com-

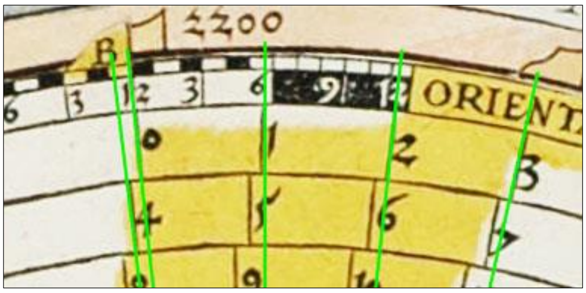

Figure 7: The year location.

puter-generated lines for the years 60, 61, 62, 63, and 64. The agreement is excellent.

5 CONCLUDING REMARKS

This volvelle is another example of the creativity and ingenuity of Apianus although perhaps its practical usage is limited because unfortunately, by comparison with a modern calculation, it turns out that the trepidation correction in the time interval CE 1300–1700 is large and causes the volvelle equinox times to be about ten hours early. The error then becomes progressively smaller and by CE 3000 it is about one hour.

A working model of the volvelle with instructtions for its construction can be downloaded from the following web site:

http://www.thep.lu.se/~larsg/EquinoxVolvelle.pdf

6 NOTES

1. Petrus Apianus was also known by his Anglicised name, Peter Apian.

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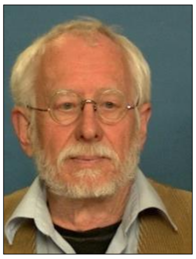

Dr Lars Gislén is a former lector in the Department of Theoretical Physics at the University of Lund, Swe-den, and retired in 2003. In 1970 and 1971 he studied for a Ph.D. in the Faculté des Sciences, at Orsay, France. He has been doing research in elementary particle physics, complex systems and applications of physics in biology and with at-mospheric physics. During the past twenty years he has devel-oped several computer programs and Excel spreadsheets imple-menting calendars and medieval astronomical models from Europe, India and South-East Asia (see http://home.thep.lu.se/~larsg/).

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MERZ TELESCOPES AT THE UNIVERSITY OBSERVATORY IN CHRISTIANIA, NORWAY

Bjørn Ragnvald Pettersen
Faculty of Science and Technology, Norwegian University of Environmental and Life Sciences, P.O. Box 5003, N-1432 Ås, Norway.
e-mail: bjorn.pettersen@nmbu.no

Abstract: Four telescopes with optics by Merz in Munich were acquired for the University Observatory in Christiania between 1840 and 1882. Two had equatorial mountings by Merz, one by Repsold, and one by Olsen. We describe the acquisition process from correspondence located in archives and libraries. The observing programs are outlined from publications in Norwegian and German, highlighting some results obtained with these instruments.

Keywords: University Observatory; Christiania (Oslo); Norway; telescopes; Merz; Repsold; spectroscopes; visual observations

1 INTRODUCTION

The University Observatory in Christiania (now Oslo, Norway) was inaugurated in 1833 and began its operation with a meridian circle from Reichenbach and Ertel and a Fraunhofer refractor from Utzschneider on an alt-azimuth mounting by Repsold. It was the only astronomical observatory in the country and was founded by Christopher Hansteen (1784–1873; Figure 1), Professor of Applied Mathematics, after years of fundraiseing and other political exercises. Over the following decades several other instruments were added, some in their own domes in the Observatory Gardens. Two were refractors on equatorial mountings from Merz. Two others had optics by Merz and equatorial mountings from Repsold and Olsen, respectively. Recent books by Chinnici (2017) and Kost (2015) address the importance and role of the Merz company and the extent of their delivery of lenses and telescopes throughout the world. Supplementing these reviews is extensive archival material in Norway and Germany that allowed detailed histories to be written of the Merz instruments at the University Observatory in Christiania.

Figure 1: Part of a drawing of Christopher Hansteen by Siegwald Johannes Dahl, made in 1848 (courtesy: Oslo Museum).

2 A REPSOLD EQUATORIAL WITH MERZ OPTICS, 1842

In 1844 the Observatory's Director, Professor Christopher Hansteen, was joined by an Assistant Astronomer, Carl Fredrik Fearnley (1818–1890; Figure 2), who had just graduated from the University. Two years earlier, an equatorial telescope had been installed in the Observatory tower. It was developed and produced by A. & G. Repsold in Hamburg between 1838 and 1841. It had a mechanical clock drive and 75-cm circles on both axes, divided to 4 arc seconds. The 12-cm f/13 achromatic objective lens had been acquired from Georg Merz in Munich (Kost, 2011), who had become a partner in Joseph Utzschneider's optical institute in 1838. The ambition for the equatorial was to determine celestial coordinates directly by reading the declination and right ascension circles with microscopes on scaled micrometers. The telescope also was equipped with a filar micrometer to obtain relative positions between reference stars and celestial objects.

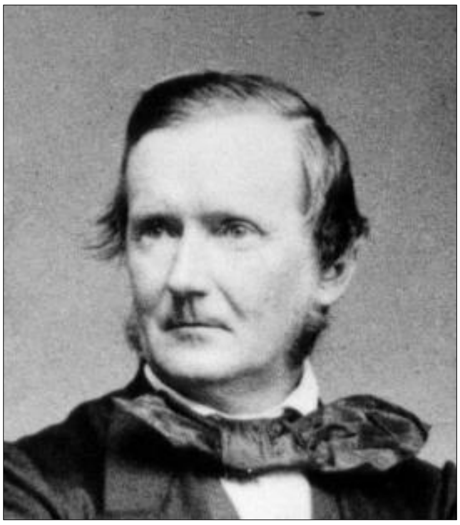


Figure 2: A photograph of Carl Fredrik Fearney (courtesy: Oslo Museum).

For ten years, Hansteen had been saving a fraction of each annual budget. In July 1837, he decided that an equatorial instrument was a wise investment, inspired by the price list from Ertel (1831). Hansteen (1837) asked the Astronomy Professor at Copenhagen University, Heinrich Christian Schumacher (1780–1850), for advice. Their relationship dated back for more than two decades, and Hansteen had visited him repeatedly at his residence and observatory in Altona. Schumacher had been the main advisor a decade earlier when the meridian circle and the first refractor were ordered for the Observatory in Christiania. Schumacher (1837) argued that Ertel's company had developed towards factory production, and that at the time Repsold was the leading astronomical instrument-maker in Germany. He noted that even Struve, who was close to Ertel, had to face the facts and had ordered both the meridian circle and the transit instrument for Pulkova from Repsold.

Schumacher discussed Hansteen's request with Repsold and informed Hansteen that Repsold would prepare a proposal drawing of the instrument so that details could be discussed before the final plan was agreed upon. To lower the costs, Repsold had suggested to Schumacher that the equatorial refractor could use the objective lens of the 6-foot refractor that Hansteen had acquired for the Observatory in 1833.

A week later Hansteen (1838a) wrote to Repsold, confirmed his intentions, and requested a drawing as a reference for further discussions. Repsold (1838a) responded immediately that he agreed to the plan. Hansteen was thrilled and reported the decision to the University. Departements-Tidende, a publication citing news from Government Ministries, reported in April 1838 that "… professor Hansteen has ordered an Equatorial-instrument for the Observatory at the expected cost of 1544 spesidaler." For comparison, this price was five times the annual salary of the Assistant Astronomer.

In July 1838 Hansteen (1838b) informed Repsold that he had wanted to visit Hamburg that summer to discuss the plans, but that because of matters beyond his control he had to postpone the visit to the summer of 1839. This gave Repsold more time for preparations, and he finished a reduced scale model of the mounting as the initial development step (Repsold, 1838b). Details were discussed with several local astronomers and ten days later Repsold (1838c) sent the proposal drawing and a description of the technical solutions, accompanied by suggestions from Schumacher, who had already seen the model and the text. Both Schumacher and Hansteen found the proposal excellent.

A novel suggestion was to produce the divided circles on glass rather than the customary brass wheel with a divided silver ring inserted. A test piece was made for Schumacher to evaluate. He found that it was difficult to read the divisions at low levels of artificial lightening, and was concerned that the use of ladders and chairs in the observing room represented a risk to glass circles. But Hansteen liked the idea of glass circles because they would not tarnish, unlike silver, and thus removed the risk of affecting the division markers when cleaned. Also, the scales could be illuminated from behind with appropriate brightness. But he feared the risk of breaking the glass, and eventually decided on customary brass circles.

The telescope tube was proposed to be made of wood, but would then need a system of counterweights to prevent deflections of the ends due to the weight of the objective lens and the filar micrometer. Schumacher suggested that a more rigid solution would be to join two short brass tubes in a central cube, as was customary with meridian telescopes. This was supported by Hansteen (1838c), who also suggested that a new objective lens should be ordered from Munich. He left the choice of lens diameter and focal length to Repsold, who accepted the technical revisions and decided on a focal length of 5 feet, after consultations with Schumacher (Repsold, 1839). Further details were tested on the model in preparation for Hansteen's expected visit.

Hansteen visited A. & G. Repsold in Hamburg as part of his scientific travels to Denmark and Germany during the summer of 1839. They discussed the revised model and construction drawings. With the plan accepted (Figure 3), Hansteen (1839) transferred an amount of 3000 thaler Hamburg Banco in November. The construction work began with the large parts, which were finished by the end of 1839. All the other parts, the test mounting, and adjustments required most of 1840. It also was decided to produce the specially shaped stone pillar in Hamburg to ensure the accurate positioning of the equatorial mount.

The entire consignment reached Christiania by ship in July 1841 (Hansteen, 1841). Hansteen had arranged for exterior scaffolding to be erected so that they could lift the pillar into the tower observing room. A window and part of the wall had been removed to maneuver the piece into position. The wall was re-bricked and the window re-inserted. The rotating roof also needed improvements, but progress was slow due to an exceptionally rainy summer.

Hansteen postponed the installation of the telescope until the summer of 1842. Upon the suggestion of A. & G. Repsold, the assembly work

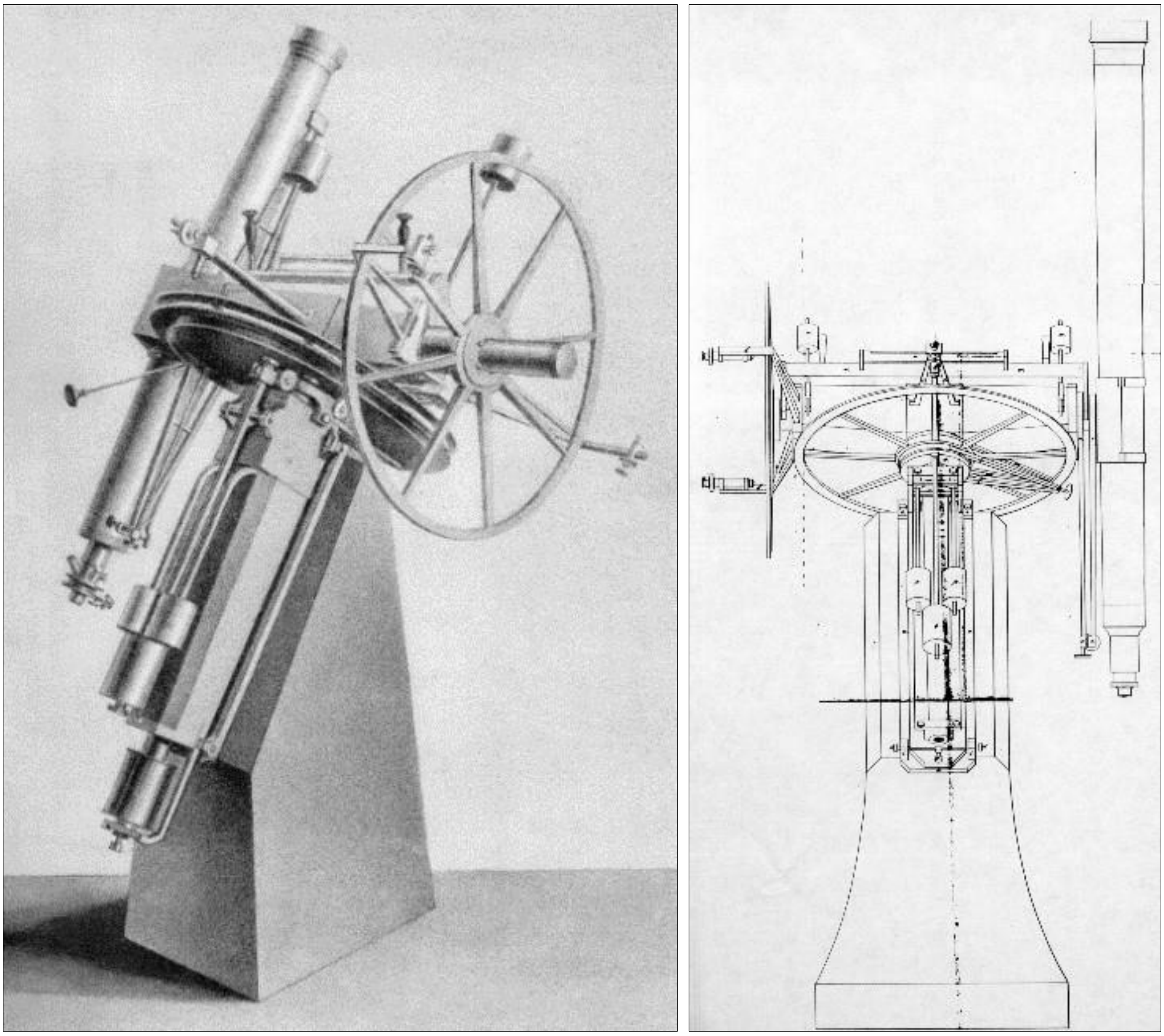


Figure 3: The equatorial refractor (left) and one of Repsold's construction drawings (right) (after Repsold, 1914).

was done by their expert, Mr Flittner. He arrived in Christiania in August 1842 and the entire instrument was ready for testing after two weeks. The polar axis pointed 2 arc minutes to the west and 22 arc minutes above the celestial pole. This was within the range of the adjustment screws and Flittner's work was complete. Hansteen ensured by observation that the two axes were orthogonal to each other and then proceeded to adjust the clock drive so the telescope would track stars. In some positions of the telescope, the drive was too weak and the tracking stopped. Hansteen experimented with heavier loads to run the clock drive, but the problem returned from time to time.

The first observing project included observations of stars across the sky to establish the transformation of coordinates read directly from the circles to the celestial coordinate system. Hansteen (1845) concluded that the small differences were random observational errors and not due to systematical effects of the instrument.

Carl Fredrik Fearnley began his tenure as Assistant Astronomer in 1844. His first task was to determine the Observatory's latitude using the meridian circle and the longitude by observing lunar occultations of stars with the equatorial telescope. When Neptune was discovered in 1846, Fearnley (1847a) began astrometry within a month of the discovery. A year later his observing program was expanded to include the newly discovered asteroids Iris and Flora (Fearnley 1847b; 1848).

Fearnley revealed great talent and skill as an observer and Hansteen decided to offer him further studies and training at foreign observatories. In 1850, the National Assembly granted a stipend that allowed Fearnley to spend two years abroad. The first year was with Professor Friedrich Wilhelm August Argelander (1799–1875) at Bonn Observatory, Germany. Fearnley was introduced to several telescopes and their auxiliary instruments. He made extensive observations of asteroids and comets with a ring micrometer. An occulting ring brings a star to

Figure 4: A ring micrometer (photograph: Bjørn Pettersen).

disappear and reappear twice when it drifts across the field of view when the telescope clock drive is disconnected. A chronometer was used to time the events. If the object was set to cross along a ring diameter, a reference star (before or after) might follow a chord if it had a different declination. Symmetrical timings represent center crossings and allowed computation of the difference in right ascension. The ratio of the chord length to the diameter was used to compute the difference in declination between the object and reference star. While he was abroad Fearnley acquired several ring micrometers that he would bring to Christiania (e.g. see Figure 4).

Figure 5: The Repsold-Merz equatorial refractor (unknown photographer/ courtesy: Norwegian Museum of Science and Technology).

During Fearnley's absence, Hansteen arranged for maintenance of the equatorial instrument. Mr Flittner returned to Christiania during the summer of 1851 to dismantle, oil, and adjust all moving parts. Then Hansteen adjusted the axes and determined the mathematical corrections to obtain celestial coordinates directly from the circles. He obtained a precision good enough to demonstrate that the corrections depended on ambient temperature. Hansteen (1851b) noted that the upper bearing of the polar axis was made of zinc. Since it expands more than brass, the polar angle of the telescope increased slightly with temperature. He restricted his use to that of a differential instrument, and observed lunar occultations and the total solar eclipse of 28 July 1851 (Hansteen, 1852a; 1852b; 1853a). From time determinations of the latter, he concluded that the northern limit of the zone of totality was closer to the Observatory than predicted by theory. The lunar tables required improvement.

Immediately upon his return to Christiania, Fearnley (1853) carried out extensive astrometry of what later turned out to be periodic comet 20D/Westphal, which was discovered by Justus Georg Westphal in Göttingen on 24 July 1852. Fearnley observed it from 20 August to 6 December 1852, using ring and filar micrometers, and the direct reading of the circles (when the comet was near the pole) to obtain celestial coordinates. He noticed a short tail of ½° on 2 September. Later it looked more like a deformed coma with an extension of a few arc minutes. A weak locking screw on the polar axis introduced erratic results for right ascension when he used the circles directly. This problem was not present on the declination axis. Fearnley (1855; 1857; 1858b) thus observed the next four comets with a ring micrometer only. When Donati's Comet (C/1858 L1) developed as a spectacular apparition in September and October 1858, Fearnley (1860) made use of both the ring micrometer and and direct microscope readings of the circles to record its positon, this time with accurate results. Three further comets were observed exclusively with the ring micrometer (Fearnley, 1861b; Mohn, 1864; Geelmuyden, 1871), before Fearnley (1874) again used the circles directly for astrometry of Comet C/1874 H1 (Coggia). Since this comet had a bright coma (magnitude 0–1), in July 1874 he used a Merz universal spectroscope (see below) to do the first spectroscopy of a comet from Norway, noting a continuous spectrum without lines or bands against the bright sky background. All later comets observed with the equatorial telescope (Figure 5) between 1877 and 1919 were observed with ring micrometers (Geelmuyden, 1877; Jelstrup, 1919; Lous, 1902; 1912; Schroeter, 1892). The telescope was dismantled after WWII and parts were used to construct instruments for the Oslo Solar Observatory in the 1950s (Rolf Brahde, pers. comm. 1990).

3 A COMET SEEKER FROM MERZ, 1851

While he was visiting Bonn Observatory, Fearnley received a Christmas letter from Hansteen (1850) asking him to consult with Argelander about a suitable comet seeker for the Observatory in Christiania. In Bonn, Fearnley (1851a) could test two short-focus f/8 Merz refractors: a 95 mm and a 75 mm. The smaller telescope was mounted in a dome and would become the core instrument for the Bonner Durchmusterung between 1852 and 1859. Both were of good optical quality, but spherical aberration was noted at the edge of each field. Including equatorial mountings, they were priced by Merz at 700 and 490 gulden, respectively.

A separate dome was not available in Christiania, so Fearnley decided on the 75-mm refractor, which he argued could easily be carried outside and placed on a platform next to the observatory tower. He even suggested that the costs could be reduced significantly if only the telescope tube assembly was bought from Merz and a local instrument-maker in Christiania was commissioned to construct the mounting. Hansteen (1851a) was skeptical, and argued that the quality of the local mechanical work might not match that of Merz. But he left the decision to Fearnley, and expressed trust in his judgement.

The order was placed with G. Merz & Söhne in early May 1851, when Fearnley (1851b) visited Munich Observatory and the instrument workshops of both Ertel and Merz. The comet seeker had a 6° field of view at a magnification of 10X. Another eyepiece gave 15X. Fearnley selected one of them as orthoscopic to address the spherical aberration. The equatorial mounting had 9-cm setting circles and fine motion screws on both axes (Figure 6).

The comet seeker left the Merz workshop in October 1851 (Merz, 1851) and arrived in Christiania on 1 November 1851 (Hansteen, 1851b). That same day the Observatory received a note about Comet C/1851 U1 (Brorsen) in Canes Venatici, which was well placed for a high latitude observatory, but a rainy fall season prevented Hansteen from searching for it and testing the telescope.

A few years later, Fearnley (1858b) monitored the position of Comet C/1857 Q1 (Klinkerfuss) and The Great Comet of 1861, C/1861 J1 (Tebbutt), and he used the comet seeker to estimate the length and shape of the comet tail of the latter comet (Fearnley, 1861b). The comet seeker also was used for an extensive program to monitor Comet C/1858 L1 (Donati) (Fearnley 1860)—which is discussed by Pettersen (2015).

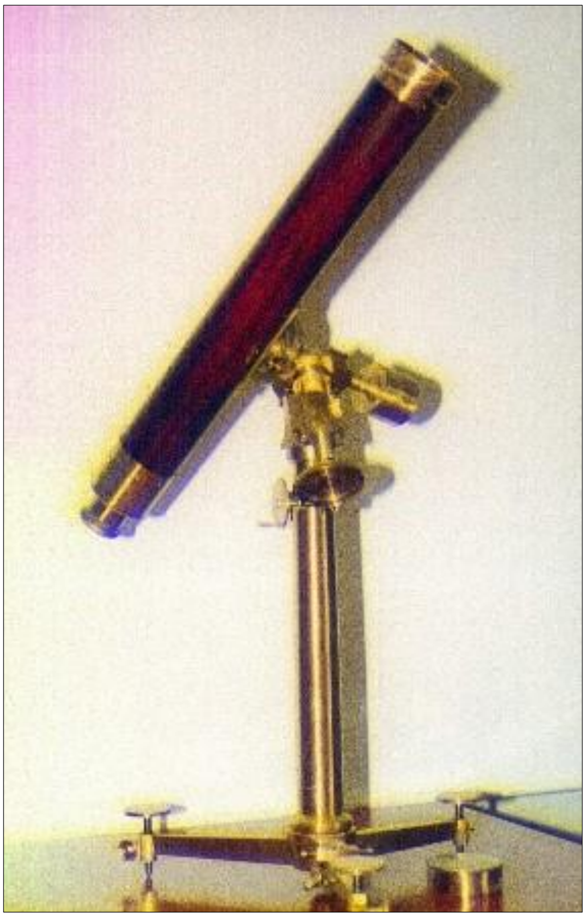
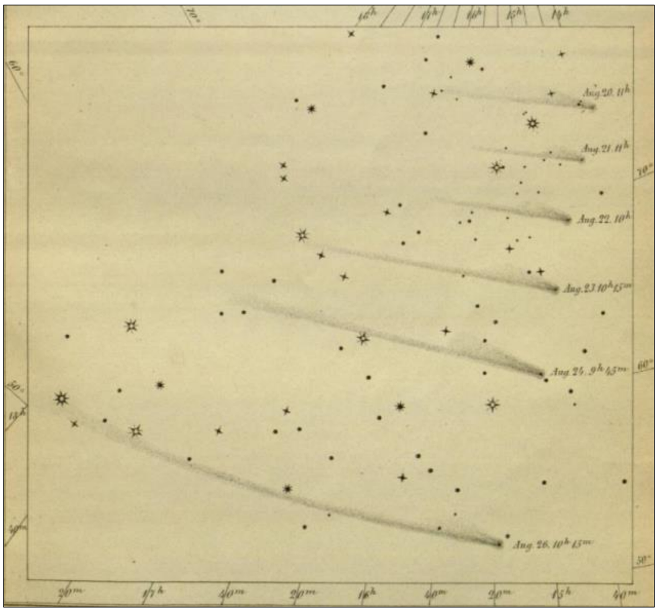


Figure 6: The Merz comet seeker (photograph: Bjørn Pettersen).

When Fearnley took over as Observatory Director in 1861 Henrik Mohn (1835–1916; Figure 7) was appointed Assistant Astronomer. He specialized in comets and was the first astronomer in Norway to attempt astronomical polarimetry, on Donati's Comet (Pettersen, 2015). In August 1862, he used the Merz comet seeker to monitor the shape, direction, and length of the tail of Comet C/1862 N1 (Schmidt) (Mohn 1863).

Figure 7: Henrik Mohn (courtesy: Norwegian Museum of Science and Technology).



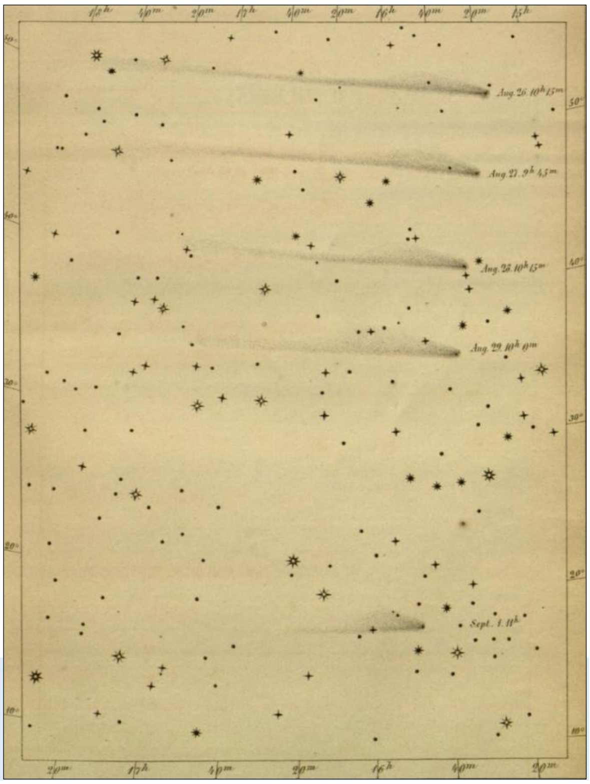


Figure 8: Drawings of Comet C/1862 N1 by Henrik Mohn, revealing its rapid motion towards the south in ten days (through the constellations of UMi, Dra, Boo, Cor Bor and into Ser), and the evolution of the comet's tail (after Mohn, 1863).

Figure 9: Above is part of a drawing by Synnøve Onsager showing the North dome in the Observatory Gardens, surrounded by buildings. The photograph (right) shows the dome being dismantled in 1908 (courtesy: Oslo Museum).

Mohn found the length grew from 5° to 22° in just five days (Figure 8), and that the curvature of the tail did not follow the great circle through the Sun and the comet. He also mounted the polarimeter on the comet seeker, but did not detect a polarized signal. The orbital plane of C/1862 N1 had an inclination of 172°, so the comet had retrograde motion in a parabolic orbit which brought it close to the Earth (0.1 AU on 4 July 1862). The coma then approached 0.5° in diameter.

On later occasions, the comet seeker would be used to time solar eclipses and lunar occultations, sometimes as student exercises. It is now on display in the Observatory.

4 THE 19 cm MERZ-REFRACTOR, 1857

When Fearnley returned from his studies abroad, Hansteen was ready to invest again. Various options for the best choice of instrument were discussed, to ensure the progress of astronomy at the Observatory and the University. During the summer of 1853, Hansteen ordered a 19-cm refractor with a focal length of 300 cm from G. Merz & Söhne in Munich. It would require its own observatory dome (Figure 9). Merz (1853), after receiving the exact latitude, suggested a dome construction and specified the location of the 2-m high stone pillar inside the observing room.

Two years later the instrument was ready for delivery (Merz, 1855). Architects Wilhelm Hanno and Heinrich Ernst Schirmer prepared drawings and a cost estimate for the building, which Hansteen submitted to the University leadership. Since the National Assembly met only every three years, the application for funds was forwarded directly to the Government. The request was to fund the building costs for the dome from the University budget. King Oscar I, who spent the summer of 1855 in Christiania, ratified the Government's decision in a Royal Decree dated 6 August 1855 (Departements-Tidende, 1855).

When the National Assembly convened two years later, during the fall of 1857, the building had been completed. The Budget Committee criticized the decision process, which had excluded the National Assembly. They expressed concern that the urgency of the matter had not been serious enough to allow deviations from standard procedure. But, in the end the National Assembly ratified the result (Stortingsforhandlingene, 1857).

When the north dome was nearing completion in the spring of 1857, Hansteen wrote to G. Merz & Söhne to request that an instrument maker come to Christiania and mount the instrument that summer. Merz (1857) had to decline because he had scheduled deliveries in both Russia and Spain. Instead, he suggested that a Norwegian instrument-maker be sent to Munich to attend the test mounting of the Madrid telescope before it was shipped, and upon his return to Christiania the 19-cm refractor (see Figure 10) was successfully mounted in the north dome.

The right ascension circle of the equatorial mounting (Figure 11) had a diameter of 24 cm and was divided to 4 time seconds (1 arc minute). The declination circle had a diameter of 38 cm and was divided to 10 arc seconds. There were five eyepieces (with magnifications from 102X to 550X), a filar micrometer (magnification from 100X to 580X), and a ring micrometer.

The first observations conducted with the new Merz refractor were a series of lunar occultations of the Pleiades in November and December 1857 (Fearnley, 1858a). When Comet Donati appeared high in the skies in the Fall of 1858, all of the telescopes at the Observatory were employed and Henrik Mohn used the new Merz telescope for astronomical polarimetry. He concluded that the light from the comet's head was reflected sunlight (Pettersen, 2015).

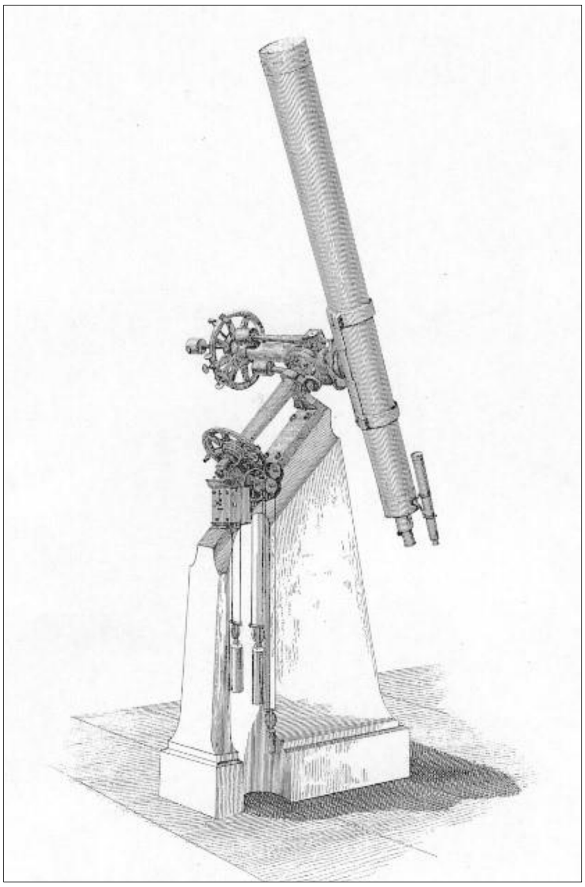


Figure 10: Merz's drawing of the completed 19-cm refractor (courtesy: Deutsches Museum Archives, Munich).

Figure 11: The Merz mounting and clock drive for the 19-cm refractor in Christiania, now on display in the Deutsches Museum in Munich with the 22-cm Merz refractor from Berlin Observatory that was used by Galle to discover Neptune (photograph: Bjørn Pettersen).

A year later Hansteen returned the objective lens to Munich. The glass was not tight inside the brass mounting, which appeared to be slightly out of shape. Merz (1859) suspected that the lens mounting had suffered a blow, but when the objective was dismantled the thin spacers between the crown glass and the flint glass were found to be in incorrect locations. Merz commented that the lens components appeared to have been mounted by untrained hands. After he had repaired, remounted and adjusted the objective it was returned to Christiania. Fearnley (1861) then made another set of observations of lunar occultations of Pleiades stars, and he observed a transit of Mercury (Fearnley, 1868). The positions of numerous comets (and some asteroids) were then determined with the ring micrometer (Mohn, 1864; Schroeter, 1892; 1894; 1895; 1896b).

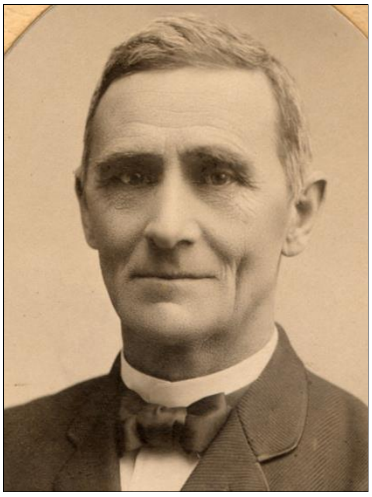


Figure 12: Hans Geelmuyden (Photo: Ludvig Forbech/MUV).

4.1 The Visual Parallax of a Nearby Star

In 1869, the Observatory in Christiania joined the Astronomische Gesellschaft sky mapping project. Two years earlier, Hans Geelmuyden (1844–1920; Figure 12) had succeeded Mohn as Assistant Astronomer. For 12 years, Fearnley and Geelmuyden used the meridian circle to determine the coordinates of 3,949 stars in a zone between declinations 65° and 70°. A serendipitous discovery during the project was a star with a large proper motion: 2.94 arc seconds per year, at position angle 274.5° (Fearnley, 1878). Geelmuyden suspected that it was also nearby and attempted to determine the parallax of AOe 11677 (= BD 66°717 = Gliese 424) by repeated visual determinations (V = 9.3 mag) of its coordinates relative to a slightly fainter comparison star nearby (7 arc seconds north and 90 time seconds west). He hoped to detect small systematic changes in the course of a year that would allow him to calculate the parallax. Geelmuyden (1879) used a filar micrometer on the Merz refractor from 4 September 1878 to 14 October 1879. He made 222 observations in right ascension and 206 observations in declination on 26 nights. When he solved for the parallax and the proper motion in the same solution, the errors were large. If he kept the proper motion at a constant value, the parallax was 0.27 ± 0.08 arc seconds in right ascension and 0.24 ± 0.04 arc seconds in declination.

The image quality of the telescope appears to have been a returning issue. In 1871, Fearnley asked if improvements were possible. Sigmund Merz (1871b), who had taken over the company four years earlier, replied that new lens components would be expensive, but he offered to cover 25% of the cost if an inspection of the objective lens suggested that the crown glass or flint glass component had to be replaced.

In 1880, Fearnley attended a geodesy conference in Munich. He visited the Merz Company, and may have brought the 19-cm objective lens to have it inspected. Sigmund Merz suggested that a new objective lens should replace the existing one. He offered one with the same diameter, but a focal length 12 cm longer, at favourable exchange conditions, as described in a footnote by Fearnley (1885). It was shipped to Norway on 29 September 1882.

With the new objective lens, Geelmuyden (1885a; 1885b) made another set of observations of AOe 11677 from 2 October 1883 to 17 November 1884. Over 30 nights he recorded 287 observations in right ascension and 283 observations in declination. The new parallax result for right ascension was about twice the value of the original one. The declination result compared nicely at 0.23 ± 0.04 arc seconds. Geelmuyden was never able to identify the cause(s) of the systematic errors.

The Hipparcos Satellite determined the proper motion of this nearby star (HIP 55360) as 2.9525 arc seconds at position angle 273.6°, and a parallax of 0.110 ± 0.001 arc seconds.

4.2 The Opposition of Asteroid Eros in 1900

Among the long succession of astrometry of comets and asteroids over the years, a special effort was made with the Merz refractor during the Eros opposition in 1900. The asteroid was observed on 49 nights from 14 October 1900 to 18 April 1901 with a filar micrometer. This was part of an international project with 58 observatories participating, to improve the solar parallax value by determining the diurnal parallax of 433 Eros. Professor Hans Geelmuyden (1902a; 1902b) and Assistant Astronomer Jens Fredrik Schroeter (1857–1927; Figure 13) made 787 observations in right ascension and 1064 in declination. The final analysis of the international dataset was made by Hinks (1910): the photographic data yielded a solar parallax of 8.807 ± 0.003 arc seconds, while the visual data, including the Christiania observations, yielded 8.806 ± 0.004 arc seconds.

4.3 The Afterlife

As the city expanded and buildings gradually surrounded the Observatory, the observing conditions also deteriorated. The Merz refractor was used for timing lunar occultations of stars (e.g. Schroeter, 1896a) and planets (Geelmuyden, 1898; 1900b), sometimes during lunar eclipses in order to include faint stars. Timings of solar eclipses were made six times until 1907, when there was also a transit of Mercury, and short reports were published in *Astronomische Nachrichten* (Geelmuyden, 1891b; 1899; 1900a; 1903; 1905; 1908).

In 1908 the Merz telescope was dismantled and the north dome was demolished in order to provide room for the new University Library. In 1920, when Jens Fredrik Schroeter became Observatory Director, he sent the Merz telescope and mounting to Munich to assess the costs of modernizing it. His plan was to mount it in the Observatory tower and dismantle the smaller Repsold refractor. The conclusion of G. & S. Merz G.m.b.H. was that the refractor might continue its service, but the mounting was considered mostly of historical interest. Modernization of the mechanics was not recommended; it would be less costly to acquire a new mounting. The refractor was returned to Christiania, but the mounting remained in store at the Merz workshops. It was later transferred to the Deutsches Museum, where it is used as a mounting on a Fraunhofer type wooden pillar for the Berlin 22-cm Merz which Galle used to discover Neptune (Fuchs, 1955). It is still on display (Figure 11).

5 MERZ SPECTROSCOPES, 1872

In October 1871 Fearnley ordered a spectroscope from Merz (1871a), who regretted a delayed delivery because many other observatories had also ordered them. The universal stellar spectroscope (Figure 14) was ready for delivery in May 1872. Merz (1872) explained that a delaying factor had been difficulties in obtaining prisms of good quality. The instrument arrived in Christiania during the summer of 1872 and the Observatory accounting book shows that Fearnley paid 240 gulden on 31 August 1872.

Another spectroscope was also received from Merz (Figure 15), but we have not found any correspondence that reveals the date of that acquisition. Merz continued to produce spectroscopes for several decades (Kost, 2015: 270).

Fearnley used the spectroscopes on the 12-cm Repsold-Merz equatorial refractor to observe the structure and dynamics of solar prominences. He adjusted the spectroscope to show the Hα-line (6563 Å) in the center of the field of view. The entrance slit was oriented perpendicular to the solar limb, and by moving the telescope, he could scan for prominences above the limb. By inserting a red filter to exclude background light from other parts of the spectrum, he opened the entrance slit to see the entire prominence. Fearnley published very little of these results, but a few drawings remain from what appears to have been a 3-year observing program. He observed both quiescent and eruptive prominences. His drawings were very detailed (e.g. see Figure 16), and he must have spent time patiently waiting for moments of good seeing to obtain such high-resolution results.

On one occasion, he noticed both a red and a yellow image of a prominence in the field of view (Figure 17). In the spectrum, he located a yellow emission line next to the Na D-lines. Today

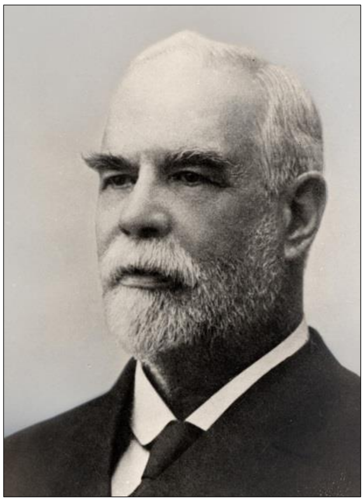


Figure 13: Jens Fredrik Schroeter (photograph: MUV).

Figure 14: A Merz universal stellar spectroscope (photograph: Bjørn Pettersen).

Figure 15: A Merz universal stellar spectroscope (photograph: Bjørn Pettersen).

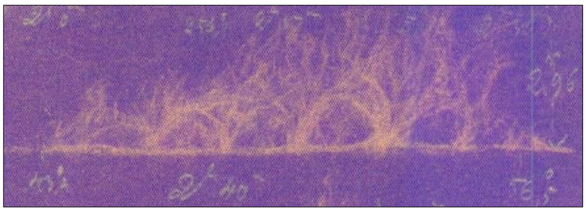


Figure 16: A group of quiescent prominences observed by C.F. Fearnley (photograph: Bjørn Pettersen).

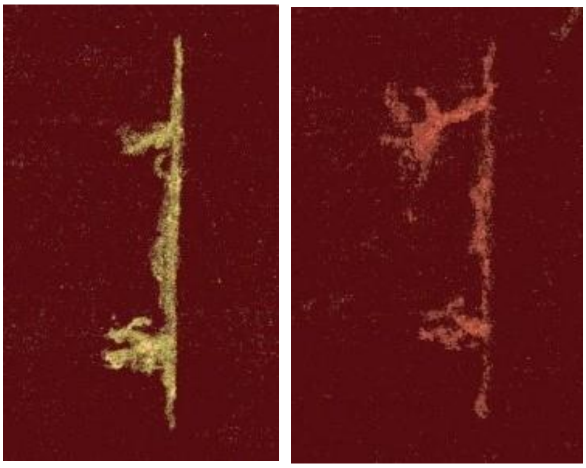


Figure 17: Drawing by C F. Fearnley of a prominence, in He D_3 (5876 Å) (left), and in Hα (6563 Å) (right) (photograph: Bjørn Pettersen).

it is labeled He D_3 (5876 Å), but at the time its chemical origin was not determined. Norman Lockyer had postulated in 1868 that a hitherto

Figure 18: The 13-cm Merz refractor on an equatorial mounting by C.H.G. Olsen (photograph: Bjørn Pettersen).

unknown element existed on the Sun. He called it helium. It would take almost three decades before the element was detected on Earth (see Nath, 2013).

6 THE 13 cm MERZ REFRACTOR, 1882

Fearnley attended the General Assembly of the European Geodetic Arc Project (the forerunner to the International Association of Geodesy, or IAG) in Munich, Germany, on 13–20 September 1880. As the leader of the National Geodetic Arc Commission, he was the official delegate for Norway. During his stay in Munich, he visited the workshops of Sigmund Merz in Blumenstrasse 31 and ordered a tube assembly with an objective lens of 13.2-cm diameter and focal length of 195 cm. It had six eyepieces and a filter for solar observations. Two years later a letter from Merz (1882a) informed Fearnley that the telescope had been shipped to Christiania. The Merz account book (1882b) records a payment from Fearnley of 1236 mark on 24 November 1882.

Fearnley also ordered an equatorial mounting with clock drive from the Christiania instrument-maker Christian Holberg Gran Olsen in. The completed instrument (Figure 18) won a silver medal at the Christiania Exhibition in 1883, where it was on display in an observatory dome in the Exhibition Grounds in the Royal Gardens (Pettersen, 2004). A small entrance fee allowed the public to view the Sun during the daytime and the Moon and planets in the evening. It was a popular arrangement with an extra income for Mr Olsen. The telescope remained in its dome for more than a year before it was moved to its new residence in the east dome in the Observatory Gardens in November 1884. There it continued to serve the public once or twice a week, but this time at no cost. On clear evenings, the Observatory Custodian would show the Moon and planets, and lecture on astronomy to the visitors. This arrangement continued until 1934.

In addition to being the Peoples Telescope, it was also used for the occasional observation of lunar occultations (Fearnley, 1885; 1888), solar eclipses (Geelmuyden, 1891b; 1900; 1905; Schroeter, 1921) and transits of Mercury (Geelmuyden, 1891a; 1908). It is now in storage.

7 SUMMARY AND CONCLUDING REMARKS

The optics of four telescopes at the University Observatory in Christiania were delivered by Merz in Munich between 1840 and 1882. Two telescopes, the comet seeker and the 19 cm, were complete instruments with equatorial mountings. The other two instruments had mountings from Repsold and Olsen, respectively. A map (Figure 19) shows the locations of the three permanently mounted telescopes, in the Observatory tower, the east dome and the north dome. Today, office and apartment buildings occupy the sites of the latter two. Only the main building of the Observatory remains.

These telescopes were extensively used for classical astrometry of comets, asteroids and planets, in addition to time determinations of eclipses, occultations and transits of Mercury. Participation in international projects contributed to an improved value for the Astronomical Unit and the detection of a star with a large proper motion. It was shown to be nearby—albeit with numerical results suffering from systematic effects. The Merz telescopes were exclusively used for visual observations. Astrophysical observations were carried out in the 1870s, i.e. observations of solar prominences and of the morphology, spectroscopy and polarimetry of bright comets. For these investigations, the Merz universal stellar spectroscope was a key instrument.

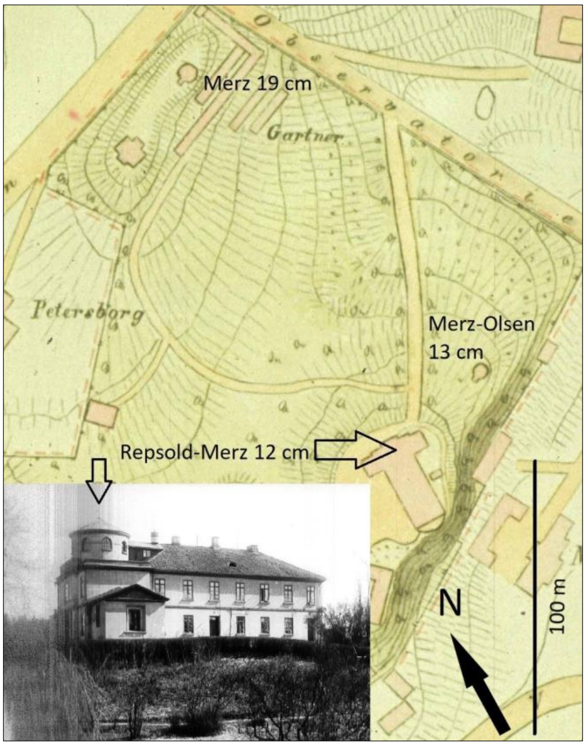


Figure 14: A map showing the Observatory's main building and telescope pavilions (photograph: Bjørn Pettersen).

Attempts to obtain funds for photographic equipment and even to relocate the Observatory outside of the city were never successful. The University Observatory was abandoned in 1934 when the astronomers moved to a new University campus that is now home to the Institute of Theoretical Astrophysics.

8 ACKNOWLEDGEMENTS

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Dr Bjørn R. Pettersen is Adjunct Professor of Astronomy at the University of Oslo and Professor of Geodesy at the Norwegian University of Environmental and Life Sciences. He has published 218 research papers and has edited proceedings from IAU symposia and other international conferences. His main research interests include observational astronomy, space geodesy, gravimetry and the history of science. He has served on the Orgnising Committee of IAU Commission 41's Working Group on Historical Instruments.

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FOUR CENTURIES OF OBSERVATIONS OF THE GALILEAN SATELLITES OF JUPITER: INCREASING THE ASTROMETRIC ACCURACY

J.E. Arlot
IMCCE/Observatoire de Paris, 77 avenue Denfert-Rochereau, F-75014 Paris, France.
E-mail: jean-eudes.arlot@obspm.fr

Abstract: The main satellites of Jupiter, named Galilean after their discovery by Galileo Galilei, are among the most studied celestial objects. The dynamics of their motions represent one of the most complex challenges in the Solar System but the most interesting, including all the dynamical problems of a gravitational system. The modeling of their motions is difficult because of their size (Ganymede has a size similar to Mars or Mercury) and mutual gravitational perturbations, because of the flatness of Jupiter, the presence of Saturn and the Sun and strong tidal effects between them and the planet Jupiter. However, a good knowledge of their dynamics may help us understand their physical nature (their internal structure influences their motions), their formation and their evolution. For these purposes, accurate astrometric observations are essential to determine the physical parameters of their dynamics. Our purpose in this paper is to explore the history of the progress made in these studies during the last four centuries and the value of using old data in present-day research.

Keywords: Galilean satellites, orbital dynamics, astrometric accuracy

1 INTRODUCTION: THE GALILEAN SATELLITES

The planet Jupiter has a lot of satellites but the Galilean ones are more than simple satellites. Their sizes, similar to small planets such as Mercury or Mars, make them interesting worlds worth exploring. They are bright enough to be observed with small instruments (they would be observable with the naked-eye if Jupiter were not so dazzling). This is why they were observed as soon as a telescope was used to look at Jupiter. The motion of the Galilean satellites seems at first to be very easy to understand: quasi coplanar and quasi circular motions around Jupiter. The first satellite, Io is 422 000 km from Jupiter (as the Moon is from the Earth) but the duration of a revolution around the planet is only 1.77 day (due to the large mass of Jupiter). The second satellite, Europa, is 671 000 km from Jupiter, and has a period of revolution of 3.55 days; the third satellite, Ganymede, is 1 070 000 km from Jupiter, and has a period of revolution of 7.15 days; and the fourth satellite, Callisto, is 1 883 000 km from Jupiter, and has a period of revolution of 16.69 days. Because of the gravitational interactions between the satellites, the longitudes of the first three satellites are linked through the relationship $l_1 - 3\,l_2 + 2\,l_3 = 180° + L_i$, known as the resonance between their motions. L_i is a small quantity named 'libration', showing that the satellites are not exactly in resonance. In fact, the orbits are not exactly circular and in the same plane, and studies of the dynamics of the satellites help us try to understand how their motion is evolving with time (are they going out of resonance?) and aids the exploration of these satellites in complement to space probes visiting the Jovian system. The other satellites of Jupiter are very small, and are either inside the orbit of Io, near the faint rings around the planet, or outside the orbit of Callisto at more than 10 million kilometers from Jupiter. Consequently, their influence on the Galilean satellites is negligible.

From their discovery until today, our understanding of the dynamics of the Galilean satellites has made it necessary to fit their dynamical parameters with astrometric observations of their positions. The accuracy of these observations is crucial and should be homogeneous with the accuracy of the theoretical model. So, the goal of the observers is to get more and more precise data: a new digit in accuracy means the discovery of a new faint effect, gravitational or otherwise, on the motion of the satellites, the signature of a previously unknown character of the satellites. Let us now see how the accuracy of the observations improved year after year, thereby bringing new information about the Galilean satellite system, and how old observations can still be useful for today's studies.

2 THE OBSERVATIONS

First of all, how to estimate the accuracy of the data since many different types of observations were performed? What are astrometric observations? They correspond to the measurement of the positions of the satellites at a given moment, (e.g. see Figure 1) on a given date referred to a common time scale and a well-defined reference frame. Then, the observation will fit the theoretical models of their motions and provide the dynamical parameters of these motions. It is easy to understand that accurate observations will provide accurate parameters. Moreover, bad models will deviate from the observations, showing the defects in these models. Only accurate observations will allow us to detect and correct the errors in the theoretical models.

The first way to get astrometric positions is to measure the celestial coordinates (right ascension and declination of the satellites). These observations are made thanks to micrometric measures, photographic plates, transit circle observations and now CCD images. These measurements are made in geocentric angle units with an uncertainty decreasing with more numerous observations, according to statistical laws.

The second way is to get positions of the satellites relative to the planet Jupiter or to other satellites since the system may be considered as astrometrically isolated. Separation and position angles or tangential coordinates are then obtained in geocentric angle units, as previously. These measurements are made using photographic plates, micrometric or heliometric observations, and now CCD images.

The third way is to have access to relative positions in kilometers in space. This is possible thanks to the space probes making measurements and also thanks to the observation of specific phenomena (mutual occultations and eclipses) involving the sizes of the satellites, which are well known nowadays thanks to space probes.

The fourth way is to get positions from the observations of phenomena such as eclipses or occultations by Jupiter. The geometry of these events is known from geocentric observations and the data obtained are the timings of these events. The uncertainty is then in seconds of time, smaller than the uncertainty in angles since timings are easier to measure than angles. This method is the oldest one since it is also the easiest.

We will analyze the different observations made since Galileo and compare their accuracies. In order to have comparable data, we will express them in angle units (arcsec), in seconds of time and in kilometers. We will convert the original data given in a specific unit (colour-coded in the tables) into the other units just for comparison. One arcsec corresponds to about 3 000 kilometers (at the mean distance of Jupiter) and one second of time to 18 km for Io, 14 km for Europa, 11 km for Ganymede and 8 km for Callisto (average 13 kilometers for all satellites together along the orbits). The values will be either in the tangential plane or along the orbits.

We will estimate the accuracy of the observations through two datasets: first the dispersion of the residuals (r.m.s. or standard deviation) around their mean value, and second, the mean residuals (O-C for positions or C-O for timings). For the calculation of these residuals, we must use the best ephemeris that fits the associated observations, in order to avoid the errors on the theoretical model used for the ephemerides. This best ephemeris to be used can be an old one well fitted to the observations, rather than a recent one that does not fit these observations. The dispersion is, of course, an estimate of the accuracy, but the mean residual may indicate some bias in the observations. The observations must be used as plain individual observations, not normal points issued from several datasets, to be sure that all the observations are comparable.

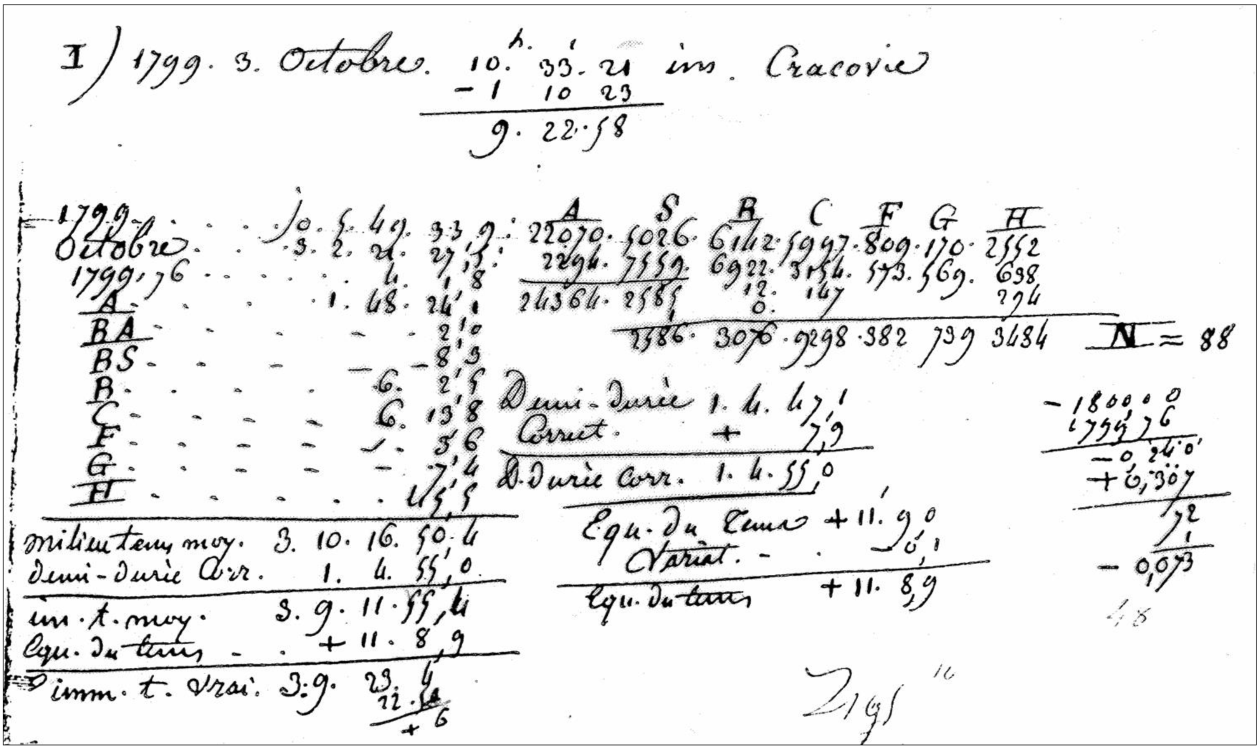

Figure 1: Delambre's calculation of the position of Io, based on an eclipse that he observed on 3 October 1799.

2.1 The Seventeenth Century: The First Observations

As soon as the satellites were discovered by Galileo Galilei, the first goal was to identify them and to be able to predict their positions in the near future. Galileo immediately thought that the motions of the satellites were so regular that they could be used as a universal clock (or more precisely as a reference for clocks) observable by everyone everywhere and so could be used to determine geographical longitudes (which was a crucial challenge at that time). In order to make even a very simple model it was necessary to make astrometric observations of the positions of the satellites as a function on time. The first measurements were made by Galileo in January 1610: he noted the dates of his observations in 'hours after sunset' and he angular measured distances between the satellites or between a satellite and the planet (Galileo, 1610; 1880).

Table 1 provides the (O-C)s and dispersion of these observations using recent ephemerides (old ephemerides are not useful for this). The dispersion of the residuals is about one arc minute, too large to make these observations useful for modern studies. One arc minute corresponds to 180 000 km in space, half the semi-major axis of Io's orbit and more than twice the diameter of Jupiter. Note that in all of the following tables we will use coloured print to show the astrometric accuracy in the unit used by the observer (seconds of time for events, angles for positions or distances and kilometers for events or space probes measures), but we also will provide the same value in the other units for comparison (using the mean velocity of the satellites as 13 km/s and the angle at mean distance as one arcsec for 3 000 km *in situ*). The accuracy of these observations was bad because of Galileo's observing method: he estimated distances using the size of Jupiter as his only reference.

In 1612, Galileo understood the phenomena of the eclipses of the satellites in the shadow of Jupiter. These eclipses occur very often, for each revolution of a satellite around the planet, so they are easily observable. Everyone can understand that an observation of an eclipse of a satellite corresponds to an observation of a position of the satellite in its orbit around Jupiter providing the size of the planet is known or taken as a reference unit. The observations of eclipses (the timing of the disappearance and/or reappearance of the satellite in the shadow) were the only way to build ephemerides predicting the positions of the satellites. The accuracy of such observations can be very good. Determining the time of an eclipse with an accuracy of 30 seconds of time, corresponds to accuracy in orbital position of 600 km for Io to 300 km for Callisto, according to the velocities of the satellites. In fact, the timing of an eclipse depended of the sensitivity of the telescope used. For small telescopes, the disappearance of the satellite occurred earlier than in a larger telescope because the image of Jupiter is more blurred. The error in the time of disappearance was supposed to compensate for the error in the reappearance, but the absorption of the air mass and the sky background (twilight ...) induced biases. This error will be reduced at the end of the nineteenth century when photometric methods using references were introduced. The true disappearance of the satellites was then better determined since the photometric method helped to determine the true zero photometric value of the signal. Eclipses have been extensively observed since Galileo's time, and the observations are still used for dynamical purpose. The accuracy of such observations made during the seventeenth century is given in Table 2. In preparing this table we se-

Table 1: (O-C)s for Galileo's Measurements of Distances: The Dispersion of these Observations is about One Arcmin.

Date (1610)	Hour	Distance	Observation	(O-C)		
				In Time	Angle	km
1 February	18h 19s	Jupiter-Ganymede	6′ 00″	4h 33m	1′ 00″	180 000
		Jupiter-Io	0′ 20″	1h 23m	0′ 30″	90 000
		Jupiter-Callisto	8′ 00″	3h 07m	0′ 30″	90 000
2 February	17h 20s	Jupiter-Ganymede	6′ 00″	6h 49m	1′ 30″	270 000
		Jupiter-Europa	4′ 00″	2h 41m	0′ 45″	135 000
		Europa-Callisto	8′ 00″	9h 05m	2′ 00″	360 000
	23h 20s	Ganymede-Io	4′ 00″	5h 45m	1′ 40″	300 000
		Jupiter-Io	1′ 40″	0h 42m	0′ 15″	45 000
		Jupiter-Europa	6′ 00″	9h 49m	2′ 45″	495 000
		Europa-Callisto	8′ 00″	6h 49m	1′ 30″	270 000
3 February	23h 20s	Jupiter-Europa	1′ 30″	0h 14m	0′ 04″	12 000
		Jupiter-Io	2′ 00″	0h 14m	0′ 05″	15 000
		Io-Callisto	10′ 00″	12h 49m	3′ 20″	600 000

Table 2: Accuracy of the Observations of Eclipses of Io during the Seventeenth Century: Dispersion σ and Mean (C-O).

Author	Opposition	n	Dispersion σ			Mean (C-O)		
			sec	″	km	sec	″	km
Pingré	1652–1654	23	1361	6.85	20565	857	4.28	12855
Pingré	1655	16	196	0.98	2940	64	0.32	960
Pingré	1671	12	89	0.46	1365	–36	–0.18	–540
Roemer	1672–1673	69	62	0.31	930	12	0.06	180

lected several samples of observations from the NSDC database (Arlot and Emelyanov, 2009), with the residuals being taken from the catalogue of eclipses (Lieske, 1986) and extracted from Pingré's compilation of old data (Pingré, 1756; cf. Bigourdan, 1901).

It is easy to see that the observers made progresses in their observing methods year after year.

2.2 The First Tables: The Inequalities from Empirical Tables to Dynamical Theories

The first observers of the motion of the Galilean satellites thought that they were seeing perfectly regular uniform motion, with the satellites orbiting in circular orbits. If this were true, the prediction of the positions would have been easy, but the first tables—calculated by Galileo in 1612 and by Mayr in 1614—appeared to be very inaccurate. The eclipses did not occur regularly: sometimes they were in advance, and at other times late. Why? The cause was what we will call 'inequalities'. The challenge was to observe, explain and understand these inequalities. Before Newton and universal gravitation, the modelling of the motions was purely kinematic. The motions were supposed to be periodic and the modelling was just describing the periodicities. Anyway, it was necessary to make observations with a sufficient accuracy to detect the changes in the uniform revolution of the satellites. Let us see the influence of these 'inequalities' on the motion of the Galilean satellites. Note that the magnitude of the inequalities introduced in the modelling of the satellites' motion must be in accord with the astrometric accuracy of the observations. If the motion of the satellites differs by one minute from the uniform circular motion, observations accurate to 10 minutes will not be able to quantify a one-minute inequality. We must have a minimum accuracy for the astrometric observations in order to be able to shed light on the discrepancy between the ephemerides and the observations. Another question will rise soon: are the satellites accelerating on their orbits? In other words, how can we discriminate between periodic and secular inequalities? We will return to this question later.

The first main cause of inequality in the occurrence of the eclipses was the speed of light. At first, the speed of light was supposed to be infinite but the observation of successive eclipses of Io by Roemer and his colleagues in Paris Observatory demonstrated in 1676 that this was not true (see Bobis and Lequeux, 2008). Because of the motion of the Earth around the Sun, the Earth-Jupiter distance was changing throughout the year: it was smaller at the Sun-Jupiter opposition and larger at the conjunction. The difference was about one astronomical unit (au) between opposition and quadrature and two aus between opposition and conjunction. This delayed the occurrence of the eclipses by about 8 minutes of time between opposition and quadrature, a quantity that was easily observable even during the seventeenth century. Moreover, the eccentricity of the orbit of Jupiter changed the mean Earth-Jupiter distance and had a similar effect with a period of 12 years. These inequalities were not due to dynamical causes, but others were dynamical. As Lagrange demonstrated, most of the motions in the Solar System were two-body problem with perturbations by other bodies implying a variation in the constants of the elliptical orbits. This is the cause of the dynamical inequalities.

Let us examine the different causes of the inequalities (see Table 3):

(1) The N-body problem is the main cause of inequalities: the attraction by other satellites is not negligible and they have a large influence on each other. The influence of Saturn and other planets may be taken into account. The deviation from positions in a uniform motion may reach more than 6 000 km (the maximum for Europa).
(2) The oblateness of Jupiter (J2) has an influence on the motion of the nodes, especially for Europa, with a deviation reaching 2 700 km.
(3) The Sun has an influence, especially on the longitude of Callisto, and the deviation may reach 1 000 km.
(4) Tides from Jupiter: the satellites have sufficient strength to dissipate energy and modify their motion (secular acceleration), and this may induce a deviation of 300 km on Ganymede, accumulated during several tens of years.
(5) The precession of Jupiter has a small influence, and creates a deviation of few tenths of kilometers.
(6) The oblateness of the satellites themselves induces a deviation of a few kilometers
(7) Relativistic effects are very small, and near to Jupiter they correspond to sub-kilometric effects.

Table 3: The maximum deviation induced by perturbations (Lainey et al., 2001).

Deviation	N-body Problem	J2 Jupiter	Sun	Saturn	Tides Over One Century	Jovian Precession	J2 Satellites	Relativistic Effects
in km	6282 (Europa)	2712 (Europa)	1052 (Callisto)	226 (Callisto)	300 (Ganymede)	80	5	2 (Io)
in arcsec	2	0.9	0.35	0.075	0.10	0.027	0.002	<0.001
in sec	449	194	131	28	27	10	0.6	0.12

Starting from Galileo, the importance of the eclipses of the Galilean satellites (useful for the determination of longitudes) encouraged the prediction of these events and the construction of tables of the movement of these bodies. The first tables by Galileo, Marius, Hodierna and Borelli were not good since they did not take the speed of light into account. The approach of the problem was purely kinematic. In 1668 Cassini published his "Tables of the movement and calculation of eclipses". In 1690, tables for the eclipses of Io appeared in the *Connaissance des temps* based upon better tables by Cassini, and they were improved further by Maraldi in 1730. In 1749, Bradley published tables and noticed an inequality of 437 days in the eclipse times of the first three satellites. Maraldi pointed out at this date the mutual action of the satellites and one began to be suspicious about the eccentricities of the orbits and the nature of the inequalities. Wargentin published improved tables in 1757. At this time, the movement of the satellites was still expressed in the form of kinematic empirical equations, and Lalande could say in the *Connaissance des temps* for 1763 that "… the inclinations and the nodes of the orbits have variations that are still poorly known."

In the eighteenth century, from Newton to Laplace, the principles of dynamics and universal gravitation were put in place, and everything changed in the modelling of motions: it became possible to write equations representing dynamic models. For the Galilean satellites, the problem was very difficult as many forces acted on the satellites: the Sun, far away but massive; the flattening of Jupiter; the planet Saturn; and also the mutual interactions between the satellites. From these interactions would result a resonance that would force the motion of satellites. The first three satellites did not move independently of each other, but their longitudes, L_1, L_2 and L_3, were linked by the relation $L_1 - 3 L_2 + 2 L_3 = 180°$.

Satellites obviously tend to escape this constraint, creating more 'inequality', but they cannot move away from it by more than one degree: the resonance brings them back to their imposed configuration.

From the dynamic equations, the tables (or ephemerides) progressed quickly: the first theories were due to Bailly and Lagrange in 1766, then came that of Laplace, the most complete in 1788. In 1791, Delambre built tables from Laplace's theory and from the analysis of more than 6 000 eclipses.

The nineteenth century was the 'golden age' of celestial mechanics and astrometric observation. From the theoretical point of view, Damoiseau improved on Laplace's work in order to publish ephemerides and predictions of eclipses with a better precision. Further improvements were made by Souillart in 1880. Then followed the monumental work of Sampson, who developed a complete analytical theory of the motion of the Galilean satellites, a theory that was used to build the ephemerides at the end of the nineteenth century but because of the complexity of the task was not published until 1921. Ephemerides were based upon this theoretical model until the end of the twentieth century. Today, computers allow us to build purely numerical solutions that are easier to obtain and include all the inequalities.

2.3 The Publication of the Tables in the *Connaissance des temps*

The *Connaissance des temps* contained the first published ephemerides, starting in 1679. Because of the strategic use of the Galilean satellites for the determination of longitudes, efforts were made in France by Colbert and Louis XIV to promote astronomy at the newly built Paris Observatory. The first ephemerides of the Galilean satellites were, in fact, only the predictions of the eclipses of Io, starting in 1690 when one became more confident in the ephemerides. Table 4 below shows the evolution of the ephemerides. Publishing eclipses or phenomena is easy: it is a list of events with precise dates. Publishing positions is much more difficult because of the high velocity of the satellites. Publishing positions hourly would take pages and pages, so that positions—useful to identify the satellites—were first published under the form of isolated points day after day, allowing the user to interpolate the position of the satellites. Latter, the points were replaced by curves. Such a representation was sufficient since the accuracy of the observations was poor but, in order to calculate (O-C)s with better observations, ephemerides have been improved. Elements used with short calculations were published giving better positions. After 1980, thanks to the arrival of electronic calculators, a representation under the form of mixed functions and latter under the form of Chebychev polynomials was provided as ephemerides. Note that the ephemerides must have a precision in agreement with that of the observation (actually they are presently one order of magnitude better).

Nowadays, the ephemerides are available through the Internet, either directly in the form of positions or in the form of coefficients. The present *Connaissance des temps* contains positions at elongations for checking of the theoretical models used for the ephemerides.

Table 4 summarizes the progresses in the ephemerides.

Table 4: Evolution of the ephemerides of the Galilean satellites of Jupiter.

Dates	Positions	Phenomena	Configurations	Theoretical Model From
1679–1689	--	--	--	--
1690–1693	--	Eclipses of Io	--	Cassini
1694–1697	--	--	--	--
1698–1729	--	Eclipses of Io	--	Cassini
1730–1733	--	Eclipses of the 4 satellites	--	Maraldi
1734	--	Eclipses of Io	--	Maraldi
1735–1762	--	Eclipses of the 4 satellites	Points each day	Maraldi
1763–1765	Daily and hourly elements	Idem	Idem	Idem
1766–1807	Idem	Idem	Idem	Wargentin-Lalande
1808–1840	Idem	Idem	Idem	Delambre
1841–1880	Idem	Idem	Idem	Damoiseau
1881–1890	Elements	Idem	Idem	Souillart
1891–1914	Idem	All phenomena for the 4 satellites	Idem	Idem
1915–1960	Idem	Idem	Idem	Sampson-Schulhof
1961–1979	Idem	Idem	Curves	Idem
1980–1984	Chebychev polynomials	Idem in a supplement	Idem in supplement	Sampson-Arlot
1985–1995	Mixed functions	Idem	Idem	Idem
1996–2005	Idem	Under the form coefficients	Idem	Idem
2006–2007	Positions at elongation	Idem	Idem	Idem
2008–Today	Idem	Idem	Idem	Lainey

Table 5: Accuracy of the observations of Delambre's eclipses made at the end of the eighteenth century (1775–1802): Dispersion σ and Mean (C-O).

				Dispersion σ			Mean (C-O)		
Obs. Sites	Events	n	Ephemeris	sec	(″)	km	sec	(″)	km
All	Immersion & Emersion	845	Delambre	42	0.18	546	3	0.01	39
			E2	64	0.28	832	–19	–0.08	–247
	Immersion	360	Delambre	39	0.17	507	20	0.09	260
			E2	39	0.17	507	40	0.17	520
	Emersion	485	Delambre	39	0.17	507	–10	–0.04	–130
			E2	39	0.17	507	–63	–0.27	–819
Paris	Immersion & Emersion	160	Delambre	28	0.12	364	6	0.03	78
			E2	44	0.19	572	–13	–0.06	–169
Viviers	Immersion & Emersion	98	Delambre	57	0.25	741	7	0.03	91
			E2	84	0.36	1092	–16	–0.07	–208
Greenwich	Immersion & Emersion	78	Delambre	24	0.10	312	12	0.05	156
			E2	47	0.20	611	–5	–0.02	–65
Prague	Immersion & Emersion	67	Delambre	52	0.23	676	1	0.00	13
			E2	73	0.32	949	–27	–0.12	–351

2.4 The Observation of Eclipses: Eighteenth and Nineteenth Centuries

As seen in Table 1, the observations of positions were not good during the first epochs of observation of the Galilean satellites, so that mainly eclipses (and also some occultations of the satellites by the disc of the planet) were observed. Eclipses were extensively observed in order to be able to build accurate predictions of future ones. These events were used for the determination of the geographic longitudes. The method was to observe the same event from two different sites. The comparison of the local true solar times of the eclipse provided the difference in the longitudes of the two sites, but one had to carry the information from one site to the other before obtaining the result. But for a traveler who needed to know his longitude immediately the use of the eclipses was different: he had to have at hand the *Connaissance des temps* to know when the next eclipse would occur and at what time in Paris, then the observed local time of the eclipse directly provided the longitude of the observing site with reference to the longitude of Paris Observatory. In that case, the accuracy of the prediction was critical.

Many observing campaigns were organized to determine longitudes and improve the predicttion of eclipses: for example, Figure 1 shows the reduction of an observation made in 1799 at Cracovie (Krakow) in Poland, while in Table 5 we present the accuracy of the sets of eclipses gathered by Delisle and Delambre (after Arlot et al., 1984).

After the end of the eighteenth century, the modelling of the motion of the satellites was no more kinematic: celestial mechanics came into the picture, thanks mostly to Laplace, and the motions were described through dynamical equations. Then, the observations were not made in order to describe the motion but to provide the constants of integration in the equations of the motion or the initial conditions of this motion. In theory, only one observation of position and velocity of each satellite was sufficient, supposing that the accuracy of the measurement was infin-

Table 6: Accuracy of the observations of Pickering-Sampson's nineteenth century eclipses, where the Dispersion σ and Mean (C-O) refer to the E2 ephemeris.

		Dispersion σ			Mean (C-O)		
opposition	n	s	(")	km	s	(")	km
1893–1894	95	58	0.25	754	−2	−0.01	−26
1899	61	45	0.20	585	−2	−0.01	−26
1901	32	34	0.15	442	−5	−0.02	−65

ite and supposing that all the gravitational and non-gravitational effects were included in the equations of the motion. In practice, a large number of observations was still necessary in order to increase the accuracy of the observational measures and to be able to detect the forgotten forces affecting the motion in the residuals. This explains the efforts of Delambre to gather numerous accurate observations of eclipses in order to prepare ephemerides using the Laplace's equations. Table 5 shows how the accuracy of the observations increased when compared to the seventeenth century observations given in Table 2.

At the end of the nineteenth century, the observations of eclipses took advantage of progress in observational techniques. One of the main difficulties of the eclipse observations was to determine the zero light level after the beginning of an eclipse or before its end. As we have seen, this level occurred apparently earlier with less sensitive telescopes. This was a problem during the seventeenth century. Delambre understood that it was necessary to model the shadow cone and to time an eclipse at the instant where the center of the satellite was on the shadow cone. However, some biases in his model were corrected by his dynamical model of motion that explaining his very small residuals (the mean C-O in Table 5) compared to the larger residuals for more recent theories and observations that did not include Delambre's biases. During the 1870's Pickering at Harvard started photometric observations of the eclipses. For these observations, a model of theoretical light curves was used in order to have some absolute measurements of the light fluxes coming from the satellites (Sampson, 1909). This allowed the accuracy of the eclipse observations to increase (cf. Table 6), and Sampson (1910; 1921) mainly based his new theory of the motion of the Galilean satellites on these eclipses due to their better accuracy.

2.5 The Nineteenth Century: Back to the Direct Observation of Positions

The increase in size of the telescopes and the improved longitudes of the observatories (providing a better timing) allowed increasing accuracy of the observations of the Jovian eclipses. However, it appeared that the results were limited by the number of actually observed eclipses (eclipses can occur when Jupiter is not observable or when the sky is cloudy) and by the fact that no observation was made of the elongation of the satellites. It was time to come back to observations of direct astrometric positions, as Galileo did, in order to have data covering more regularly the orbits of the satellites. Bessel (1841-1842) suggested using micrometers or heliometers to make these measurements. They comprised measuring the angular distances and position angles between the satellites or between a satellite and Jupiter, as shown by Figure 2.

Bessel used a Fraunhofer heliometer starting in 1838. This instrument was first built in order to measure the diameter of the Sun but was well adapted to the Galilean satellites. These objects were sufficiently bright, of the same brightness and not too far from (and not too close to) each other. The heliometer consisted in a lens cut down the middle whose two halves could move along their common side (see Figure 3). The observer had to superimpose the two images made by the two half-lenses and then to measure the distance between the two half-lenses. A rotation of the system provided the position angle. Observations of reference stars were necessary to calibrate the distance between the half-lenses. It was also necessary to take refraction into account. The astrometric accuracy of such measurements was amazing.

Bessel made many observations of positions of the Galilean satellites in order to determine the mass of Jupiter. The dispersion of the measures may be estimated at 0.30 arcsec, but we are unable to calculate mean (O-C) residuals since no ephemeris fitting Bessel's observations exists. After Bessel, heliometers were improved and their aperture increased, such as the one at the Cape Observatory in South Africa, thanks to Sir David Gill (1896).

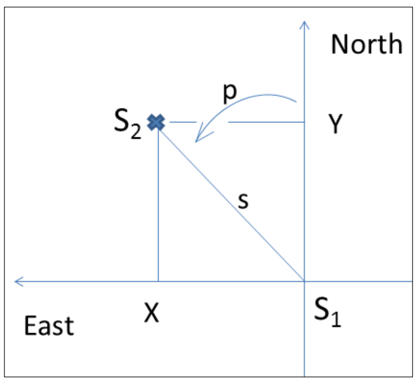

Figure 2: Separation (s) and position angle (p) and corresponding tangential X and Y co-ordinates between two satellites S_1 (reference) and S_2.

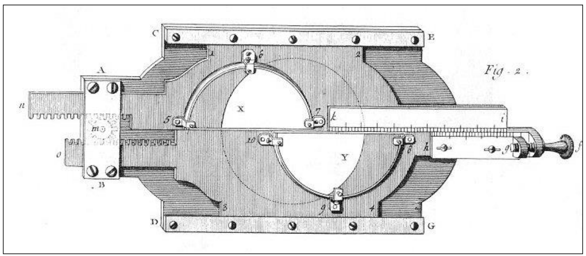

Figure 3: The principle of the heliometer (after Les instruments ..., 1774).

Table 7 provides mean (O-C)s and dispersion of the measurements made with heliometers. It seemed that an increase in aperture and focal length of the heliometers would increase the accuracy but in spite of the wishes of the astronomers no larger heliometers were built.

2.6 The Occultations

Eclipses in the shadow of Jupiter were the most observed phenomena. However, as we saw, astronomers wished to increase the possibility of observations. Observations of the occultations of the satellites by the disk of the planet brought a solution to that problem. It was more difficult to make these observations because the disc of Jupiter is very bright and the limb is not well defined. But with good seeing, the contrast between Jupiter and the satellites was not too large and the observations were accurate. Most such observations were made during the interval 1870–1910 (Fairhead et al., 1986) and Table 8 provides the mean (O-C)s and the dispersions.

2.7 The Photographic Technique

The photographic technique was introduced at the end of the nineteenth century. The innovation was that the observations were recorded and preserved so that their analysis could be made several times in order to exclude systematic or personal errors and to improve the precision of the measurements. As with the micrometric and heliometric observations, the measures were in millimeters and astronomers had to link these measurements to angles and reference frames. The main method for reducing the images and deriving astrometric positions was to use reference stars to link the positions of the satellites to an absolute reference frame. The problem with the Jovian system was that the satellites and Jupiter were very bright and the reference stars very difficult to see on the same plates. A compromise had to reached on the focal length of the telescope. A long focus gave a better astrometric measuring accuracy but a lower sensitivity. However, a short focus telescope presented a larger field for the same size of plate and then more reference stars could be found, allowing a better calibration of the scale (transformation of millimetres into angles). In the case where there was a lack of reference stars, it was possible to determinate the scale using another field that included good reference stars and to record the trail of a star by stopping the diurnal motion of the telescope. This trail provided the equator of the date, allowing a link of the measurements to the reference frame. Table 9 shows the different astrometric accuracies that were obtained by the photographic technique with instruments at various observatories. It is evident that long focus instruments provided a better accuracy than the short focus ones. However, with the recent algorithms of astrometric reduction and the new star catalogues, short focus observations may now reach the same accuracy as the long focus ones.

Table 7: Accuracy of Heliometer Observations: Dispersion σ and Mean (O-C).

			Dispersion σ			Mean (O-C)		
Observers	Opposition	n	sec	(″)	km	sec	(″)	km
Gill	1891	214	35	0.15	450	35	0.15	450
Cookson	1901	171	44	0.19	570	46	0.20	600
Cookson	1902	215	44	0.19	570	39	0.17	510
USNO	1903	149	67	0.29	870	65	0.28	840
USNO	1904	149	67	0.29	870	58	0.25	750
USNO	1905	85	67	0.29	870	53	0.23	690

Table 8: Accuracy of Occultation Observations by the Disk of Jupiter: Dispersion σ and Mean (C-O).

				Dispersion σ			Mean (C-O)		
Observer and Sites	Dates	Satellite	n	sec	(″)	km	sec	(″)	km
R.T.A. Innes (South Africa)	1909	1	84	25	0.15	450	24	0.14	432
		2	38	40	0.19	560	19	0.09	266
		3	36	72	0.26	792	32	0.12	352
		4	8	102	0.27	816	105	0.28	840
J. Tebbutt (Windsor, Australia)	1889	1	65	59	0.35	1062	31	0.19	558
		2	36	63	0.29	882	68	0.32	952
		3	20	178	0.65	1958	198	0.73	2178
		4	5	113	0.30	904	103	0.27	824
All observatories	1836–1972	1	2084	111	0.67	1998	27	0.16	486
		2	1129	165	0.77	2310	54	0.25	756
		3	1009	232	0.85	2552	121	0.44	1331
		4	189	291	0.78	2328	–12	–0.03	–96

Table 9: Accuracy of Photographic Plates Series: Dispersion σ and Mean (O-C).*

					Dispersion σ			Mean (O-C)		
Author	Observing Site	F	Opposition	n	sec	(″)	km	sec	(″)	km
Renz	Helsingfors	3.4	1892–1893	144	62	0.27	800	–12	–0.05	–156
Renz	Pulkovo	3.4	1895–1896	204	55	0.24	720	–6	–0.03	–80
Kostinsky	Pulkovo	3.4	1907–1908	161	78	0.34	1020	24	0.10	310
Chevalier	Zô-Sé	7.1	1917–1918	110	185	0.80	2400	0	0.0	0
De Sitter	Greenwich	6.9	1918–1919	252	85	0.37	1100	–6	–0.03	–80
De Sitter	Capetown	6.9	1924	246	60	0.27	800	–2	–0.01	–26
Petrescu	Bucharest	6.1	1934	54	50	0.22	660	–16	–0.07	–210
Petrescu	Paris	3.4	1936	25	110	0.46	1400	3	0.01	40
Biesbroek	Yerkes	2.3	1962	66	200	0.88	2640	15	0.07	195
Soulié	Bordeaux	3.4	1966–1967	36	83	0.36	1100	–15	–0.07	–195
Pascu	Charlottesville	9.9	1967–1968	95	25	0.11	330	–3	–0.01	–40
Pascu	Washington DC	9.9	1974	123	23	0.10	300	10	0.04	130
Ianna	Charlottesville	9.9	1977–1978	109	37	0.16	480	0	0.0	0

* F= focal length of the telescope in meters; n= number of exposures

One problem to be solved is the brightness of Jupiter, especially if bad seeing is spreading the light of the satellites over a larger area. Moreover, a kind of halo is always around Jupiter, increasing the brightness of the sky background. The challenge was to eliminate this halo, which makes the measurement of the positions of the satellites more difficult and inaccurate. This was solved using masks or filters. Figure 4 shows three different kinds of masks. The mask in Figure 4a was used by Chevalier (1921), a kind of shutter that made it possible to take shorter exposures for the planet than of the satellites. Figure 4b is the system used by Petrescu (1938; 1939): a mask that allowed Jupiter to be exposed in the middle of a photograph of the satellites. Figure 4c is a system of filters developed by Pascu (1977) that were different for Jupiter, for the brightest satellites and for the faintest satellites, and allowed measurable images to be taken with reference stars in the background, thanks to longer exposures.

The interest of these techniques also made it possible to measure the planet Jupiter and the relative positions of the Jovian satellites. However, the use of Jovicentric positions was not used very often since the satellites are orbiting around the center of mass of the Jovian system and not around the center of the planet. Note that no photographic observations or other types of observation of the Galilean satellites were performed during the interval 1920–1970, except for some rare observations. This was due to the fact that the ephemerides were supposed to be perfect after the triumph of celestial mechanics in the nineteenth century. The need for new observations appeared only before the 1970's during the preparation for the space missions. Ephemerides had to be improved for the launch of space probes to the Jovian system.

2.8 The Transit Circle and the Astrolabe

These instruments measured the time of transit of an object on the local meridian of the observing site using a transit circle or at a given elevation using an astrolabe. This timing associated with the measured elevation of the object provides the right ascension and declination of the observed objects as a function of sidereal time. Many such observations were made for building catalogues of reference stars. Since the Galilean satellites are bright, it was possible to observe them with a transit circle. At first the visual observations were not very accurate but the arrival in the 1980s of new CCD detectors used in the TDI scanning mode (continuous readings of the target) introduced a large improvement in the astrometric accuracy. Strips of sky containing the satellites and reference stars were thus observed providing astrometric positions. Table 10 gives the accuracy of transit circle observations made at Bordeaux Observatory during the period 1998–2005 using this technique.

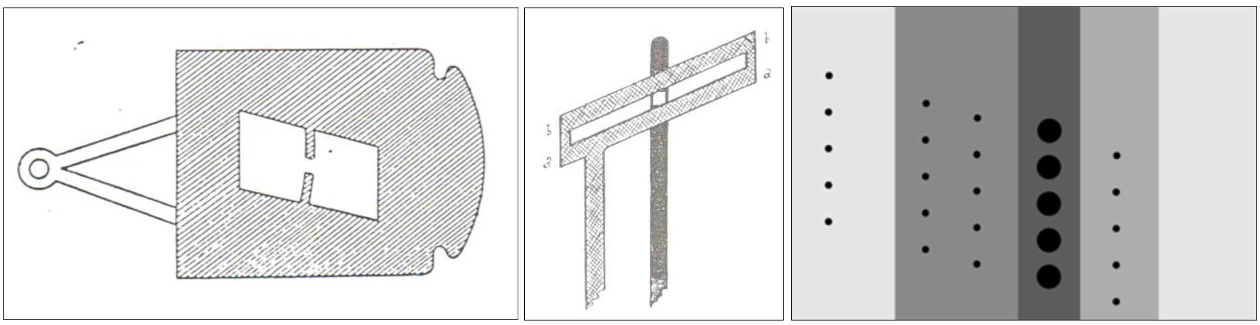

Figure 4: Systems used to decrease the brightness of Jupiter and the satellites on photographic plates. Figure 4a (left): the rotating system used by Chevalier in Zô-Sé; Figure 4b (middle): the system used by Petrescu in Bucharest and Paris; Figure 4c (right): the filtering system used by Pascu in Washington, DC.

Table 10: Accuracy of CCD Transit Circle Observations: Dispersion σ and Mean (O-C).

		Dispersion σ			Mean (O-C)		
Satellite	n	sec	(″)	km	sec	(″)	km
Io (RA)	153	8	0.047	141	–1	–0.007	–21
Io (Dec)	153	7	0.040	120	0	0.002	6
Europa (RA)	167	11	0.050	150	2	0.010	30
Europa (Dec)	167	9	0.044	132	1	0.003	9
Ganymede (RA)	176	16	0.058	174	–1	–0.004	–12
Ganymede (Dec)	176	16	0.055	165	–2	–0.007	–21
Callisto (RA)	188	21	0.055	165	0	0.001	3
Callisto (Dec)	188	16	0.043	129	1	0.002	6

2.9 The End of the Twentieth Century: Back to the Observation of Phenomena for a Better Accuracy

At the end of the twentieth century, the progress made with theoretical models, the observations from space probes and the search for tidal effects on the motion of the Galilean satellites required new accurate ground-based observations in order to complement space observations that were made on very short time intervals and could not detect the astrometric signatures of long-term effects. The first CCDs were difficult to use for the Galilean satellites because of their small field and because of the brightness of the satellites inducing short exposures and a lack of reference stars. CCDs were then useful in order to increase the astrometric accuracy of transit circles but were not able to replace completely the photographic observations. The observers went back to the phenomena: however, the atmosphere of Jupiter was still not modelled and the attention of the observers went to other phenomena of the Galilean satellites: the mutual occultations and eclipses. These events are rarer than the classical occultations and eclipses by Jupiter that occur for each revolution of the satellites: the mutual events occurred only when the Earth (for the occultations) or the Sun (for the eclipses) were in the orbital plane of the satellites (Figure 5).

This configuration corresponds to the equinox on Jupiter (the Sun being in the Jovian equatorial plane which is the orbital plane of the satellites) and occurs every six years. During one year, numerous mutual phenomena are observable. Since the satellites have no atmosphere, the mutual events provide very sharp light curves not affected by any atmosphere and it is easy to go back from the light curve to the relative positions of the two involved satellites with an accuracy not depending on the distance to the observer, i.e. in kilometers through the size of the satellites. The observation consists in the timing of the light curve which will be fitted on a model, allowing to determine the relative positions of the two involved satellites. Table 11 indicates the astrometric accuracy of such observations. We see that the dispersion increases with time: the more recent observations have a larger dispersion since amateur astronomers were involved in the observations while in 1973, only professional photometrists were observing.

These observations began when their predictions were possible, i.e. after the arrival of computers. These events are very sensitive to the relative inclinations of the orbits of the satellites and need complex computations. The first observing campaign took place in 1973, and there were further campaigns that regularly provided a source of very accurate astrometric data.

For the last observing campaigns CCDs were used, providing a series of images. Each image was analyzed and a photometric signal was extracted in order to get the light-curve of the phenomenon. Some observers thought that these ser-

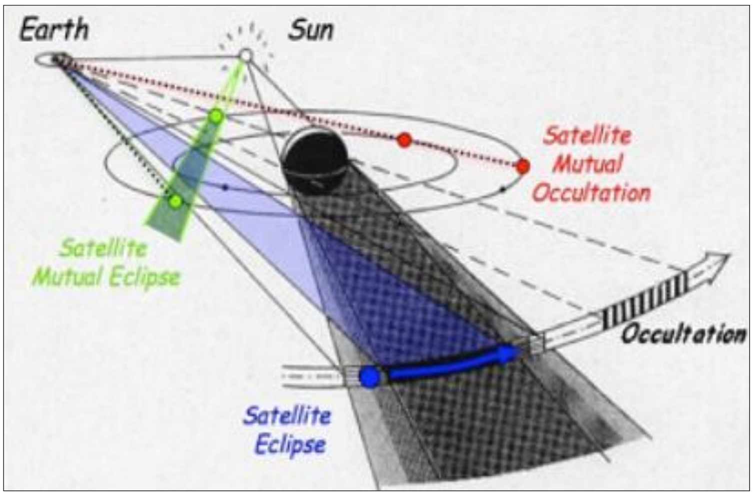

Figure 5: Geometry of the Eclipses and of the Mutual Phenomena of the Jovian Satellites.

Table 11: Accuracy of Observations of Mutual Events: Dispersion σ and Mean (O-C).

			Dispersion σ			(C-O)		
Occurrence	Satellite	n	sec	(″)	km	sec	(″)	km
1973	1	15	3.3	0.020	60	1.0	0.006	18
	2	66	3.0	0.014	42	0.4	0.002	6
1985	1	43	3.7	0.022	66	0.7	0.004	12
	2	92	8.6	0.040	120	1.5	0.007	21
1991	1	148	3.5	0.021	63	2.2	0.013	39
	2	36	7.3	0.034	102	3.9	0.018	54
1997	1	12	15.8	0.095	285	6.3	0.038	114
	3	19	32.7	0.120	360	6.5	0.024	72
2003	1	86	14.7	0.088	264	1.0	0.006	18
	2	114	19.5	0.091	273	2.6	0.012	36

ies of images might be analyzed as astrometric images during the close approach between two satellites independently of the occultation or the eclipse. Moreover, such series of images could be made even when no event was predicted, providing, as for an event, the timing of the minimum separation distance. Very few observers made such observations but Morgado et al. (2016; 2019) published results using this technique. It is too early to make statistics on the accuracy of such a method but the first data are encouraging. In fact, the large number of measured images increases the astrometric accuracy of the measurements. In their second paper, Morgado et al. (2019) announce a combined (C-O) (offset) for all their data of 3.8 mas, i.e. 11 km or 1 second of time and a standard deviation of 2.9 mas, i.e. 9 km or less than one second of time (as shown in Tables 12a and 12b). These results seem to be very good, but they need to be confirmed by more observations. The measurement of the minimum of distance during the close approach should be improved, and will provide better astrometric accuracy.

2.10 New CCD Observations

Let us recall the main problem of the observation of the Galilean satellites: they are too bright. This explains that we have more observations of the Saturnian system than of Jupiter even if the Galilean satellites were observed earlier. The arrival of the CCDs was not at first a progress for the Galileans. Using photographic plates, several devices were necessary in order to decrease their brightness allowing stars to be observed in the same field. The small CCDs were not adapted for this method. However, the progress of the CCDs, their increase in size, in sensitivity and in rapidity of reading the pixels allowed astronomers to stack many images made with short time exposures. The Galilean satellites were overexposed and stars were visible on the images. The sum of all images allowed us to have well-measurable objects. Table 13 (after Lainey et al., 2017) shows the (O-C)s and the dispersion of the observations obtained with large CCDs.

2.11 Observations From Space

2.11.1 Voyager Space Probe

The space probes used accurate ephemerides for their navigation to Jupiter but, once on site, they were able to provide astrometric observations of the satellites. The Voyager space probes came very close to the satellites so that one arcsec as seen by Voyager corresponded to 5 km in space position of the satellites. The accuracy of 10 km corresponds to an accuracy of 3 mas for ground based observations (and to an event accurate to one second of time). The dispersion of space probes observations is 820 mas (milliarcseconds) as seen from the probe, i.e. 3 mas geocentric.

Note that these observations were made during a short interval of time. Even though they are accurate, they do not contain information on long-term residuals and must be complemented

Table 12a: Accuracy of observations of close approaches between satellites: the timings.

	n	Dispersion σ			(C-O)		
		sec	(″)	km	sec	(″)	km
2016	14	5	0.021	63	1.4	0.006	18
2019	104	0.7	0.003	9	0.9	0.004	11

Table 12b: Accuracy of observations of close approaches between satellites: the distances.

	n	Dispersion σ			(O-C)		
		sec	(″)	km	sec	(″)	km
2016	14	7.5	0.032	96	−4.7	−0.020	−60

Table 13: Accuracy of CCD Observations with Stacking Imaging: Dispersion σ and Mean (O-C).

		Dispersion σ			Mean (O-C)		
Sat.	n	sec	(″)	km	sec	(″)	km
Io (RA)	25	3	0.019	57	−1	−0.006	−18
Io (Dec)	25	3	0.017	51	1	0.003	9
Europa (RA)	25	4	0.017	51	0	−0.001	−3
Europa (Dec)	25	3	0.015	45	−2	−0.008	−24
Ganymede (RA)	25	7	0.027	81	5	0.022	66
Ganymede (Dec)	25	6	0.022	66	0	−0.001	−3
Callisto (RA)	25	13	0.035	105	−5	−0.014	−42
Callisto (Dec)	25	9	0.023	69	2	0.006	18

Table 14: Accuracy of HST Astrometric Positions: Dispersion σ and Mean (O-C).

			Dispersion σ			(O-C)		
Satellites		n	sec	(")	km	sec	(")	km
Io	RA	32	7.2	0.043	130	–6.8	–0.041	–123
	Dec	32	7.2	0.043	130	8.9	0.053	160
Callisto	RA	10	7.9	0.021	63	0.9	0.002	6
	Dec	10	6.7	0.018	54	5.6	0.015	45

Table 15: Accuracy of newly digitized and re-reduced photographic plates (1986–1990): Dispersion σ and Mean (O-C).

Satellite	n		Dispersion σ			(O-C)		
			sec	(")	km	sec	(")	km
Io	333	Right ascension	4.4	0.027	80	−0.3	−0.002	−6
	333	Declination	6.7	0.040	120	1.7	0.010	30
Europa	333	Right ascension	5.0	0.023	70	−0.1	−0.0005	−1.5
	333	Declination	8.6	0.039	120	−1.4	−0.007	−20
Ganymede	355	Right ascension	5.4	0.020	60	0.5	0.002	6
	355	Declination	10.9	0.039	120	0.5	0.002	6
Callisto	369	Right ascension	7.5	0.019	60	−0.1	−0.0002	−0.6
	369	Declination	8.2	0.022	66	−1.5	−0.004	−12

by long series of ground-based observations. Another result from the space probes is the determination of the masses of the satellites during the close approaches between the probes and the satellites. Their masses were easily determined by analyzing the orbital deviation of the space probes during such close approaches (Jacobson, 2013). Finally, the space probes provide accurate values for the sizes of the satellites, which are the basis of the reduction of the observations of mutual phenomena.

2.11.2 *Hubble Space Telescope*

We must notice also that observations were made from the HST: Table 14 shows the accuracy of HST astrometric positions.

2.12 The Twenty-first Century and the Gaia Revolution: Back to the Old Observations

The effects due to long-term residuals, especially the secular terms, must be determined by long-term series of observations. A new idea was to reduce past observations using today's accuracy, but how to do this? At the beginning of the twenty-first century it became possible to scan and digitize old photographic plates with modern scanners accurate to a few nanometers (Robert et al., 2010) and to reduce them using the new accurate catalogues of reference stars. Many errors made in the past can now be eliminated and accurate positions of the satellites can be derived from observations made many years ago. Table 15 provides the accuracy of positions obtained with the new reduction, and can be compared with Table 9 that shows similar data obtained using old manual reduction techniques.

Table 16 shows the accuracy of several catalogues of reference stars with the dates they were obtained. The astrometric accuracy of these reference stars has a direct consequence on the accuracy of the astrometric reduction of most of the observations of the Galilean satellites. Each time a new more accurate catalogue is published, a new reduction of old observations (photographic plates or CCD) can bring better data for analysis. However, we must notice that the astrometric observations of the Galilean satellites generally give relative positions either between the satellites themselves or between the satellites and Jupiter. The use of right ascension and declination positions started during the twentieth century as soon as the star catalogues allowed

Table 16: Accuracy of Reference Star Catalogues.

Year	Name	Number of stars per square degree	Number of stars	Magnitude limit	Accuracy in mas (0.001 arcsec)
1907	NFK	<1	925		187
1937	FK3	<1	1 535	7	120
1937	GC	1	33 342		214
1975	AGK3	10	181 581	11	215
1963	FK4	<1	1 535	7	98
1966	SAOC	6	258 997		281
1991	PPM	10	378 910		138
1997	Hipparcos	3	100 000	12.4	0.8
1998	USNO A2		526 280 881	20	250
1998	USNO SA2		54 787 624		250
2000	Tycho 2	62	2 500 000	16	60
2001	GSC	500	19 000 000		360
2003	2MASS		470 000 000	16	60–100
2004	UCAC2	1200	48 000 000	7.5–16	20–70
2015	GAIA	25 000	1 billion	20	0.01

such astrometric reductions. The right ascension and declination observations of the satellites allows us to obtain the right ascension and declination positions of the center of mass of the Jovian system and to determine its motion around the Sun.

In 2018, the Gaia astrometric telescope provided its DR2 Reference Catalogue with positions of stars to 0.01 mas. Even better, the DR2 Catalogue will give proper motions of reference stars to an accuracy of one mas per century. As a consequence, the astrometric accuracy of old re-reduced photographic plates will have an accuracy at least at the level of those of Table 16 (around 30 mas) instead of the usual accuracy of several hundreds of mas of the reductions made at the time of the observations. The Gaia DR2 Catalogue opens a new era for the astrometry of the Galilean satellites for which we have photographic plates starting at the end of the nineteenth century.

3 DYNAMICAL MODELS: NEW RESULTS AFTER 400 YEARS OF STUDIES

The need to improve astrometric accuracy was mainly guided by the research on small effects in the residuals. One of these effects that the astronomers were looking for was the tidal effects in the Galilean system. As Jupiter induces tides on the satellites, then, the satellites are moving towards Jupiter, their motions being accelerated because of the dissipation of energy inside the satellites. But as the satellites also induce tides on Jupiter, they lose energy and are flying away from Jupiter (as the Moon does from the Earth). Then astronomers try to find an acceleration in the motion of the satellites, this acceleration being the signature of a dissipation of energy.

These searches started at the beginning of the twentieth century (De Sitter, 1928) even though the observations then had too poor an astrometric accuracy and did not extend over a sufficiently long period of time. Table 17 gives the values of acceleration obtained for the first three Galilean satellites. The first results were wrong because of the deceleration of the Earth's rotation, so the solar time scale used at that time was not uniform. The apparent acceleration of the satellites was in fact the deceleration of the Earth's rotation! However, after taking this effect into account, a real acceleration was found, but due this time to forgotten long-periodic terms in the motion of the satellites, mistaken for a possible secular acceleration.

It was necessary to wait until the beginning of the 2000s and the use of numerical models to reach an internal precision of the models at the level of the physical effects we were looking for. In particular, in spite of the efforts made at the end of the twentieth century, the accuracy of the equations (internal precision) was still of the order of several hundred kilometers over one century, i.e. of the same order of magnitude (or even a little more) than the effects of the tides themselves. In the same way, the satellites were still modelled as points, which added a little more to the overall error of the model. The new models now take into account not only the usual N-body perturbations and Jupiter's oblateness but also its extended gravitational field (harmonics c_{20} and c_{22}), the precession of Jupiter, and the effects of tides in Jupiter and in Io (cf. the Section on inequalities).

After improving the dynamical model by taking into account all the long period terms, it was possible to detect the true acceleration of the satellites. The last line in Table 17 provides updated values for this acceleration, which are in agreement with the measured flux of heat at the surface of Io (Lainey et al., 2009). The acceleration is then explained as tidal effects of Jupiter on Io, dissipating energy inside the satellite.

Table 17: Acceleration found for Io, Europa and Ganymede.

10^{-11}/year unit	n'_1/n_1	n'_2/n_2	n'_3/n_3
De Sitter (1928)	+33 (±5)	+27 (±7)	–15 (±6)
Greenberg (1986)	+32 (±8)	–16 (±4.5)	–16 (±4.5)
Goldstein (1996)	+70 (±75)	+56 (±57)	+28 (±20)
Vasundhara et al. (1996)	+22.7 (±7.9)	–6.1 (±9.3)	+10.6 (±10.6)
Aksnes et al. (2001)	+54.7 (±16.9)	+27.4 (±8.4)	–27.4 (±8.4)
Lainey et al. (2009)	+4.0 (±11.0)	–5.0 (±7.0)	–7.0 (±7.0)

4 CONCLUSION: PROGRESS ON THE ASTROMETRIC ACCURACY OF THE OBSERVATIONS

Since 1610 the Galilean satellites have been regularly observed: astrometric observations were made during these four centuries and the dynamical models took advantage of this long series of observations. Coherence between the accuracy of the dynamical models and the observations was necessary. Improvements in both the models and the observations have allowed us to determine today some parameters that were not accessible several decades ago. The goal of astrometry has always been to reach another digit in the accuracy of the measurement. Each time a new digit is obtained, our knowledge of the Jovian system increases from several thousands of kilometres of accuracy 400 years ago to a few kilometres today. We may see future progress coming soon: the analysis of old observations will allow us to reduce past observations with today's accuracy using new star catalogues such as GAIA (e.g. see Arlot et al., 2018).

Finally, it is our hope that a permanent space probe will orbit in the Jovian system. Then, the astrometric accuracy will reach a few meters and will offer us a better understanding of those wonderful worlds that are the Galilean satellites.

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Dr Jean-Eudes Arlot was born in France in 1948 and became an astronomer in astrometry and celestial mechanics. He first worked at the U.S. Naval Observatory in 1974 while observing the Galilean satellites with Dan Pascu in order to prepare the navigation of the Voyager mission. He joined the French CNRS and developed a new astrometry of the natural planetary satellites and analyzed and used old observations in his thesis, which he defended in 1982. He published a dynamical model and ephemerides of the Galilean satellites, predicted mutual events of these bodies, and organized worldwide campaigns of observations. He became Director of the Institut de Mécanique Celeste et de Calcul des Éphémérides from 1992 to 2001. He was Chairman of the IAU Working Group on Natural Planetary Satellites and Vice-President of the Ephemerides Commission. He provided lessons in astrometry for students at Paris Observatory and supervised eight Ph.D. theses on astrometry and celestial mechanics. He made many astrometric and photometric observations of Solar System objects. IAU minor planet 17893 discovered in 1999, was named after him. He promoted the building and the use of a sub-micrometric digitizing device for photographic plates and proposed a new use of these data. He is working on the history of the ephemerides and arranged the digitizing of the complete collection of *Connaissance des temps*, the ephemerides published since 1679. He published and coordinated several books such as *The 2004 Transit of Venus* and *Astronomie au Service de Tous*. He has prepared encyclopedia articles, and an "Introduction to Ephemerides". He is now Astronomer Emeritus at Paris Observatory.

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A HISTORY OF WESTERN ASTRONOMICAL ALMANACS

P. Kenneth Seidelmann
Astronomy Department, University of Virginia,
9203A Wescott Place, Rockville, MD 20850-3468, USA.
Email: pks6n@virginia.edu

Abstract: Astronomical data were the basis for calendars, time, phenomena predictions, and theories about the universe from the earliest days. Knowledge developed independently in different countries and then was exchanged when international trading developed. There was an apparent lack of development of knowledge during the middle ages. Then at the reformation period a new increase in theories, observations, and knowledge developed. The advent of the printing press brought the availability of almanacs in large numbers for everyday use. The requirements of calendars, navigation, and astronomical information led to national almanacs and improved accuracies. The need for standards for reference systems, including ephemerides, time scales, astronomical constants, and star catalogs led to international cooperation. New technologies, computers, and the space age led to improved accuracies and new reference systems. Calculators and computers led to new methods of access to almanac data, including data online.

Keywords: almanacs, ephemerides, calendars, cultures BC, astronomical phenomena, celestial navigation, national almanac offices, astronomical history.

1 INTRODUCTION

From earliest times astronomical information was used for determining calendars, time, climate, farming, seasons, and phenomena predictions, including eclipses. Some evidence includes astronomical alignments, stone circles, clay tablets, and oral histories. Many cultures developed calendars based on solar and lunar cycles, with varying accuracies and methods of adjusting for the differences in the even cycles. Religious holidays were based on equinoxes as the epoch of calendars. Star catalogs and planetary motions were recorded. Determinations of geographic locations and distances were attempted. Times of day were based on sunrises and sunsets, with varying lengths of hours. The difference between apparent and mean solar times was recognized and uniform lengths of hours were introduced based on methods of timekeeping. Developments in different cultures took place independently and knowledge was shared due to international trade and communication (see Nha et al., 2017; Stern, 2012).

The first observer, probably in the third millennium BC, noted the motions of the Sun, Moon, planets, and stars. This led to the first ability to predict positions of planets and eclipses. The earliest records of astronomical data are found in India, Babylonia, Greece, Egypt, and the Far East (China and Korea). The astronomies of India and Greece are very different. It appears developments took place independently in the different countries, and then there was communication due to trade between the countries.

This paper takes a narrower geographical perspective and only examines 'Western almanacs' and their origins. For our purposes, the following definitions are used. *Treatises* are 'how to texts', such as Ptolemy's *Almagest* of AD 150 and Copernicus's *De Revolutionibus* of AD 1543. *Tables* are orbital elements and tables of terms, usually Fourier terms, which are calculated for a specific date. These were used to determine the positions of planets for astronomical and astrological purposes. In most cases multiple dates were not desired. Examples are Ptolemy's *Handy Tables* of AD 150, the Ptolemaic-based *Alfonsine Tables* of AD 1320, which were not significantly improved over the *Handy Tables*, and Copernican based *Prutenic Tables* of AD 1551 (Gingerich, 2017). The word *ephemeris* is derived from ancient Greek *epi*, which means about and *hemera*, which means day. Ephemeron means short lived and temporarily valid, i.e. something that is valid for a day. In Greek an ephemeris can be a newspaper. Thus, in astronomy an *ephemeris* (plural *ephemerides*) is a tabulation of the positions of a planet or satellite for a series of equally spaced dates, such as daily for a year. These were computed from tables until the availability of punched card equipment and computers. *Almanacs* provide ephemerides and astronomical data usually for a year, with daily information as useful for the purpose of the almanac. Thus, astronomical, nautical, and air almanacs are designed for astronomical observations and astronomy, navigation of ships, and airplanes, respectively. *Calendars* are designed to follow the solar and/or the lunar periods, with some relations to the vernal equinox for religious purposes (McCarthy and Seidelmann, 2018).

2 THE ORIGIN OF THE WESTERN ALMANAC

2.1 Babylonia

Writing on clay tablets was invented near the end of the fourth millennium BC in the city of Uruk in southern Mesopotamia. During the third millennium BC stars and constellations were included on the tablets. In the second millennium

BC texts of astronomical phenomena appeared. A large number of clay-baked cuneiform tablets recorded the passage of daily life on the plains between the Tigris and Euphrates Rivers, and some gave the positions of the Sun, Moon, planets, and stars. Sumerian astronomy and record keeping was adopted by their neighbors to the north, the Babylonians, after conquest and absorption. Initially, the Babylonians' motivation seemed primarily calendrical, but became a religious conduit between Earth and Heavens. From these beginnings around 2500 BC, there is a continuous path to present-day astronomy (Steele, 2000).

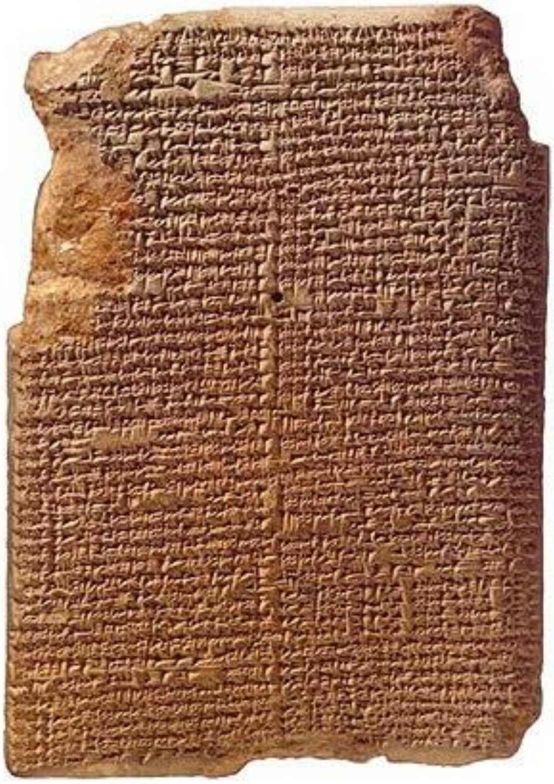


Figure 1: One of two clay tablets containing the astronomical text, *Mul-Apin* (https://es.wikipedia.org/wiki/MUL.APIN).

The Babylonian tablets dating from the first half of the second millennium BC gave celestial omens. For Mesopotamia, the events in the sky were considered messages from the gods to warn people of potential events. By prayers, rites, and sacrifices, the predictions could be prevented. Astrology, from Hellenistic times, implied belief in powers emanating from the stars and planets, which caused things to happen on Earth, and they could not be escaped (Hunger, 2009).

After the Hittite Conquest in 1530 BC astronomical traditions were improved and catalogs of helical risings of the Moon and stars appeared. The organization of the sky was sought, such as the *Three-stars-each* texts, probably dating to between 1500 and 1000 BC. For each month of the Babylonian calendar three constellations, which would be visible, were listed, one to the North, one near the equator, and one to the South. Tablets from 1500 and 1250 BC gave methods of calculating the position of Venus; a simple pattern repeated at intervals of about eight years. These tablets were part of the set of omens known as *Enuma Anu Enlil*, astronomical compilations and omens that may have been from as much as a thousand years earlier. By the seventh century BC timings of lunar eclipses appear. By the fifth century BC a celestial coordinate system, in the form of the zodiac with 12 constellations of 30 degrees each, was developed. By the time of Cambyses in 521 BC the phases and positions of the Moon were recorded within a fraction of an *usb,* a time unit of about 4 minutes (Steele, 2000).

In the second half of the first millennium BC new techniques for insight into the future were developed and one was called *horoscopes*. It is really not correct to call these Babylonian texts *horoscopes*, because they lack consideration of the point of ecliptic rising at the time of birth, which was called *horoskopes* in Greek. So the detail, from which the name *horoscope* is derived, is not present in the Babylonian *horoscopes.* Babylonian horoscopes were computed for private persons, as well as for the king, and rarely contained predictions. There were almanacs containing predicted data as needed for composing horoscopes, such as in which zodiacal sign the different planets were in a given month. The almanacs were likely prepared based on the periods when astronomical phenomena reoccur (Hunger, 2009).

An astronomical text, *Mul-Apin* (Figure 1), which means Plough star after its first word, probably goes back to the thirteenth century BC. It contained six lists of stars and constellations, periods of visibility of planets, two schemes of intercalation of calendars, and a table of the length of the shadow of a stick at different times of the day and seasons. In the seventh century BC Babylonian scholars tried to forecast when and where certain phenomena would happen. Eclipses of Sun and Moon were described in detail. The Babylonian calendar used lunar months beginning with the first visibility of the lunar crescent after New Moon. The months were 29 or 30 days long, 12 months being approximately 354 days. A month was added when the seasons no longer fitted the calendar. In early times the king decided intercalation. Regular intercalation, according to the *Mul-Apin,* was applied from the seventh century BC. By around 500 BC a cycle of 19 years with 7 fixed intercalations was introduced. The *Mul-Apin* lists the amount of water to flow in or out of a water clock to measure daylight at different times of the year. At night, time was measured by the culmination of stars. Appropriate stars were listed in the *Mul-Apin* (Hunger, 2009).

The Babylonians used a 'Metonic' year of 12 ordinary and 7 intercalary (13 month) lunar years, i.e. a cycle of 235 lunations. The Metonic year is 14 minutes short of the sidereal year and 6 minutes longer than the tropical year. The years are usually counted in the "Seleucid Era" (S.E.) beginning with the new crescent of 3 April –310 (Neugebauer, 1967). The synodic month was their fundamental time measurement. Ptolemy retained the Metonic year, but took it as his tropical year. This difference is small, but accumulates to a day in 240 years and a whole week by Copernicus' time, so the *Almagest Tables* of solar motion had fallen behind by 7 degrees (Moesgaard, 1983).

After the fall of the Assyrian empire (612 BC) and the rise of Persia (539 BC), systematic observations of planetary events began, astronomy that was missing from earlier years in Babylonia. The oppositions of Jupiter repeating in 80 year intervals, Saturn at 59 years, Mars at 47 years, and Venus at 8 years, were known. Predictions joined observations on tablets (Steele, 2000). Astronomical diaries from Babylonia contain records of continuous and systematic observations, so they are sources of natural and astronomical phenomena in the BC era (Hayakawa et al., 2016). A diary tablet usually covers half a year, but some cover single months. There are only a half dozen from before 400 BC, but there is coverage for almost every year for the second century BC (Sachs and Hunger, 1988; 1989).

Once Babylonian influence was not so dominant, the Greek astronomers decided on cinematic models, and the Babylonian methodology became inapplicable. The historical significance of Babylonian astronomy is that here, for the first time in human history, purely mathematical methods were shown to provide a most successful description, and hence prediction, of natural phenomena, free of philosophical principles —which have been the obstacle to scientific development (Neugebauer, 1967; 1983).

2.2 Greece

The first Greek philosophy took place in Miletus, a trading center on the Asiatic coast. Indian and Babylonian science was antecedents of Greek science. Greek Culture was due to Mesopotamians and Egyptians, which together formed the basis of western science (Kak, 2007).

Greek astronomy was shaped by Babylonian observations and mathematical astronomy as transmitted in the second and first millennia BC (Jones, 2015a). The Greeks inherited records of thousands of heavenly occurrences from the Babylonians. The Greeks obtained entire complex computational schemes from Babylonia (Neugebauer, 1988). The Babylonians kept records of eclipses and calculated their recurrences by series known as Saros, intervals of 18 years and 11 days. Thales of Miletus (624–546 BC), the 'Father of Philosophy', learned geometry in Egypt about 600 BC and brought it back to Greece. He forecast the total eclipse of the Sun of 28 May 585 BC. However, the Chinese kept eclipse records from 2137 BC (Ionides and Ionides, 1941). The Greeks sought accurate planetary tables after accepting astrology from the Babylonians. Greek mathematical astronomy was fundamentally geometrical in conception, but became more quantitative and numerical due to Babylonian astronomy (Jones, 2015b). The Greeks also adopted the sexagesimal number system from the Babylonians. About 300 BC Euclid's *Elements* synthesized the achievements of his predecessors.

Around 200 BC Apollonius of Perga (fl. late third to early second centuries BC) proposed the use of eccentric circles, where the planets move at a uniform angular velocity, but with the center of the circle not at the Earth. This let the planet to vary in distance from the Earth. He also proposed for the planet to move uniformly on a little circle, or epicycle, whose center moved uniformly on a large circle centered on the Earth. According to Archimedes and Plutarch, in 270 BC Aristarchus of Samos (310–230 BC) proposed that the Earth spun on its axis and moved in a circular orbit around the Sun with the Moon orbiting the Earth. While astronomy was becoming more sober, serious, and technical at that time, this proposal was not generally accepted. Aristotle (384–322 BC), his greatest pupil, disagreed due to the lack of feeling of motion on Earth.

The spherical shape of the Earth was known to Pythagoreans, long before Plato (ca. 428–348 BC). The Greek sense of symmetry required a spherical Earth at the center of spherical heavens. The stars rotated daily about the Earth, except for the 'wandering stars', in Greek the planets. Multiple spinning spheres explained the motion of these planets. Aristotle studied scientific geography and gave reasons for the Earth being a sphere (Ionides and Ionides, 1941).

In the second century BC Hipparchus of Rhodes (ca 120–190 BC; Figure 2) was the first careful observer and competent mathematical Greek astronomer. He compiled a catalog of over 800 stars and discovered precession of the equinox. He prepared a table of eclipses for the next 600 years. He used Apollonius' tools to construct geometrical models of the motions of the Sun and Moon. A number of Greek papyri from Oxyrhyncus in Egypt, dating from the first century BC to the sixth century AD, are closely related to Babylonian arithmetic schemes and depend on Greek kinematic models (Jones, 1999).

Figure 2: Hipparchus of Rhodes (https://en.wikipedia.org/wiki/Hipparchus#/media/File:Hipparchos_1.jpeg).

In AD 150 Ptolemy (ca AD 100–170; Figure 3) created accurate geometrical models for compiling positions of the planets for centuries in the *Almagest,* largely based on the work of Hipparchus. This was unrivaled for 1400 years until the fifteenth century (Hoskin, 1983). Due to the availability of Euclid's and Ptolemy's works, writings of their predecessors largely vanished.

By the second century AD the Greeks could predict eclipses, chart the planets, catalog stars, discover precession, know the Earth was spherical, and guess that the Earth moved around the Sun.

Figure 3: Ptolemy as depicted by a sixteenth-century engraving (https://en.wikipedia.org/wiki/Ptolemy#/media/File:Ptolemy_16century.jpg).

3 PRE-SEVENTEENTH CENTURY ALMANACS

3.1 The Early Period

After the end of the Roman Empire the science of astronomy declined in Western Europe. Barbarians and empire building took attention away from sciences, which were pursued in monasteries, by noblemen, and the Islamic Golden Age. Nicolaus Copernicus (1473–1543; Figure 4) formulated a heliocentric model of the Universe with the Sun at the center. He published this in *De Revolutionibus Orbium Coelestium* (*On the Revolutions of the Celestial Spheres*) just before his death in 1543. This started the Copernican Revolution and new determinations of positions of the Sun, Moon, and planets. Erasmus Reinhold (1511–1553), Professor of Higher Mathematics, Dean, and Rector at the University of Wittenberg, published *Prutenicae Tabulae* (*Prussian Tables*) in 1551. The tables spread the calculation methods of Copernicus, however according to Gingerich (1973) they were framed to be independent of the movement of the Earth. These tables and Copernicus' writings were the foundation of Calendar Reform by Pope Gregory XIII in 1582.

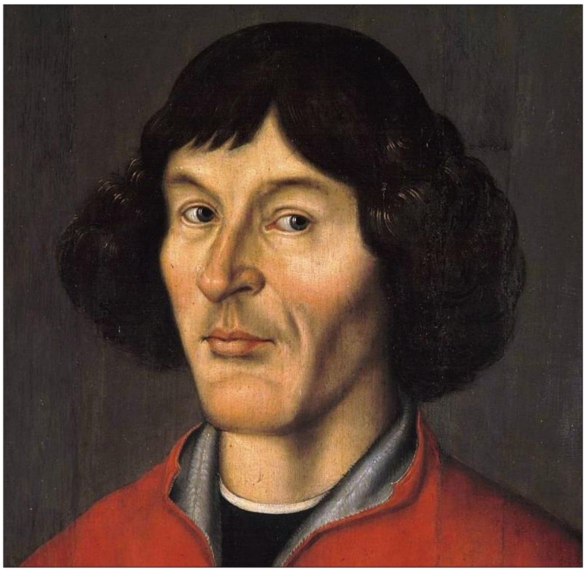


Figure 4: A portrait dated about 1580 of Nicolaus Copernicus at the Town Hall in Toruń (https://en.wikipedia.org/wiki/Nicolaus_Copernicus#/media/File:Nikolaus_Kopernikus.jpg).

Nostradamus (1503–1566), an astrologer for wealthy patrons, wrote an almanac for 1550 and years after. In 1555 he published *Les Propheties*, a collection of 942 poetic quatrains supposedly predicting future events. Nostradamus has attracted supporters, who with the popular press have claimed he has accurately predicted major world events. Most academic sources consider his predictions vague and useless for accurate predictions. The translations of the original sixteenth century French are of poor quality and maybe deliberately mistranslated.

The Romans, Hebrews, and Greeks used a cumbersome numerical system using letters of the alphabet. This made it difficult to deal with large numbers and to do mathematics. The Babylonians counted in base 60, so they could multiply and divide large numbers. This gave them an advantage in dealing with long time periods and calendars.

Prior to the seventeenth century there was neither the need for nor the ability to provide ephemerides or almanacs. The needs for astronomical positions were for observing and astrology, so positions of astronomical bodies were only needed for individual dates. Computations for unneeded dates were wasted. There were no movable-type printers for printing tabular material. Only three manuscripts are currently known of calculated daily planetary positions, that date between 24 BC to AD 1450.

3.2 Islamic Astronomy

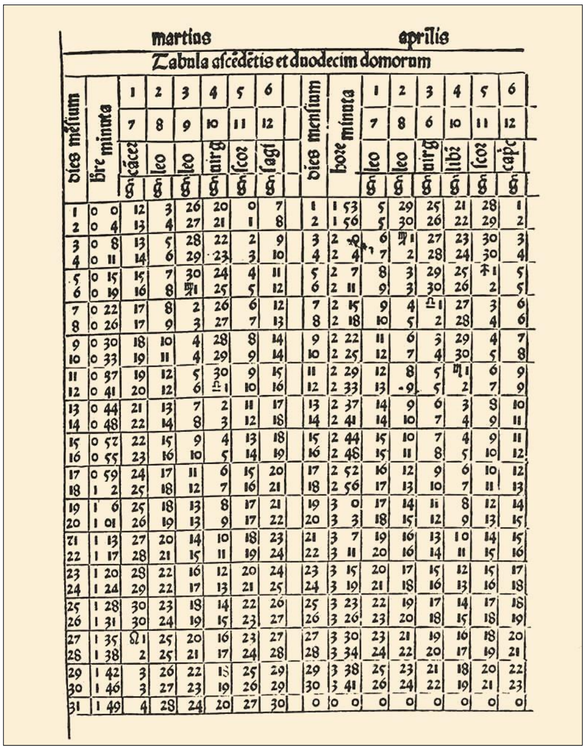
In AD 762 the Abbasid Caliphate became prominent in the growing Islamic Empire and moved to Baghdad. The House of Wisdom was an academy established in Baghdad for astronomical research. The trade routes allowed the mixing of knowledge from India, China, Persians, Greeks, Egyptians, and Jews. Islamic scholars preserved knowledge while translating it into Arabic and increasing it. Arabs knew astronomy and used it to navigate in the deserts. They also needed to know the direction of Mecca and time of day for prayers. During the Islamic period AD 900–1400 astronomical *zijes*, which are texts with astronomical tables, were numerous, but few have survived (see King and Samso, 2001). One Arabic ephemeris for AD 1326–1327 is preserved in the Egyptian National Library (2011).

Zij al-Sindh by al-Khwarizmi (ca 780–850) in AD 830 contains tables for the motions of the Sun, Moon, and five planets (Toomer, 1973). Al-Battani (858–929) wrote *Klitabal-Zij,* improving on Ptolemy's *Almagest,* and including a star catalog, solar, lunar, planetary, and trigonometric tables. This and other books reached Europe and would influence Kepler, Galileo, and Tycho (Hartner, 1970). Rahman Al Sufi (903–986) wrote his *Book of the Fixed Stars* (Figure 5) correcting mistakes by Ptolemy and documenting the order of magnitudes of stars and giving Arabic names to stars that remain in use (Hafez et al., 2011). Al Biruni (973–1048) invented the first planisphere to track the movements of the stars and constellations over the year. This device is considered one of the first analog computers (Boilot, 1955). Abu Ishaq Ibrahim al-Zarqali (1029–1088), also known as Arzachel, invented the equitorium to chart the movement of the Sun, Moon, and planets, and he devised a lunisolar computer to calculate the time of year and phases of the Moon (Puig, 2014). In 1267 Jamal ad-Din, a Persian astronomer, presented Kublai Khan with an astronomical almanac, which was later known in China as the *Ten Thousand Year Calendar,* or *Eternal Calendar*. In China he was known as Zhamaluding and in 1271 he was the first Director of the Islamic Observatory in Beijing. Omar Khayyam and collaborators constructed a *zij* and the Persian Solar Calendar, the *jalali calendar,* a modern version of which is still in official use in Iran (Dalen, 2014). This was the Islamic Golden Age leading up to the Renaissance (see Kennedy, 1998; King, 1999; King and Samso, 2001; Saliba, 1994).

Figure 5: The constellation "Lepus" (The Hare) in al-Sufi's *Book of the Fixed Stars*. At the top of the figure is an image of the constellation (in duplicate). In the lower part is the table of stars in this constellation, including their ecliptical coordinates and estimated magnitudes (after Hafez et al., 2011: 124).

3.3 Early Ephemerides

Prior to the printed ephemerides, two manuscript ephemerides were prepared by European astronomers or astrologers. One for AD 1426 is preserved in the Bibliotheque Nationale in Paris, and another for AD 1442–1458, by London astrologer Richard Trewythian, is in the British Library (re the latter, see Page, 2001). The format of these manuscripts is similar to earlier fragments and future printed ephemerides. They have



martius								aprilis							
Tabula ascẽdẽtis et duodecim domorum															
dies mensium	hore minuta	1 / 7 cãcer g	2 / 8 leo g	3 / 9 leo g	4 / 10 virg g	5 / 11 scor g	6 / 12 sagi g	dies mensium	hore minuta	1 / 7 leo g	2 / 8 leo g	3 / 6 virg g	4 / 10 libr g	5 / 11 scor g	6 / 12 capc g
1	0 0	12	3	26	20	0	7	1	1 53	5	29	25	21	28	1
2	0 4	13	4	27	21	1	8	2	1 56	5	30	26	22	29	2
3	0 8	13	5	28	22	2	9	3	2 [illegible]	6	♍ 1	27	23	30	3
4	0 11	14	6	29	23	3	10	4	2 4	7	2	28	24	30	4
5	0 15	15	7	30	24	4	11	5	2 7	8	3	29	25	♐ 1	5
6	0 19	16	8	♍ 1	25	5	12	6	2 11	9	3	30	26	2	5
7	0 22	17	8	2	26	6	12	7	2 15	9	4	♎ 1	27	3	6
8	0 26	17	9	3	27	7	13	8	2 18	10	5	2	28	4	6
9	0 30	18	10	4	28	8	14	9	2 22	11	6	3	29	4	7
10	0 33	19	11	4	29	9	14	10	2 25	12	7	4	30	5	8
11	0 37	19	12	5	30	9	15	11	2 29	12	8	5	♏ 1	6	9
12	0 41	20	12	6	♎ 1	10	16	12	2 33	13	9	5	2	7	9
13	0 44	21	13	7	2	11	17	13	2 37	14	9	6	3	8	10
14	0 48	22	14	8	3	12	18	14	2 41	14	10	7	4	9	11
15	0 52	22	15	9	4	13	18	15	2 44	15	10	7	4	9	11
16	0 55	23	16	10	5	14	19	16	2 48	15	11	8	5	10	12
17	0 59	24	17	11	6	15	20	17	2 52	16	12	9	6	10	12
18	1 2	25	18	12	7	16	21	18	2 56	17	13	10	7	11	13
19	1 6	25	18	13	8	17	21	19	3 0	17	14	11	8	12	14
20	1 01	26	19	13	9	17	22	20	3 3	18	15	12	9	13	15
21	1 13	27	20	14	10	18	23	21	3 7	19	16	13	10	14	15
22	1 17	28	21	15	11	19	24	22	3 11	20	16	14	11	15	16
23	1 20	28	22	16	12	20	24	23	3 15	20	17	15	12	15	17
24	1 24	29	22	17	13	21	25	24	3 19	21	18	16	13	16	18
25	1 28	30	23	18	14	22	26	25	3 23	22	19	17	14	17	18
26	1 31	30	24	19	15	23	27	26	3 26	23	20	18	15	18	19
27	1 35	♌ 1	25	20	16	23	27	27	3 30	23	21	19	16	18	20
28	1 38	2	25	21	17	24	28	28	3 34	24	22	20	17	19	21
29	1 42	3	26	22	18	25	29	29	3 38	25	23	21	18	20	22
30	1 46	3	27	23	19	26	29	30	3 41	26	24	22	19	21	23
31	1 49	4	28	24	20	27	30	0	0 0	0	0	0	0	0	0

Figure 6: A page from Zacuto's *Book of Tables on the Celestial Motions or the Perpetual Almanac* (https://upload.wikimedia.org/wikipedia/commons/c/cd/AlmanachPerpetuum.jpg).

vertical columns for the different celestial bodies and horizontal rows for specific dates.

Johannes Muller (1436–1474) from Konigsberg in Bavaria took the name Regiomontanus and made observations and wrote a book on trigonometry. In the 1470s he used the *Alfonsine Tables* to calculate 32 years of daily planetary positions, which were used to print ephemerides in 1474 for 1475–1506 (Zinner, 1990). Abraham Ben Samuel Zacuto (1452–1515; Chabás and Goldstein, 2000) was a Professor at the University of Salamanca in Spain and took refuge in Lisbon, Portugal, where he was Royal Astronomer and Historian to King John II. While in Salamanca from 1470–1478 he wrote *The Great Book*, which contained 65 detailed astronomical tables (ephemerides) in almanac format of the positions of the Sun, Moon, and planets on the meridian of Salamanca. The calculations were based on the *Alfonsine Tables*. His book was translated into Castillan and Latin, and had the title, *Book of Tables on the Celestial Motions or the Perpetual Almanac* (Figure 6). The almanac gave solar declinations, so navigators could use the Sun for determining latitude. Supposedly Columbus used Zacuto's tables.

Johannes Angelus (1453–1512) (also called Engel), a medical doctor and mathematician in Vienna, published almanacs and astrological calendars in German and Latin from 1484. *Astrolabium Planum*, with tables of astrological calculation and horoscopes, was published in Augsburg in 1488. Further editions were published in 1494 and 1502. He published ephemerides in 1510 and 1512 with daily planetary positions and planetary aspects. These were in the format of the ephemerides of Regiomontanus. Angelus titled the ephemerides *Almanach Aovum atque Correctum* and said in the prefaces the planetary longitudes were more accurate than in common almanacs. Studies show that his ephemerides are different from those from the *Alfonsine Tables*, but not more accurate (Dobrzycki and Kremer, 1996).

Figure 7: A drawing of Johannes Stoffler made by Jean-Jacques Boissard in 1630 (https://upload.wikimedia.org/wikipedia/commons/e/ef/Stoeffler1.jpg).

Johannes Stoffler (1452–1531; Figure 7), Chair of Mathematics at the University of Tubingen, published his *Almanach Nova* in 1499, in collaboration with Jacob Pflaum. This continuation of the ephemeris of Regiomontanus had a large circulation with 13 editions until 1551. In 1518 Stoffer published *Calendarium Romanum Magnum,* whose tables were restricted to the positions and syzygies of the Sun and Moon. The introductory chapters described how the tables could be used for keeping time, administering medical remedies, predicting eclipses, and calculating mobile feast days (Vescovini, 2014).

Johannes Stadius (1527–1579), sixteenth century Professor of Mathematics at the University of Leuven, went to Turin in 1554 and also worked in Paris, Cologne, and Brussels. His 1554 *Ephemerides Novae at Auctae* corrected and improved the ephemerides of the *Alfonsine*

Tables predicting the positions of the Sun, Moon, and planets at a given moment of time. This was both an astronomical and astrological work and the joining of medicine and mathematics.

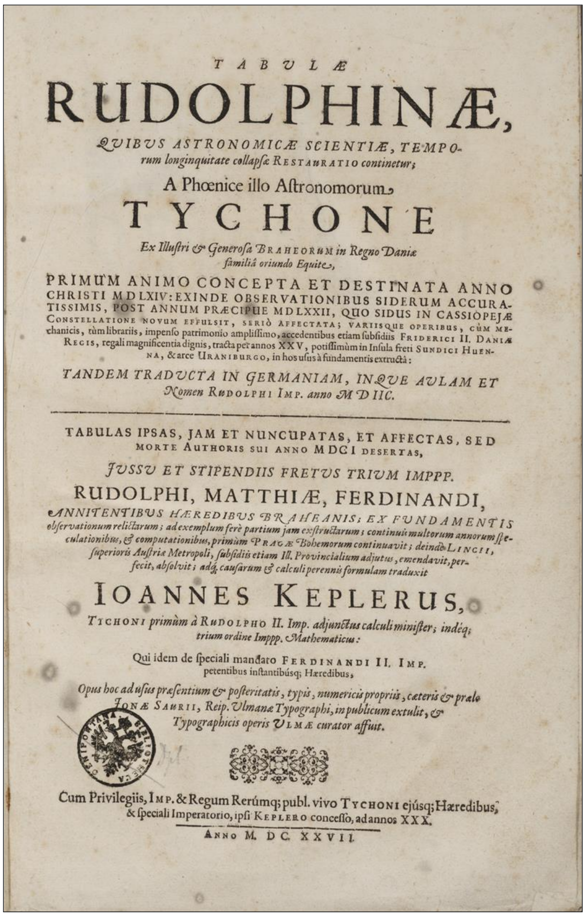
Contrary to popular stories there were no real improvements in the calculation tables from Ptolemy until Johannes Kepler (1571–1630; Figure 8) published his *Rudolphine Tables* (Figure 9) in 1627 (Gingerich, 2017). Using observations made by Tycho Brahe, Kepler improved the predictions by two orders of magnitude. Kepler's first volume for 1617–1620 was not based on the complete *Rudolphine Tables*, but volumes for 1621–1636 followed the new tables precisely. A competing, simpler, old-fashioned, complete set of tables was published a little later by Dutch astronomer Philip Lansbergen (1561–1632). In the 1630s astronomers had little means to judge the results from Kepler's complex methods of computing planetary positions versus Lansbergen's simpler tables, which were similar in style to the *Alfonsine Tables*. Later, Noel Duret proved that Kepler's results were superior (Gingerich, 2017).

Subsequently the distribution of astronomical data and ephemerides began in different countries at different times and for different reasons. For an overview of British almanacs at this time see Capp (1979). There is a series of publications, in *Nature* in 1873 and 1874 under the title "Astronomical Almanacs", without a designated author, on the detailed history of the *Connaissance des temps, The Nautical Almanac*, and the J*ahrbuch* of Berlin. The changes in personnel, sources of data, changes in accuracies, and sources of errors are detailed (Astronomical Almanacs, 1873, 1874).

3.4 Calendars

Printed calendars and almanacs became popular in the fifteenth century and provided ordinary people with basic knowledge for their daily routines (Nha et al., 2017). Gutenberg published a calendar. Earlier calendars were superseded by Regiomontanus' calendar, which was much more accurate. Johannes Muller von Konigsburg (1436–1476; Figure 10) was better known as Regiomontanus (Zinner, 1990). He was Professor of Astronomy and Mathematics at the University of Vienna and then Astronomer to King Matthias Corvinus of Hungary. He built an observatory in Nurenberg in 1471 and his own private press to publish his discoveries. He printed the first edition of his calendar in 1472. In 1475 he was summoned to Rome by Pope Sixtus IV to assist in the reform of the calendar. On the way to Rome he commissioned the publication of his *Calendarium* by Erhard Ratdolt of Venice in 1476. Although Regiomontanus' calendar was only valid for the location of his ob-

Figure 8: A portrait of Johannes Kepler by an unknown artist, painted in 1610 (https://en.wikipedia.org/wiki/Johannes_Kepler#/media/File:Johannes_Kepler_1610.jpg).



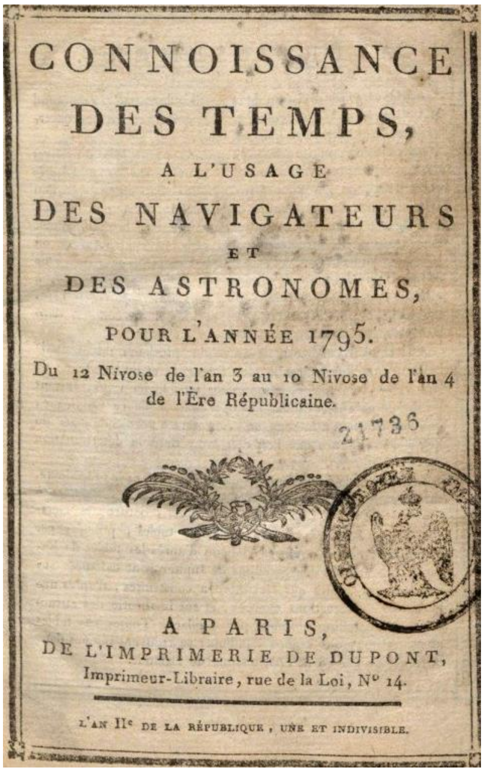
TABULÆ
RUDOLPHINÆ,
QVIBVS ASTRONOMICÆ SCIENTIÆ, TEMPOrum longinquitate collapsæ RESTAURATIO continetur;
A Phœnice illo Aſtronomorum
TYCHONE
Ex Illuſtri & Generoſa BRAHEORUM in Regno Daniæ familiâ oriundo Equite,
PRIMUM ANIMO CONCEPTA ET DESTINATA ANNO CHRISTI MDLXIV: EXINDE OBSERVATIONIBUS SIDERUM ACCURATISSIMIS, POST ANNUM PRÆCIPUE MDLXXII, QUO SIDUS IN CASSIOPEJÆ CONSTELLATIONE NOVUM EFFULSIT, SERIÒ AFFECTATA; VARIISQUE OPERIBUS, CÙM MEchanicis, tùm librariis, impenſo patrimonio ampliſſimo, accedentibus etiam ſubſidiis FRIDERICI II. DANIÆ REGIS, regali magnificentia dignis, tracta per annos XXV, potiſſimùm in Inſula freti SUNDICI HUENNA, & arce URANIBURGO, in hos uſus à fundamentis extructâ:
TANDEM TRADVCTA IN GERMANIAM, INQVE AVLAM ET Nomen RUDOLPHI IMP. anno M D IIC.

TABULAS IPSAS, JAM ET NUNCUPATAS, ET AFFECTAS, SED MORTE AUTHORIS SUI ANNO MDCI DESERTAS,
JVSSV ET STIPENDIIS FRETVS TRIVM IMPPP.
RUDOLPHI, MATTHIÆ, FERDINANDI,
ANNITENTIBVS HÆREDIBVS BRAHEANIS; EX FUNDAMENTIS obſervationum relictarum; ad exemplum ferè partium jam exſtructarum; continuis multorum annorum ſpeculationibus, & computationibus, primùm PRAGÆ Bohemorum continuavit; deindè LINCII, ſuperioris Auſtriæ Metropoli, ſubſidiis etiam Ill. Provincialium adjutus, emendavit, perfecit, abſolvit; adq; cauſarum & calculi perennis formulam traduxit
IOANNES KEPLERUS,
TYCHONI primùm à RUDOLPHO II. Imp. adjunctus calculi miniſter; indéq; trium ordine Imppp. Mathematicus:
Qui idem de ſpeciali mandato FERDINANDI II. IMP. petentibus inſtantibúsq; Hæredibus,
Opus hoc ad uſus præſentium & poſteritatis, typis, numericis propriis, cæteris & prælo JONÆ SAURII, Reip. Ulmanæ Typographi, in publicum extulit, & Typographicis operis ULMÆ curator affuit.
Cum Privilegiis, IMP. & Regum Rerúmq; publ. vivo TYCHONI ejúsq; Hæredibus, & ſpeciali Imperatorio, ipſi KEPLERO conceſſo, ad annos XXX.
ANNO M. DC. XXVII.

Figure 9: The title page of Kepler's *Rudolphine Tables* (https://en.wikipedia.org/wiki/Johannes_Kepler#/media/File:8107-2Keplertp.png).

Figure 10: An eighteenth-century drawing of Regiomontanus (https://en.wikipedia.org/wiki/Regiomontanus#/media/File:Johannes_Regiomontanus.jpg).

servations, a table of selected latitudes and time differences enabled the data to be corrected for different locations. The calendar could aid navigators in gauging their positions from calculating the altitudes of stars and planets. Columbus used a similar book for his first journey to the Americas in 1492 (Coleman, 1999).



CONNOISSANCE
DES TEMPS,
A L'USAGE
DES NAVIGATEURS
ET
DES ASTRONOMES,
POUR L'ANNÉE 1795.
Du 12 Nivose de l'an 3 au 10 Nivose de l'an 4 de l'Ère Républicaine.
21736
A PARIS,
DE L'IMPRIMERIE DE DUPONT,
Imprimeur-Libraire, rue de la Loi, N° 14.
L'AN II^e DE LA RÉPUBLIQUE, UNE ET INDIVISIBLE.

Figure 11: The title page of the 1795 issue of *Connaissance des Temps*, which announced the formation of the Bureau des Longitudes (https://www.france-pittoresque.com/spip.php?article5864).

4 THE EMERGENCE OF 'MODERN' ALMANACS

4.1 France

In 1666 Jean de la Caille (1645–1723), a bookseller in Paris published, at his expense, the *Astronomical Ephemerides* of Johannes Hecker (1611–1687; also known as Hevelius), a Danzig astronomer. These ephemerides were based on the rules of the *Rudophine Tables* and the observations of Tycho Brahe and Kepler (Astronomical Almanacs I, 1873).

Jean Picard (1620–1682; Picolet, 1987), a French astronomer, created the *Connaissance des Temps* in 1678 and the first issue for 1679 for astronomers was by a private publisher. While this was a private undertaking, it was with the aegis of King Louis XIV, and astronomers were quoted as responsible for the contents. In 1702 the Académie Royale des Sciences took scientific responsibility, and after that a member of the Académie, such as le Fevre, Lalande, or Mechain, was responsible for the contents. The computations were made by the publisher's staff or outside scientists.

The Bureau des Longitudes (BdL) was established in 1795 by the Convention (during the Revolution) as an Academy that specialized in astronomy, time, geodesy, and navigation (see Figure 11). Initially it had ten members, but now there are thirteen. With only a consultative voice there are corresponding members and representatives of major establishments, such as CNES, Institut Geographique National, Paris Observatory, and the Hydrographic Institute of the Navy. Until 1854 the BdL was the governing body of Paris Observatory and all national astronomical instruments. It replaced the Academy with responsibility for the *Connaissance des Temps*, but it was only in 1802 that computations were performed by a staff of seven, supervised by a member of the BdL. In the second part of the nineteenth century the BdL was responsible for all French discovery and astronomy missions, such as for the two transits of Venus. New publications were added, like the *Annuaire du BdL*, a popular, reduced precision ephemerides, *Éphémérides Nautiques* in 1889, and *Éphémérides Aéronautiques* in 1938, for navigation. In 1916 the edition of the *Connaissance des Temps* introduced GMT. The tables for the Moon were improved by Rodolphe Radau (1835–1911), and the satellites of Jupiter by Marie Henri Andoyer (1862–1929), while tables prepared by Urbain Jean Joseph Le Verrier (1811–1877) were used for the planets until 1965. After Andoyer's death in 1929, BdL members ceased significant interventions, one principal calculator remained in the BdL offices, and com-putations and proof reading were done by ten home calculators.

In 1959 André-Louis Danjon (1890–1967), Director of Paris Observatory and member of the BdL, asked Jean Kovalevsky (1929–2018) to take over the office and create a modern scientific group. Most of the calculators accepted full time positions and learned programming on the Paris Observatory computer, which was acquired in 1960 at the Meudon Annex. Young scientists began research in celestial mechanics and by 1963 all of the *Connaissance des Temps* was computerized and sent to the printer in machine-readable form (Kovalevsky, pers. comm., 2017). Since 2015, the BdL is no longer responsible for the *Éphémérides Aéronautiques*.

The great increase of the staff (between 30 and 40 persons) involved the transformation of the “Service des Calculs” into the “Service des Calculs et de Mécanique Céleste du Bureau des Longitudes”. Since the space for the personnel became too small, it progressively moved to a new building at Paris Observatory. The full Service settled at Paris Observatory and became an Institute attached to the Observatory under the name of “Institut de Mécanique Céleste et de Calcul des Éphémérides” (IMCCE) by the decision of the Ministry on 2 June 1998. Within Paris Observatory, responsible for its administration, it has a certain independence compared with other bodies of the Observatory. The responsibility of the BdL for the Éphémérides is ensured by the presence of four members of the BdL on the Directing Board of the IMCCE and within a “Commission des Éphémérides” composed of four members of IMCCE, four members of the BdL, and two exterior members (Kovalevsky and Barlier, pers. comm., 2018).

The IMCCE has developed a planetary and lunar ephemerides development program both by numerical integration and general theories (Fienga et al., 2015). Since about 1968, all the contents of the *Connaissance des Temps* were progressively computed from theories elaborated by the staff. The variations in the theories used for the *Connaissance des Temps* (successive versions of INPOP) are a continuous history found in the prefaces.

4.2 Germany

On 10 May 1700 Kurfurst Friedrich III von Brandenburg, an elector of the German kings and emperors, whose castle at Colin an der Spree later became the center of Berlin, issued the Calendar Edict (‘Kalender-Patent’ in German). This edict introduced the Catholic Gregorian Calendar into the Protestant country. To introduce the calendar correctly positions for astronomers and an observatory were created in Berlin (see Wielen, 2001). To finance the astronomers a calendar tax was established. Each calendar required a tax stamp for permission to sell it or to own it. This tax paid the salaries of the astronomers. The tax was waived in the nineteenth century.

While the main task of the astronomers was to prepare the calendar, they became active in both observational and theoretical research. *Astronomical Ephemerides* started in 1749 by Grischow in Berlin and continued until 1754. In 1774 Lambert revived the ephemerides as the (Berliner) *Astronomisches Jahrbuch* (BAJ) for 1776 with ephemerides and news concerning astronomical sciences (cf. Figure 12). The first issue of the German Nautical Almanac, *Nautisches Jahrbuch,* was published in 1776 and it was separate from the BAJ, unlike the British,

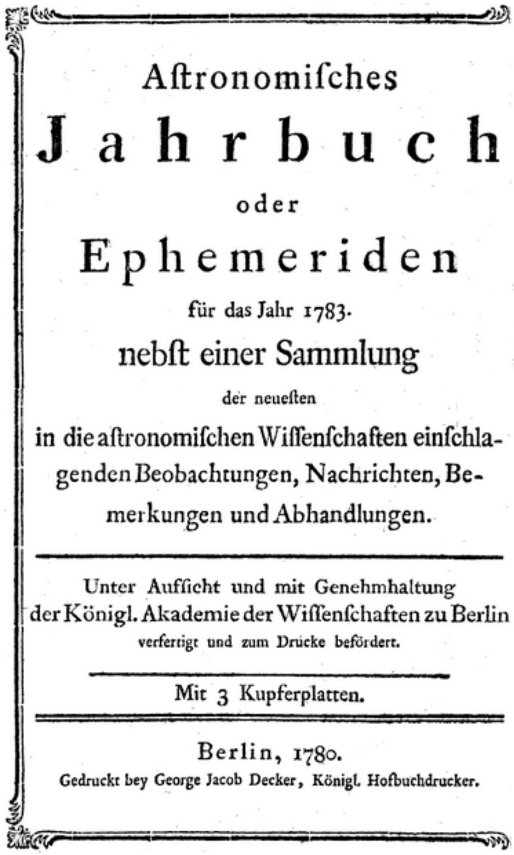

Aſtronomiſches
Jahrbuch
oder
Ephemeriden
für das Jahr 1783.
nebſt einer Sammlung
der neueſten
in die aſtronomiſchen Wiſſenſchaften einſchlagenden Beobachtungen, Nachrichten, Bemerkungen und Abhandlungen.
Unter Aufſicht und mit Genehmhaltung der Königl. Akademie der Wiſſenſchaften zu Berlin
verfertigt und zum Drucke befördert.
Mit 3 Kupferplatten.
Berlin, 1780.
Gedruckt bey George Jacob Decker, Königl. Hofbuchdrucker.

Figure 12: The title page of the *Astronomisches Jahrbuch* for 1783 (https://de.wikipedia.org/wiki/Berliner_Astronomisches_Jahrbuch#/media/File:Berliner_Ephemeriden_178).

American, and Spanish nautical almanacs. In 1776 the Prussian Academy published a collection of astronomical tables, *Sammlung Astronomischer Tafelin,* in three volumes. They were the bases for the BAJ ephemerides from 1779 for many years. In the period, of about 1790–1820, Lalande said in his *Bibliographie Astronomique* about the J*ahrbuch,* that “… all astronomers are obligated to know German, for this work cannot be dispensed with.” (Astronomical Almanacs VII, 1873). The 1830 edition contained many reforms by Johann Franz Encke (1791–1865; Figure 13) of the astronomical data to improve accuracies and correct errors. The BAJ was published from 1776 to 1959. From

1844 to 1851 the BAJ included lunar distances for navigational purposes. From 1852 the *Nautisches Jahrbuch* (NJ) was published by the Prussian Ministry of Trade based on the ephemerides of the BAJ (Wielen, pers. comm., 2017). The Theoretical Department of Berlin Observatory was separated into the Rechen-Institut zur Herausgabe des Berliner Astronomischen Jahrbuchs in 1874. In 1896/1897 the Institute became independent of the Berlin Observatory and was named the Konigliches Astronomisches Rechen-Instutut, a Royal Prussian Institute linked to the University of Berlin. The BAJ used the Berlin meridian from 1776 to 1915. In 1916 the Greenwich meridian was introduced in accordance with the Paris Conference of 1911. In May 1944 the Astronomisches Rechen-Institut was attached to the German Navy.

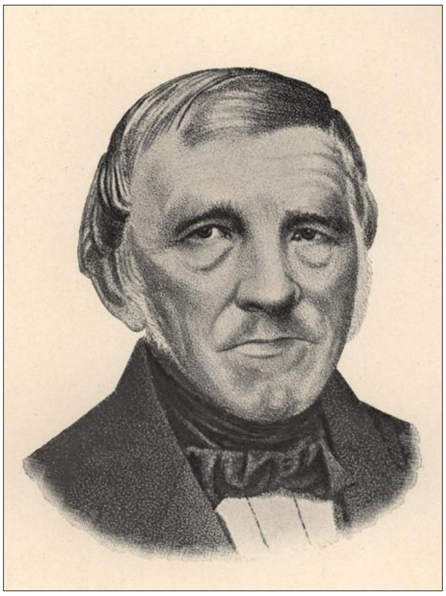


Figure 13: Johann Franz Encke (https://en.wikipedia.org/wiki/Johann_Franz_Encke#/media/File:Johann_Franz_Encke.jpg).

During World War II the exchange of astronomical ephemerides and almanac data between the U.S. Naval Observatory and H.M. Nautical Almanac Office and the Astronomisches Rechen-Institut continued as before. This was accomplished through Bertil Lindblad of Stockholm Observatory in neutral Sweden (Wielen and Wielen, 2016). This was done with approvals from the highest levels, as I understand it, on the basis that safe navigation at sea by all was in the best interests of everyone. Germany did not join the IAU until 1952, as the IAU was originally for allied countries (Kochhar et al., 2015).

In July 1944 the Astronomisches Rechen-Institut was moved from Berlin to Sermuth to avoid bombing in Berlin. In April 1945 the US Army occupied Sermuth. In June 1945 the US Army moved the institute to Heidelberg, before the area around Sermuth was turned over to the Soviet Army in exchange for the Western Sectors of Berlin. A few members of the institute, who lived on the eastern side of the river Mulde at Sermuth, had to stay under Soviet control. They moved to the Observatory at Potsdam-Babelsberg near Berlin and remained an eastern part of the Astronomisches Rechen-Institut until 1956, when they became part of the Babelsberg Observatory (Wielen, 2001). By international agreement the BAJ was discontinued in 1960 and the *Apparent Places of Fundamental Stars* (APFS) was taken over by the Astronomisches Rechen-Institut in 1960. The Astronomishes Rechen-Institut considers the Calendar Edict its foundation.

4.3 Great Britain

Around AD 1500 almanacs with calendars and astronomical data were printed in England. After 1540 astrological prognostications were added to the almanacs, which increased the popularity of the almanacs. In the sixteenth century about 600 almanacs were printed. In the seventeenth century essays on subjects like astronomy, astrology, and medicine were added and about 200 almanacs were published (Chapman, 2007; Nicolson, 1939). In 1664 40,000 copies of Vincent King's Almanak were sold, and more than 360,000 copies of other almanacs were sold (Kelly, 1991).

The motions of the Sun and planets are sufficiently slow that the differences in appearance in different parts of Europe could be ignored, however, the Moon's motion is more rapid so constant correction factors were applied for the different locations. The data were determined from some of the ephemerides available at that time, but the sources were not usually identified. The sources could be identified by the values listed (ibid.). At first the accuracies were not very good. There were no English tables for the Sun, Moon, or planets. The ephemerides were all for Europe. Computational astronomy was not well known in England. In the 1650s Wing and Leybourne compiled the first English planetary tables.

The Royal Observatory was founded in 1675 by decree of King Charles II with John Flamsteed (1646–1719) as the first Royal Astronomer (Forbes et al., 1975). On 22 October 1707 four Royal warships struck the reefs of the Isles of Sicily and 2,000 men were drowned. In 1714 the Longitude Act was passed by Parliament and the Board of Longitude was established to examine the problem and set up a prize of 20,000 pounds for a person who solved the problem of accurate navigation. The practical use of chronometers for navigation at sea dates to John Harrison's first time piece, H1, in 1735. In February 1765 Nevil Maskelyne (1732–1811; Figure 14) proposed to the Board of Longitudes the publication of a Nautical Ephemeris designed to determine longitude at sea by the method of lunar distances. In 1765 Parliament approved authorizing compilation and printing of *The Nautical Almanac and Astronomical Ephemeris*. The first issue was for 1767 (see Figure 15). A handbook for using the method of lunar distances, *Tables Requisite to be Used with the Astronomical and Nautical Ephemeris*, was published by Maskelyne. While the use of Harrison's chronometer was more accurate, the use of lunar distances was cheaper.

The Nautical Almanac fell into disrepute due to many errors in the early 1800s, when John Pond (1767–1836) and Thomas Young (1773–1829) were responsible. In 1831 William S. Stratford (1789–1853) was appointed superintendent with the task of setting up an Office and improving the Almanac. The Nautical Almanac Office (HMNAO) was established as a separate institution under the Admiralty in 1832. The Almanac for 1834 contained more data for astronomers and improvements in content and presentation. John R. Hind (1823–1895) was the longest serving superintendent, holding the office for 38 years, from 1853 to 1891. He introduced many changes and ensured an accurate and on schedule almanac. In 1896 the first part of the *Nautical Almanac & Astronomical Ephemeris*, the *Nautical Almanac*, was published separately for mariners. In 1914 it was renamed the *Nautical Almanac Abridged for the Use of Seamen*, but generally known as the *Abridged Nautical Almanac,* which was the title on the book's spine (Reed, 2015). After the Conference de 1896 at the Bureau des Longitudes, Newcomb's tables and constants were adopted for 1901 and onwards.

Leslie J. Comrie (1893–1950) was Superintendent from 1930 to 1936. He introduced the use of punch card equipment for the calculation using Fourier synthesis of the principal terms in the motion of the Moon for 1936–2000. He used the equipment for computations for the publications and for other projects. After an investigation and formal enquiry concerning the operations of the office, Comrie's appointment was terminated and Donald H. Sadler (1908–1987) was appointed the new Superintendent, from 1936 to 1970. He continued the use of punched card equipment and, in addition to the almanac publications, took on outside computations for the Admiralty. HMNAO was one of the first Departments of the renamed Royal Greenwich Observatory to move to Herstmonceux Castle in Sussex in 1949. It then acquired its own punch-card machines and in 1959 its own electronic computer.

Joint publications by HMNAO and the US Nautical Almanac Office (USNAO) of *The Nautical Almanac*, *The Air Almanac*, and the publication with different titles in the two countries, *The American Ephemeris and Nautical Almanac* and *The Astronomical Ephemeris*, began in 1960. The title of the nautical almanacs were both changed to *The Nautical Almanac* in 1960, the content was changed in the two publications to

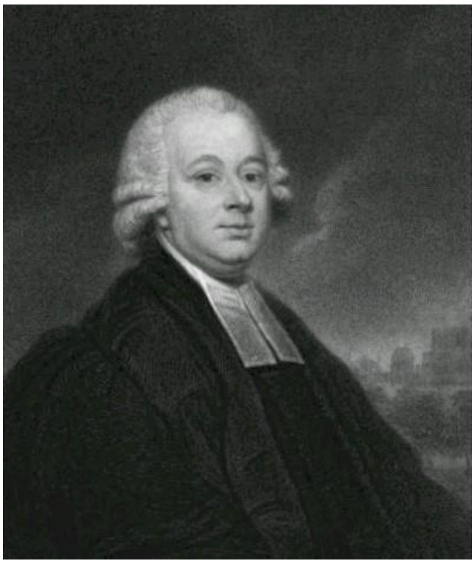
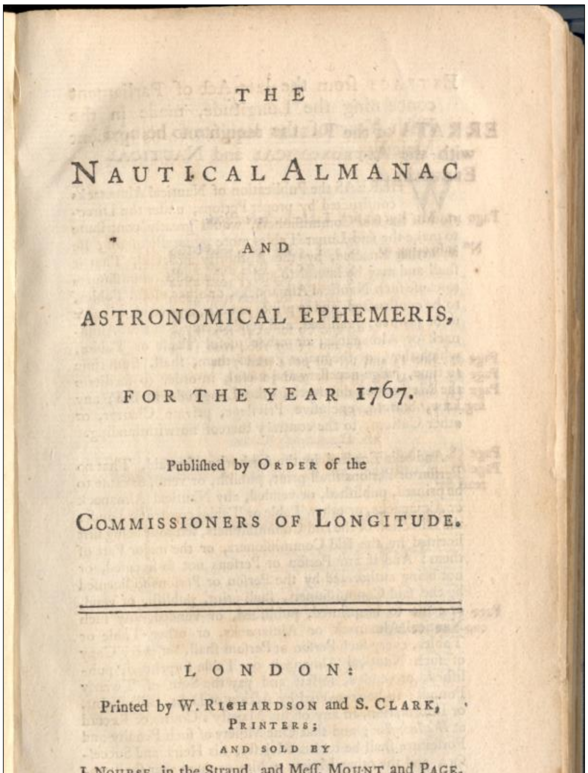


Figure 14: The Reverend Dr Nevil Maskelyne (https://en.wikipedia.org/wiki/Nevil_Maskelyne#/media/File:Maskelyne_Nevil.jpg).



THE

NAUTICAL ALMANAC

AND

ASTRONOMICAL EPHEMERIS,

FOR THE YEAR 1767.

Publiſhed by ORDER of the

COMMISSIONERS OF LONGITUDE.

LONDON:

Printed by W. RICHARDSON and S. CLARK, PRINTERS;

AND SOLD BY

J. NOURSE, in the Strand, and Meſſ. MOUNT and PAGE, on Tower-Hill,

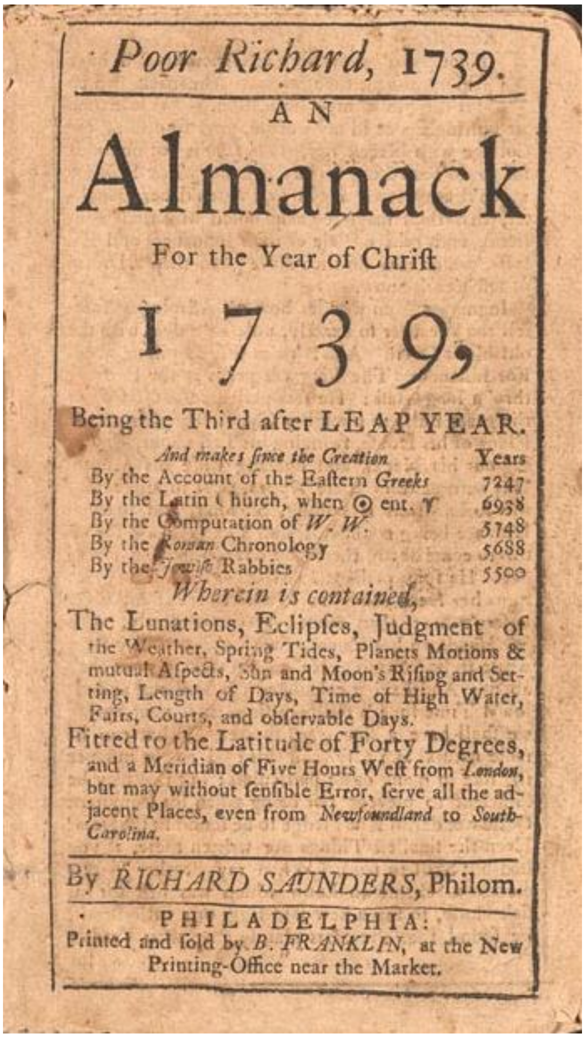
Bookſellers to the ſaid COMMISSIONERS.

M DCC LXVI.

Figure 15: The title page of the first *Nautical Almanac* (http://astro.ukho.gov.uk/nao/history/nao_1767.html).

be identical in 1958. All publications were calculated jointly, shared with the other, and published in both countries. In 1981 the astronomical ephemeris was completely redesigned by George Wilkins, the HMNAO Superintendent (1970–1989), and P. Kenneth Seidelmann, the USNAO Director. The computations were shared, and a single printing of *The Astronomical Almanac* in the USA was begun (see Wilkins, 1999).

The Royal Greenwich Observatory was relocated to Cambridge in 1990, with Bernard D. Yallop as Superintendent of HMNAO from 1989 to 1996. Andrew T. Sinclair was named Head of HMNAO for 1996–1998. When the RGO was closed in 1998, HMNAO was moved to Rutherford Appleton Laboratory, and in 2006 to the UK Hydrographic Office in Taunton in Somerset, back under the Admiralty (Hohenkerk, 2016).


Poor Richard, 1739.

AN

Almanack

For the Year of Chrift

1739,

Being the Third after LEAP YEAR.

And makes fince the Creation	Years
By the Account of the Eaftern *Greeks*	7247
By the Latin Church, when ☉ ent. ♈	6938
By the Computation of *W. W.*	5748
By the *Roman* Chronology	5688
By the *Jewifh* Rabbies	5500

Wherein is contained,

The Lunations, Eclipfes, Judgment of the Weather, Spring Tides, Planets Motions & mutual Afpects, Sun and Moon's Rifing and Setting, Length of Days, Time of High Water, Fairs, Courts, and obfervable Days.

Fitted to the Latitude of Forty Degrees, and a Meridian of Five Hours Weft from *London*, but may without fenfible Error, ferve all the adjacent Places, even from *Newfoundland* to *South-Carolina*.

By *RICHARD SAUNDERS*, Philom.

PHILADELPHIA:

Printed and fold by *B. FRANKLIN*, at the New Printing-Office near the Market.

Figure 16: The title page of *Poor Richard's Almanac* for 1739 (https://en.wikipedia.org/wiki/Poor_Richard%27s_Almanack#/media/File:Poor_Richard_Almanack_1739.jpg).

4.4 The United States

Almanack Calculated for New England by Mr. Pierce was published in 1639 on the first printing press brought from England. From 1643 to 1649 almanacs were published yearly in Cambridge, Massachusetts. Annual almanac prints were of 3,000–5,000 copies. More than 14,000 different almanacs were printed in America from the colonial period through the nineteenth century. Almanacs developed from ephemerides into information on the basic needs and interests of a family. The times of sunrise/sunset, phases of the Moon, and positions of specific stars were of greatest interest. Weather prognostication became a popular feature of almanacs. Astrology was of interest for agricultural chores, medical treatments, and undertaking long voyages. Almanacs added literary material such as proverbs, verses, essays, and short stories. *Poor Richard's Almanac* (Figure 16) by Benjamin Franklin (1706–1790), published from 1736 to 1758, contained humor and satirical material converted from sayings of great writers of the past. With the approach of the American Revolution almanacs included maps of the progress of the war (Kelly, 1991). From 1802 to 1850s Blunt, Garnett, Megarey, Patten republished the British *Nautical Almanac and Astronomical Ephemeris* in America (Reed, 2015).

The naval appropriations act of 3 March 1849 authorized the publication of data necessary for navigation. The US Nautical Almanac Office (USNAO) was established in Cambridge, Massachusetts, that year with Lt. Charles Henry Davis (1807–1877) as the first Superintendent. *The American Ephemeris and Nautical Almanac* was published in 1852 with data for 1855, and included an Appendix with Chauvent's tables for correcting lunar distances. The purpose was to provide data for the USA and to avoid buying British publications. There were separate tables based on the Greenwich Meridian as preferred by navigators and on a prime meridian through the U.S. Naval Observatory, for promoting astronomy in the USA (Waff, 1997). In 1858 the *Almanac for the Use of Navigators*, a concise book for navigators with reprinted portions of *The American Ephemeris and Nautical Almanac,* was published, and in 1882 the title was officially changed to *The American Nautical Almanac*.

In 1866 the almanac office moved to Washington DC and in 1893 it was physically located at the present site of the U.S. Naval Observatory (USNO—see Figure 17), of which it became a part over the next few years. Simon Newcomb (1835–1909; Figure 18) was Superintendent from 1877 to his retirement in 1897. Newcomb supervised the development of theories of the motions of the Sun, Moon, and planets, and the establishment of a reference system, including astronomical constants, mean solar time, and ephemerides. In 1916 the *American Nautical Almanac* was no longer an extract from the

Figure 17: In 1893 the US Nautical Almanac Office moved to the newly-built main building of the U.S. Naval Observatory, shown here (courtesy: Geoff Chester).

American Ephemeris and Nautical Almanac, but a separately prepared volume. A list of 55 numbered navigation stars appeared for the first time. In 1934 the *American Nautical Almanac* was significantly revised with Greenwich Hour Angles in parallel with Right Ascensions. This followed the experimental publication of the *Air Almanac* with extensive GHA tables in 1933 (Reed, 2015).

In 1940 Wallace Eckert (1902–1971) left Columbia University to serve as Head Astronomer and Director of the Nautical Almanac Office at the U.S. Naval Observatory. With the war approaching and the need for publishing *The Air Almanac*, Eckert adopted machine methods he had perfected at Columbia. *The Air Almanac* went through three stages: the 1941 issue (the first regular issue) was printed with hand-set movable type; the 1942–1945 issues were printed directly on a modified IBM 305 accounting machine; and the 1946 and subsequent issues were printed on a card-operated table printer, designed by Eckert in 1941, but not delivered by IBM until 1945. Not a single error was ever reported in those Air Almanacs. Paul Herget (1908–1981) adopted the machine methods to *The American Ephemeris and Nautical Almanac* beginning in 1940. On the night shift Herget built tables for locating German U-boats by triangulation of radio signals. When published in 1943, allied shipping loses in the Atlantic were reduced from 30% to 6%.

In 1958 the unified *Nautical Almanac* was introduced for the US and British navies, but the title *American Nautical Almanac* was retained until 1960. UT replaced GMT in the nautical and air almanacs in the 1980s. In 1981 *The Astronomical Almanac*, printed in the US, replaced *The Astronomical Ephemeris* printed in the UK and *The American Ephemeris and Nautical Almanac* printed in the US. The bases for the publication were changed by international agreement in 1984. *The Air Almanac* was reduced from three to two volumes per year in 1977 and to one volume in 1987. The *Almanac for Computers* was introduced in 1977, *The Floppy Almanac* in 1986, and *MICA* in 1993.

In 1983 *The Nautical Almanac: Yachtsman's Edition* was licensed for sale by independent publishers: Paradise Cay Yacht Sales. The content was identical to the Nautical Almanac, with occasional brief articles, additional tables, sight reduction forms, and advertisements (Reed, 2015). In 1989 concise sight reduction tables and instructions for sight reductions by computer

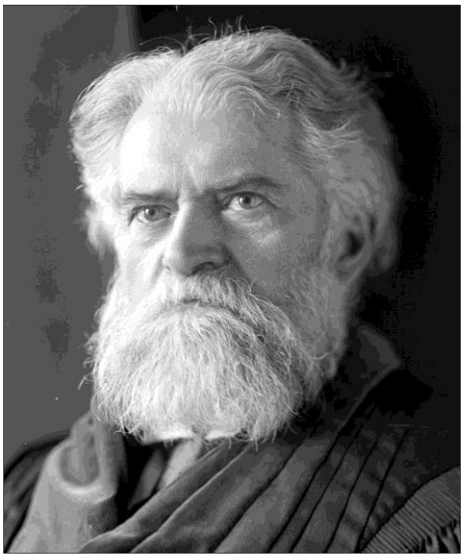


Figure 18: Canadian-born Simon Newcomb (https://en.wikipedia.org/wiki/Simon_Newcomb#/media/File:Simon_Newcomb_01.jpg).

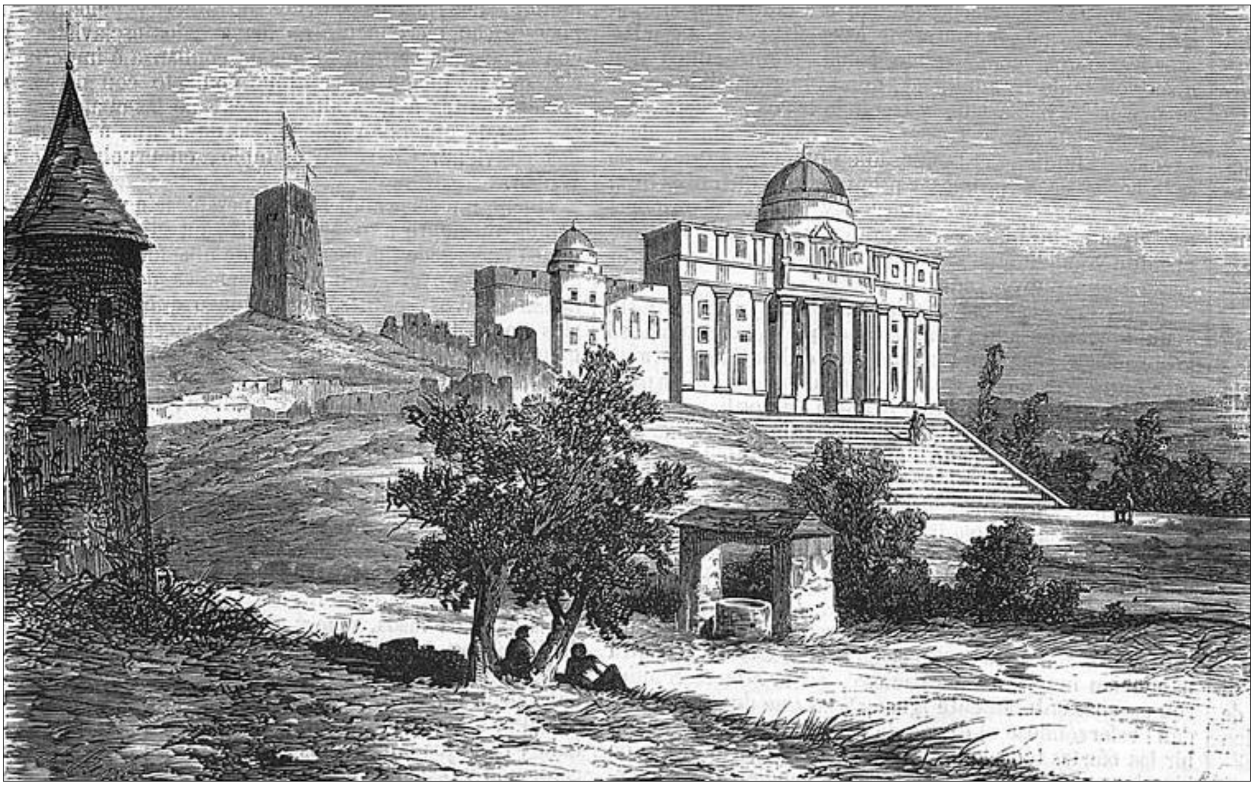


Figure 19: An 1861 drawing of the Real Instituto y Observatorio de la Armada in San Fernando https://es.wikipedia.org/wiki/Real_Instituto_y_Observatorio_de_la_Armada#/media/File:1861-03-17,El_Museo_Universal,_Vista_del_Observatorio_de_San_Fernando,_Ruiz.jpg 17,_

were introduced, so *The Nautical Almanac* was a self-contained edition for navigators.

The Explanatory Supplement to The Astronomical Ephemeris and The American Ephemeris and Nautical Almanac was published in 1961, giving an explanation of the methods used to determine the material published in the almanacs and the documentation of reference material. Editions of *The Explanatory Supplement to the Astronomical Almanac* were published in 1992 and 2012, updating the explanations and documenting the new developments and reference systems (*Explanatory Supplement*, 1961; Seidelmann, 1992; Urban and Seidelmann, 2012). Detailed histories of the US Nautical Almanac Office are given by Steven Dick (1999; 2003).

4.5 Spain

Jorge Juan (1713–1773), Director of the Naval Academy, had the idea of an astronomical observatory in the tower at the *Castillo de la Villa* in Cadiz, where the Naval Academy was located. In 1753 the first instrument was placed at the Real Observatorio de Cadiz (Royal Cadiz Observatory) as it was originally called. The Real Instituto y Observatorio de la Armada (Royal Institute and Observatory of the Spanish Navy) was founded in 1753 in San Fernando for navigation purposes (Figure 19). The Royal Observatory in Madrid was built for purely astronomical work in 1790. The *Almanaque Nautico y Ephemerides Astronomicas* was first published in 1792. In 1855 the Spanish Nautical Almanac name was simplified to *Almanaque Nautico*. In 1961 the Spanish *Almanaque Nautico*, which had evolved into a publication primarily for astronomers, was renamed *Efemerides Astronomicas*. A year later *Alamanaque Nautico para uso de los navegantes* recovered the name *Almanaque Nautico* (Reed, 2015).

Now the San Fernando Observatory includes, as one of four scientific departments, the Ephemeris Department, whose main duty is determination of ephemerides and dissemination to sailors, astronomers, and geodesists. The Time Department of the Observatory is responsible for determining the Official Time in Spain.

4.6 Russia

Pulkova Observatory was opened in 1839 with Fredrick Georg Wilhelm von Struve (1793–1864) as the first Director. The principal work was star positions and astronomical constants, including precession, nutations, aberrations, and refractions. The Pulkova meridian passes through the observatory main building and is the reference meridian of geographical Russian maps.

The astronomical institutions in Russia went though management changes, ideological offenses, and purges and disappearances after the October Revolution of 1917. Pulkova Observatory and the astronomical institutes in Petrograd were seriously affected. Many prominent astronomers resisted the changes and paid dearly for their efforts. In 1919 two scientific institutes were founded connected to Petersburg University; the Calculating Institute and the Astronomical-Geodetic Institute. The Calculating Institute was led by B.V. Numerov (1891–1941; Figure 20) and undertook publication of an astronomical annual. In 1923 the two institutes were united as the Astronomical Institute led by B.V. Numerov, until his arrest in 1936. The Institute published astronomical annuals and studied motions and computation of positions of minor planets (Aitken, 1924). Many astronomers were arrested or dismissed in 1936–1937 (Nicolaidis, 1990). In 1939 The Astronomical Institute was renamed the Institute of Theoretical Astronomy (ITA) of the USSR Academy of Sciences. The Pulkova Observatory buildings were destroyed during the siege of Leningrad (1941–1944), but the main instruments and much of the library were saved. The Observatory was reopened in May 1954. In 1989 the Institute of Applied Astronomy (IAA) of the Russian Academy of Sciences was founded and replaced the ITA. The IAA has developed a planetary and lunar ephemerides development program since 2012 (Pitjeva and Pitjeva, 2013).

The Russian publications are *The Astronomical Yearbook of the USSR* since 1922, *Bulletin of the Astronomical Institute* since 1924, *Ephemerides of Zinger's Pairs* since 1930, *Naval Astronomical Yearbook* since 1930, and *Air Astronomical Yearbook* since 1936.

4.7 Vienna, Austria

Astronomy played an important role in the University of Vienna since its beginning in 1365. Vienna's first observatory was built in 1730 by Giovanni Giacomo Marinoni (1676–1755). The Jesuits built their observatory in 1733 (Udias, 2003). Upon Marinoni's death in 1755, his instruments went to the University for the first university observatory. Maximillian Hell (1720–1792), Director of Vienna Observatory from 1755, published ephemerides on the meridian of Vienna. The ephemerides of Vienna started for the year 1757 upon the model of the Abbé de la Caille of France. *Canon of Eclipses* (Figure 21) by Theodor Ritter von Oppolzer (1841–1886) was one of the famous books written at Vienna Observatory (Universitat Wien, 2018).

4.8 Milan, Italy

In 1774 the *Ephemerides of Milan* for 1775 appeared and the series continued into the late nineteenth century.

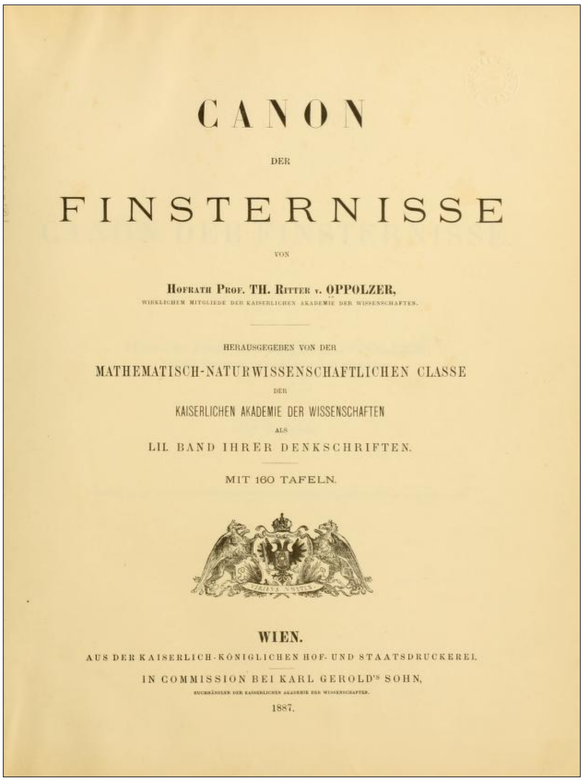
4.9 Portugal

The Portuguese ephemerides began in 1799 (Astronomical Almanacs III, 1873).

Figure 20: Boris Numerov (https://en.wikipedia.org/wiki/Boris_Numerov#/media/File:%D0%9D%D1%83%D0%BC%D0%B5%D1%80%D0%BE%D0%B2_%D0%91%D0%92.jpg).

4.10 The Jet Propulsion Laboratory (JPL)

In the 1960s JPL began a program of Development Ephemerides by numerical integration of the Solar System planets and a lunar ephemeris. The main purpose was for radar observations and to determine improved ephemerides for planetary missions. They collected available optical observations to be fitted with the ephemerides. When retroreflectors were placed on the Moon (see Figure 22), significant improvements of the lunar ephemeris were possible (e.g. see Bender et al., 1973). They produced a series of improving Development Ephemerides over the years. In 1976 a new reference system, including astronomical constants, time scales, star catalog, and ephemerides was adopted. Development Ephemerides/Lunar Ephemeris (DE200/LE200) was adopted as the international ephemerides and introduced in 1984. Since then, improved ephemerides have been adopted as international standards (Standish et al., 1992; Standish and Williams, 2012) and JPL continues



CANON
DER
FINSTERNISSE
VON
HOFRATH PROF. TH. RITTER v. OPPOLZER,
HERAUSGEGEBEN VON DER
MATHEMATISCH-NATURWISSENSCHAFTLICHEN CLASSE
DER
KAISERLICHEN AKADEMIE DER WISSENSCHAFTEN
ALS
LII. BAND IHRER DENKSCHRIFTEN.
MIT 160 TAFELN.
WIEN.
AUS DER KAISERLICH-KÖNIGLICHEN HOF- UND STAATSDRUCKEREI.
IN COMMISSION BEI KARL GEROLD'S SOHN,
1887.

Figure 21: Title page of the Canon of Eclipses, 1887 (https://archive.org/details/canonderfinstern00oppo/page/n5).

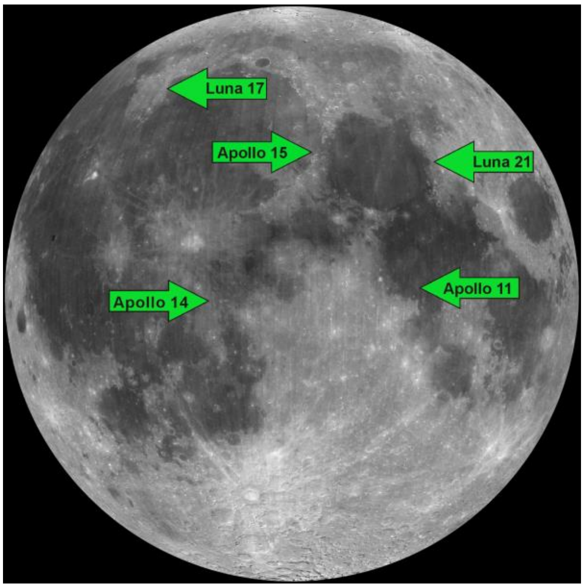


Figure 22: Locations of the retroreflectors left on the Moon during various Apollo and Luna missions (https://ilrs.cddis.eosdis.nasa.gov/images/figure1_reflectors.jpg).

to develop improved ephemerides (Folkner et al., 2014).

4.11 Massachusetts Institute of Technology (MIT)

In the 1960s MIT began a program of determining Solar System ephemerides in parallel with JPL for radar observations. The two programs competed for a number of years and did some comparisons to establish the accuracies of the ephemerides (Ash et al., 1996; 19967).

5 MERIDIANS

Each country used their own prime meridian for geographic locations until the International Meridian Conference in Washington in October 1884 (Bartky, 2007; Howse, 1980). The meridian passing through the center of the transit instrument at the Observatory in Greenwich was adopted as the initial meridian for longitude (Figure 23). Longitude was to be counted in two directions up to 180 degrees, east longitude being positive and west longitude being negative. The mean solar day was to begin at midnight on the initial meridian (*Explanatory Supplement*, 1961). Until computers required the use of plus and minus values, W and E were generally used to designate West and East longitudes. Since the relationship between local meridians in distant countries and Greenwich could not be accurately determined, many countries continued to use their own prime meridian for geographical positions and the Greenwich meridian for navigation. Over the years with better determinations of the distances and adoption of international cooperation, the Greenwich meridian was adopted as the international standard for longitudes and time scales.

With the availability of GPS receivers in the 1990s people could hold a receiver on the Greenwich prime meridian and discover the receiver did not read zero (see Figure 23). The zero meridian was in fact 102 meters to the east. In 1984 the BIH changed from astronomical coordinates to geodetic coordinates for geographical locations. The Earth Orientation observations had changed from optical astronomical observations to Very Long Baseline Interferometry (VLBI) radio observations and lunar and satellite laser measurements. The difference between the two coordinate systems is the Deflection of the Vertical at each location, and at Greenwich that difference is 102 meters (Malys et al., 2015).

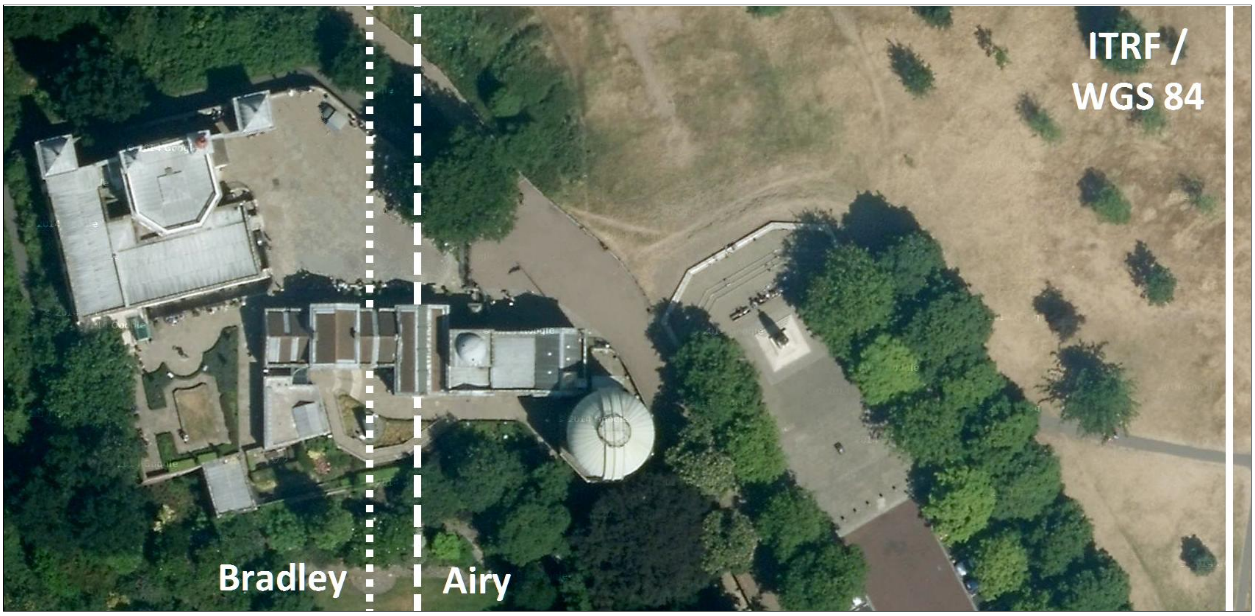


Figure 23: The Airy meridian (dashed line) adopted by the 1884 Meridian Conference and the actual ITRF zero meridian (solid line) (imagery copyright 2014 Google Maps. Infoterra Ltd & Bluesky).

6 INTERNATIONAL COOPERATION

In May 1896 the Conference Internationale des Étoiles Fondamentales was held in Paris. Resolutions concerning the fundamental catalogue, calculation of apparent places of stars, and nutation, aberration and solar parallax fundamental constants were adopted. Also Newcomb's definitive values of luni-solar and planetary precession were agreed upon. The Congrès International des Éphémérides Astronomiques at Paris Observatory in 1911 (Figure 24) was the beginning of active cooperation between the national ephemerides offices. Distribution of calculations between the ephemerides offices of France, Germany, Great Britain, Spain, and the United States, and exchanges of data were recommended. Official approval of the recommendations was required in some cases.

CONGRÈS INTERNATIONAL

DES

ÉPHÉMÉRIDES ASTRONOMIQUES.

INTRODUCTION.

L'extrait suivant du registre des procès-verbaux des séances du Bureau des Longitudes fixe les origines officielles du *Congrès international des Éphémérides astronomiques;* déjà, d'ailleurs, dans des séances antérieures, M. H. Andoyer avait attiré l'attention du Bureau sur l'opportunité d'une telle réunion.

Extrait du procès-verbal de la séance du 5 *avril* 1911.

M. le Président souhaite la bienvenue à Sir David Gill et à M. W. Foerster, qui assistent à la séance.

Sur la proposition de M. le Président, la discussion est ouverte sur la question des éphémérides des étoiles fondamentales. M. Baillaud expose qu'en réunissant les catalogues de MM. Auwers, Boss, Newcomb, Backlund et Hough, il y a environ 3000 étoiles qu'on peut considérer comme fondamentales, et qui seront observées dorénavant chacune un grand nombre de fois. Il serait utile d'avoir les réductions au jour pour ces étoiles calculées à l'avance; et, à cet effet, les directeurs des différentes éphémérides pourraient s'entendre pour partager le travail.

M. Gill approuve cette proposition.

M. Foerster dit que M. F. Cohn est très favorable, lui aussi, à cette proposition.

Figure 24: First page of the Discussion in the report of the Congrès International des Éphémérides Astronomiques, published in the *Annales du Bureau des Longitudes*, Volume 9, page A3 (1913).

The International Astronomical Union was founded in 1919 and Commission 4 (Ephemerides) provided formal contacts among the directors of the national ephemerides offices. In 1938 Commission 4 recommended the single publication of the Apparent Places of Fundamental Stars, which avoided duplicate calculations and publications. Further cooperation has continued as specified for the different countries (*Explanatory Supplement*, 1961).

7 WORLD WAR II

As discussed under Germany above, Nautical Almanac data were provided by the US and British to Germany through Sweden for the purposes of safe navigation. During the war some of the sharing of computations by the countries was suspended and countries had to do their own computations of additional data. After the war a number of astronomers migrated to Western countries to continue their careers and provide scientific expertise. Radar capabilities developed for the war found scientific applications in astronomy and led to the field of radio astronomy (see Sullivan, 2009).

8 THE COLD WAR

During the 'Cold War' international exchanges of almanacs, ephemerides, and observations continued. The US Nautical Almanac Office provided copies of the almanac data and ephemerides to the Institute of Theoretical Astronomy in Leningrad. It was recognized that a number of observatories in Eastern Europe gave incorrect longitudes and latitudes for their locations. In some cases occultation observations were reported, in which cases it was possible to determine the accurate locations of the observatories from the observations.

9 ACKNOWLEDGEMENTS

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P. Kenneth Seidelmann received an Electrical Engineering and a Ph.D. in Dynamical Astronomy (1968) from the University of Cincinnati. After military service as a Research and Development Coordinator at the U.S. Army Missile Command (1963–1965), he joined the Nautical Almanac Office of the U.S. Naval Observatory, and in February 1976 became Director of the Office. In September 1990, the Nautical Almanac Office was reorganized into two departments and he became Director of the Orbital Mechanics Department. In June 1994, the U.S. Naval Observatory was reorganized and Dr Seidelmann became Director of the Directorate of Astrometry, which included three departments dealing with astrometry and astronomical data. In 2000 he retired from the U.S. Naval Observatory and became a Research Professor in the Astronomy Department of the University of Virginia.

He has taught courses in Celestial Mechanics at the Catholic University of America and the University of Maryland. He has co-authored three books: *Fundamentals of Astrometry* (2004, Cambridge University Press; co-authored by J. Kovalevsky); *Time: From Earth Rotation to Atomic Physics* (2009, Wiley-VCH; 2018, 2nd Edition, Cambridge University Press; co-authored by D.D. McCarthy) and *Celestial Mechanics and Astrodynamics: Theory and Practice* (2016, Springer; co-authored by P. Gurfil), and is co-editor of the *Explanatory Supplement to the Astronomical Almanac* (University Science Books; co-edited by S.E. Urban).

In 1994 P. Kenneth Seidelmann hosted the US Russian Orbit Determination and Prediction Workshop. He has been the General Chairman of the Second (1996) through Ninth (2012) US Russian Space Surveillance Workshops. He was the General Chairman of the US China Space Surveillance Technical Interchanges in 2009, 2011, and 2013.

Dr Seidelmann is a member of the International Astronomical Union, American Astronomical Society, American Institute of Astronautics and Aeronautics, and a Fellow of the American Association for the Advancement of Science, the Institute of Navigation, and the Royal Astronomical Society.

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POWER, POLITICS AND PERSONALITIES IN AUSTRALIAN ASTRONOMY: WILLIAM ERNEST COOKE AND THE TRIANGULATION OF THE PACIFIC BY WIRELESS TIME SIGNALS

Ian Tasker
University of Western Sydney, Locked Bag 1797, Penrith, NSW 2751, Australia.
ian.tasker@westernsydney.edu.au

Abstract: In 1916 the New South Wales Government Astronomer, Professor Ernest Cooke, proposed the triangulation of the Pacific by wireless time signals, in order to improve mapping. The world was at war, and this scientific advancement was urgently required. The State Government gave Cooke authority to proceed, but later rescinded this decision. It also prevented Cooke from attending the first International Astronomical Union (IAU) General Assembly in Rome in 1919. Although Cooke became Chairman of the Longitude Committee of the Australian National Research Council in 1922, attended the Pan-Pacific Science Association Congress in 1923, joined the IAU's Commission 18 (Longitude by Wireless) in 1925, and continued to promote triangulation of the Pacific by wireless, the Sydney Observatory Board of Visitors, bureaucrats and politicians all continued to block him. This paper examines the interplay between Federal and State politics in international astronomy, using Cooke's triangulation of the Pacific project as a case study.

Keywords: Sydney Observatory, W.E. Cooke, Board of Visitors, triangulation of the Pacific, wireless time signals, State-Federal politics

1 INTRODUCTION

Power, politics and personalities often are intricately intertwined in science, allowing some scientists continuing success and others continual disappointments. Even excellent projects promoted in the public good and proposed at auspicious times—e.g. during wartime—can fail to gain official approval and funding if certain determining factors intervene. This paper is about such a case, Professor William Ernest Cooke's desire to get Sydney Observatory involved in a strategic military project, the triangulation of the Pacific by wireless time signals during World War I (henceforth WWI).

A number of episodes occurred in Australia astronomy at the apex of colonial science in the midst of WWI and its aftermath that are central to our current understanding of the relationship that an Observatory Director, such as Cooke, had with his superiors. The episode being scrutinised here is the 'insufficient authority' of Cooke in internationally managed science that, under the Australian Constitution, should have been a Federal matter.

Firstly, it is noted that Cooke appointed Sydney Observatory's Board of Visitors to support his efforts to triangulate the Pacific by wireless time signals. Cooke had hoped to solicit their combined influence and support to encourage the NSW Government to allow this scientific venture to proceed. The Board, however, had its own agenda and was of no assistance in furthering astronomical interests with this technologically innovative professional.

Secondly, to contrast the original war-time effort, the effects of the 1923 Pan-Pacific Science Association Congress are considered. Cooke presented the same scientific proposal that he had put forward in 1916, although on this occasion he gained the public support of visiting international peers and favourable media attention. Cooke was the President of the Astronomy Section and Chairman of the Longitude Committee for the Australian National Research Council, leading up to and organising the Pan-Pacific Science Association Congress program. This public exposure still proved ineffective in gaining Government support for triangulating the Pacific, although it did cultivate the soil for future efforts.

Thirdly, Cooke's influence in the IAU General Assembly Commission 18: Longitude by Wireless, up until his forced retirement in 1926, is examined. A few months after Cooke's departure, international wireless time signals connected Australia with the rest of the world. However, Cooke's 1926 demise, requires a more comprehensive treatment, which is beyond the scope of this paper.

Fourthly, the manner in which Cooke handed over the international time signal project to his replacement, the former distinguished amateur astronomer and Director General of Technical Education, James Nangle, and William Raymond, the Chief Transit Observer at Sydney Observatory, is detailed.

Finally, it is noted that when authority and funding decisions are placed in the hands of politically motivated individuals rather than scientists, the latter are sometimes unable to pursue their science uninhibited.

Before examining the aforementioned topics in detail we provide background information on Sydney Observatory and a biographical sketch of W.E. Cooke. Australian localities mentioned in this paper are shown in Figure 1.

1.1 A Brief History of Sydney Observatory, 1858–1912

Sydney Observatory, along with several other colonial observatories, was established in the mid-nineteenth century, as part of the imperial science agenda of the British Government (Haynes et al., 1996: 69–95). In its early years, the primary purpose of Sydney Observatory was to provide a time service for both the shipping and business communities. It also offered meteorological and trigonometric functions to the inhabitants of the colony of New South Wales (henceforth NSW) and conducted astronomical research (Wood, 1958).

In order to understand the relationship between Cooke and Sydney Observatory, it is useful to gain a sense of the history of the Observatory and the impact of its various directors and their research programs, prior to Cooke's time, to appreciate the context in which he operated.

Sydney Observatory (Figure 2) opened in 1858, mainly as a result of several years of relentless lobbying by New South Wales' sole astronomer of that time with any international visibility, Phillip Parker King (1791–1856; Orchiston, 1988a) and Sir William Denison (1804–1871), the new Governor of New South Wales. The inaugural Director was the Reverend William Scott (1825–1917; Orchiston, 1998b), a British academic who was not a professionally trained astronomer. It was not until the new Merz 7.25-in (18.4-cm) refractor was mounted in 1861 that observational astronomy actually commenced (e.g. see Orchiston, 1998b; 2017: 144–156). Scott took a broad approach to astronomy, instigating astronomical and non-astronomical programs. In the astronomical sphere, he made cometary and transit observations, and in 1861 recorded a partial solar eclipse and a transit of Mercury. In other fields, he was responsible for regulating Sydney's time service, making meteorological measurements and recording sea water temperatures. Scott was also involved in the telegraphic determination of the Observatory's longitude, an early antecedent to Cooke's proposal to triangulate the Pacific.

Scott's successor was fellow-Britain George Robarts Smalley (1822–1870), who was Director from 1863 to 1870. During Smalley's time, astronomy deteriorated, as his interests were largely non-astronomical. He focused on meteorological, magnetic and tidal measurements, although he occasionally observed comets (Orchiston, 1988b; Russell, 1871; Wood, 1958).

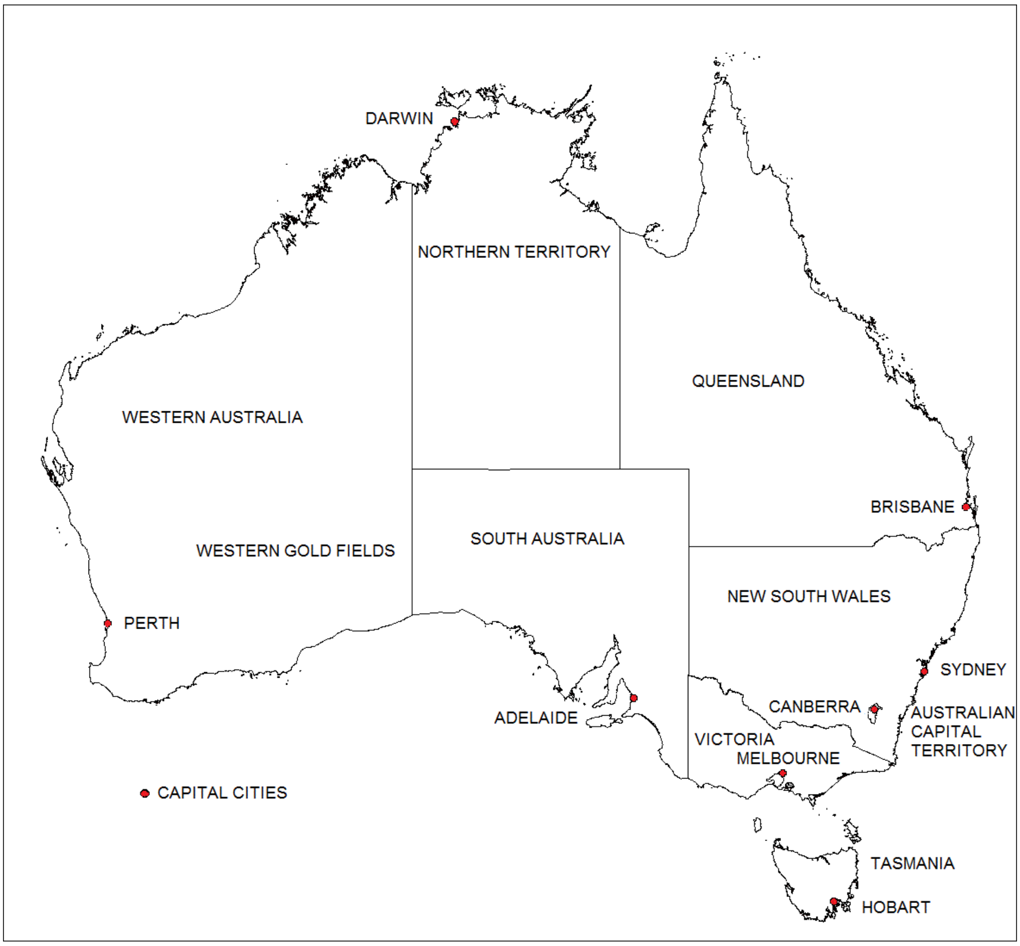

Figure 1: Australian localities mentioned in the text (map: Ian Tasker).

It was not until Henry Chamberlain Russell (1836–1907; Bhathal, 1991) became Director in 1870 that Sydney Observatory came into its own as an astronomical institution (Orchiston, 1988b; Wood, 1958). Russell's impact on Australian astronomy was felt during the last three decades of the nineteenth century, up to his retirement in 1905. Even though he continued the non-astronomical work of his predecessors, it was with the introduction of new instruments, such as a 6-in (15.2-cm) transit telescope, an 11.5-in (29.2-cm) refractor and a 13-in (33-cm) astrograph (Russell, 1892a), that astronomical research flourished. Russell also initiated an important double star project; conducted cometary work (e.g. see Russell, 1881) and meridian observations; led a solar eclipse party to northern Australia (Lomb, 2016); and organised groups to observe the various transits of Mercury and of Venus (e.g. see Lomb, 2011; Russell, 1892b). At Red Hill, away from city lights, he set up a field station of the Observatory for the Sydney section of the International Astrographic Project (Wood, 1858). Significantly, Russell independently invented the horseshoe telescope mounting (Orchiston, 2000), a design that would later benefit international astronomy.

Russell was also a member of the Senate of his *alma mater* at Sydney University for over three decades (Wood, 1958). He was a founder of the Royal Society of New South Wales' Section A (Orchiston and Bhathal, 1991) and of the Australasian Association for the Advancement of Science (MacLeod, 1988), but during the last decade of the nineteenth century became estranged from most of those in the large powerful Sydney-based amateur astronomical community (e.g. see Orchiston, 2017: 393–448; Tebbutt, 1891).

The analysis of Australia's earliest astronomical groups and societies illustrate some of the crucial elements in the development of an emerging discipline (Orchiston, 1998a). Building upon this work, several new elements are introduced and discussed in this paper, including the significance and influence of external stakeholders and their role in Australian astronomy.

At the beginning of the twentieth century, the newly formed Commonwealth Government of Australia assumed responsibility for meteorology, but not astronomy. As a result, Sydney Observatory and the other Australian State observatories lost one of their most public utilities, forecasting the weather (Home and Livingston, 1994).

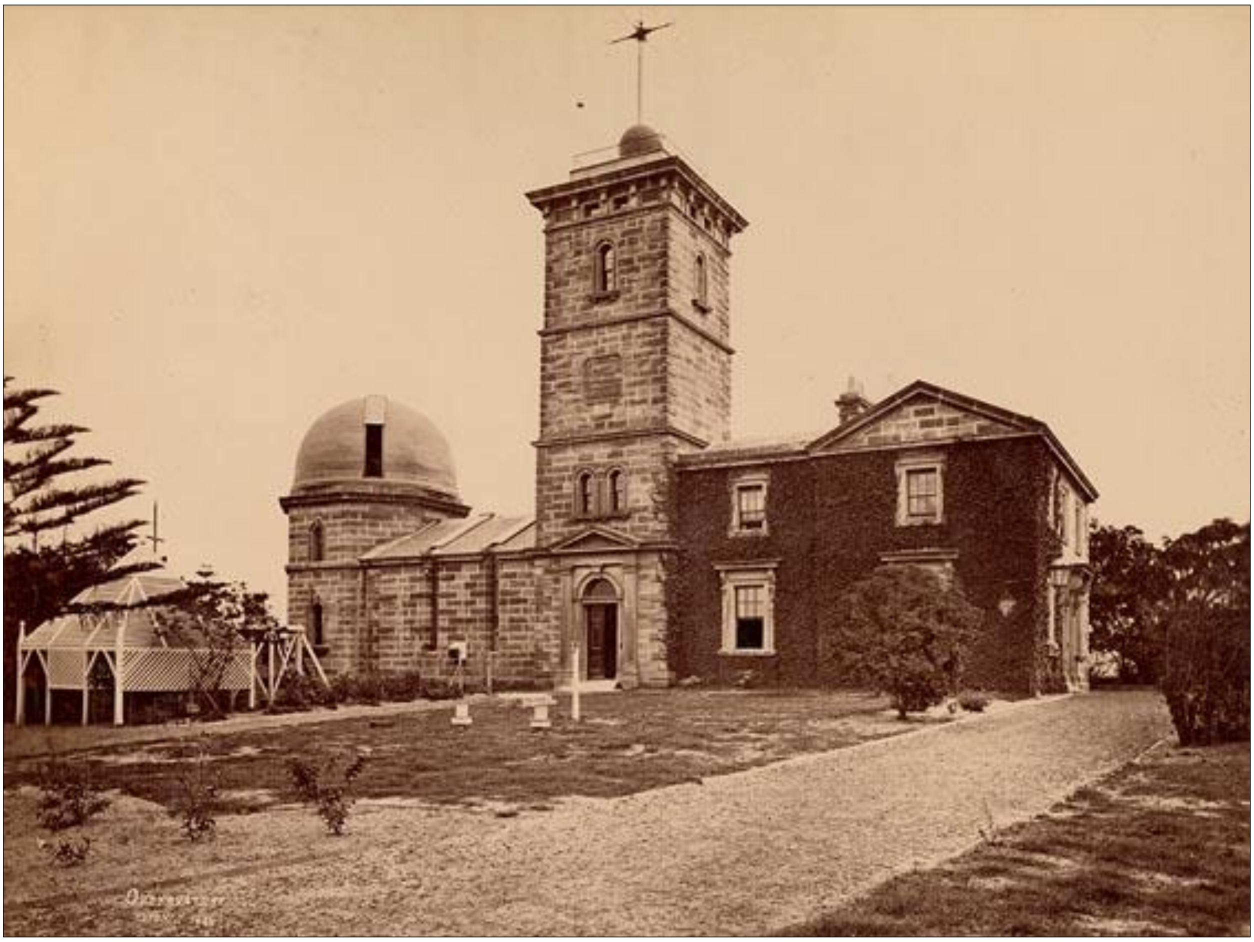

Figure 2: Sydney Observatory in 1874. By the time Cooke began as Government Astronomer of New South Wales the left hand dome housed an 11.5-in (29.2-cm) Schroeder refractor. The section of the building to the right of the time-ball tower was the Government Astronomer's residence (https://en.wikipedia.org/wiki/Sydney_Observatory#/media/File:ObservatorySydney1874.jpg).

In the final period before Cooke's term, 1903 to 1912, Sydney Observatory had two Directors, Henry Lenehan and William Raymond. They continued established programs, including solar eclipse expeditions (see Orchiston, 1988b; Wood, 1958).

It was Cooke's appointment in 1912 as the next Government Astronomer that was to put Sydney Observatory back on the international stage, in a deliberate move by the Public Service Board (*Investigation*…, 1909) to place New South Wales ahead of other Australian State observatories.

1.2 W.E. Cooke: A Biographical Sketch

William Ernest Cooke (1863–1947; Figure 3; Hutchison, 1980; 1981), more commonly known as W. Ernest Cooke or simply Ernest Cooke, was born in Adelaide (South Australia) on 25 July 1863. He excelled at The Collegiate School of St Peter and in 1878 commenced a Civil Service cadetship at Adelaide Observatory under Sir Charles Todd (1826–1910); he was

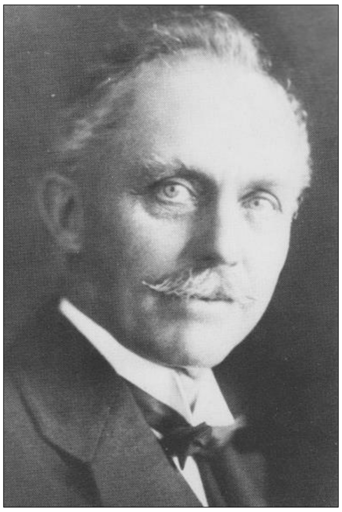

Figure 3: W.E. Cooke (after Hutchison. 1981: 58).

only 15 years old. In 1883 and 1889 Cooke received BA and MA degrees from the University of Adelaide. He then became the founding Director of Perth Observatory in Western Australia, on Todd's recommendation (Utting, 1989), and toured continental cities to study observatory design and to purchase instruments. He arrived back in Perth in 1896, just 33 years old, promoting meteorological, geodesy and wireless innovations.

Cooke produced the first daily weather maps and daily forecasts for Perth, the 'Western Gold Fields' and the State. By around 1900 a general weather report, a special rainfall report, an isobar map and a forecast were produced each morning and posted for viewing in Perth and its port, Fremantle. He also established the first official time service on his arrival in Perth. Using a chronometer and a borrowed theodolite, he determined accurate solar time daily, clear skies permitting, and a time signal was telegraphed to the General Post Office at noon each day (Hutchison, 1980).

Around 1901, the International Astrographic Congress asked Perth Observatory to collaborate on the international star cataloguing and charting project, the *International Photo-Durchmusterung* or *Cape Photographic Durchmusterung* (*CPD*). Perth Observatory's allocation was 32°–40° south latitudes, and *A Catalogue of 420 Standard Stars* was subsequently published (Cooke, 1907). Cooke produced a critique of the international program, referring to lack of coordination, refinements that he had made in observation methods and suggesting procedures to be used at other sites around the world. As a result, he received wide acclaim from his international peers. The Astronomer Royal of Scotland, Frank Watson Dyson (1868–1939), wrote to the Government Astronomer in Adelaide—where Cooke had undertaken his cadetship with Sir Charles Todd—advising that they were

> … to follow the head of the Perth Observatory implicitly … [and] copy their methods, their catalogues are excellent, and they seem to be able to maintain maximum efficiency with the minimum of energy. (cited in Hutchison, 1981: 67).

Here is seen an example of where the student had become the teacher.

During his time in Western Australia Cooke was the founding Chairman of the Civil Service Association (in 1902), and he also served as the Government Meteorologist until 1908 (Hutchison, 1980).

Cooke later attended the International Astrographic Conference in Paris in 1909, now aged 46, and he presented his ideas before the Congress (see Cooke, 1911). Cooke joined their ranks as one of the 18 members of the Permanent Committee of the Congress. Six volumes of meridian observations were published by 1913 as part of the Astrographic Catalogue (henceforth AC) (Utting, 1989; White, 1988). These were based on photographs taken and measured at Perth Observatory under Cooke's direction, and contained the positions of about 9,000 reference stars between declinations –31° and –41°.

Cooke was then enticed by the NSW Government to accept a dual role as NSW Government Astronomer and Professor of Astronomy at Sydney University, and was promised another investigative world tour, a dark sky site for the Observatory and the latest astronomical equipment (Cooke, 1913).

Cooke's success at Perth Observatory partly stemmed from the childhood influence in Adelaide of his father Ebenezer Cooke (1832–1907; Hawker, 2006), who was the perfect role model. Cooke Senior was possibly the most influential South Australian public servant of his time, in his position as the Commissioner of Audit. Cooke Senior advised the Government on a wide range of matters, in addition to book-keeping and auditing procedures. He played a valuable role in revealing financial swindles connected with the system of tenders for Government contracts. Cooke Senior also served as Chairman of several interdepartmental committees and supported the formation of the Public Service Association in 1884, serving as its inaugural President and as a member of its governing Council for five years (ibid.). While Ernest Cooke shared many of his father's attributes, these would not be enough to bring him the success he anticipated when he chose to accept the Sydney appointment in 1912—as the events portrayed in this paper will reveal.

2 COOKE'S FAILED ATTEMPT IN 1916 TO TRIANGULATE THE PACIFIC BY WIRELESS TIME SIGNALS

The problematic relationship that Professor Cooke had with his superiors provides critical insights into the man and those who governed him. Their assistance, once given, was condiional and could be withdrawn. In the end, Cooke's superiors were prepared to sacrifice him for political expediency. This paper focusses on the 'insufficient authority' of a State Observatory Director in internationally managed science, in this case the triangulation of the Pacific by wireless time signals. Cooke had much to contribute to the international war effort but was hampered by the political impediments placed in his path.

Triangulation is a process of measuring the time difference between several stations that are looking at the same star as it passes overhead, with the first station recording its passage and transmitting this to the second station, which then confirms when the star crosses their zenith. Probable errors are reduced, and the accuracy in determining the location of each observatory improves, as more stations are connected around the globe.

When Cooke was the NSW Government Astronomer, he requested that the Sydney Observatory Board of Visitors be reformed, and he nominated its members. He aimed to gain their considerable combined influence and political astuteness, to encourage the Government to let him proceed with experiments and fulfil the Government's initial promises that secured his employment in 1912. The Board's minutes and official correspondence, as primary sources, provide a fascinating insight into their charged interplay, for matters did not play out as Cooke had anticipated.

Cooke's peers, Australian university academics, were distinguishing themselves abroad in their wartime service, while Australia made only limited contributions to the fields of science and technology during that period. There are many examples of their contributions (e.g. see Endacott, 2014; Hartcup, 1988). Professor Sir William Bragg focussed on problems of submarine detection. His son, also a Professor and Knight, led a team that designed a method of sound-ranging enemy artillery batteries. Professor Sir Richard Threlfall was engaged in research on tracer ammunition and phosphorus in smoke screens. Professor Sir Edgeworth David led the mining corps. Professors Hubert Whitfield and Norman Wilsmore worked with British munitions producers. Honorary Lieutenant-Colonel Sir Samuel Barraclough led the Australian Munitions Workers in England and France. Professor Major James Pollock, a physicist, created a geotelephone for underground listening.

Cooke's 'limited authority' to carry out a triangulation of the Pacific proved futile, even though the results would have contributed to the war effort. Throughout the 1916 negotiations, Cooke's proposal remained unactioned, as the NSW Government rescinded the authority to proceed that it had initially granted him. What follows is an account of the minutia of the requests for authorisation that Cooke was forced to make from numerous parties, and whether this authority was ever granted or not.

In a casual conversation, the Chairman of the NSW Public Service Board, John Taylor, suggested to Cooke that he might be able to make good use of Henry Spendlove Hawkins. Hawkins (1824–1888) was the former Head of the Fieldwork of the Trigonometrical Survey of NSW, with unique qualifications (Cooke, 1916q: 397; Government Gazette, 1880: 5; Hawkins, 1876; 1881; Orchiston, 1987; 2017: 154). The NSW Surveyor General, Frederick Poate (1855–1935; Figure 4), proposed, partly in the interests of economy, to discontinue the geodetic survey for a couple of years or so as the fieldwork component of the survey had run considerably ahead of computations (Cooke, 1916b: 280). This freed up Hawkins, who could now work on other Government projects.

Cooke followed up on Taylor's lead when he wrote to Poate on the 8 June 1916 and then to the Under Secretary for Education on the 15 June (ibid.; Cooke, 1916e: 288). Poate was a Fellow of both the Royal Society (from 1881) and the Royal Astronomical Society (from 1912). Poate was at that time a PSB Actuary, Director of Trigonometric Surveys and Metropolitan District Surveyor with the NSW Department of Lands,

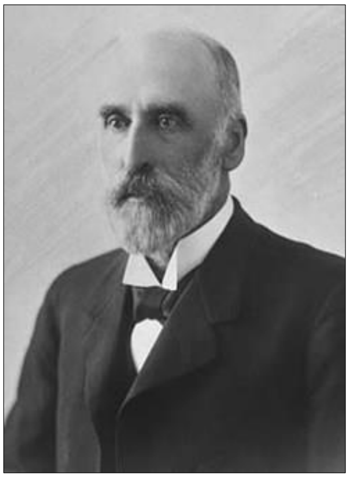

Figure 4: Frederick Poate in 1916, recorded by an unknown photographer (courtesy: State Library of New South Wales, FL1864557).

as well as a Lecturer in Geodesy and Astronomy at the University of Sydney (Atchison, 1988). At the same time, Cooke, also a FRAS, was the Foundation Professor of Astronomy at the University of Sydney.

Cooke's appeal for funding considered the fact that, in May 1912, Poate had attended a conference with the Commonwealth Directors of Lands and Survey and the Survey Generals of the Australian states, and taken an active part at that meeting. This conference decided that the compilation of the map of the world would probably be done in NSW (Kass, 2008: 275).

Poate's reply (see *Simple Practical Astronomy*, 1940: 19) informed Cooke that the Minister for Lands, (William Ashford) was sympathetic to the proposition to triangulate the Pacific and would support it to the extent of £750[1] per annum, provided the Observatory could raise a further £400 per annum. Poate was about to retire and wished that the work would commence within his last three months of work, adding that it would be a "… crowning jewel to his career."

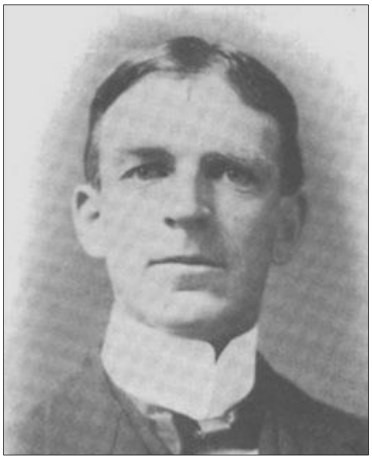

Figure 5: W.W. Campbell (after Macpherson, 1905: facing 240).

Cooke then wrote to the Marconi Wireless Telegraph Company of America. Marconi was in charge of the radio station at Honolulu. Hawaii and Fiji were to be the intermediates between America and Australia with New Zealand (henceforth NZ). Cooke began proceedings before Poate's retirement, with the provision that he had

> … to secure the assistance of several gentlemen, and may encounter a fatal obstacle since a three-month time limit had been assigned to commence this project. (Cooke, 1916d: 292).

Likewise, Cooke contacted Professor William Wallace Campbell (1862–1938; Figure 5), Director of Lick Observatory in California. He noted that, as

> … before completing any arrangements as I shall have to secure assistance in various quarters, I may experience a check, but at present, the way seems, so far, open. (Cooke, 1916c: 294).

For this particular section, Cooke's official correspondence is cited so that the reader may hear his voice, to gain a feel for the man and his plight.

Cooke, after a conversation with Layton, an Associate of the Sydney Town Clerk, then asked the Town Clerk to obtain permission to extend their wireless aerial and fasten the ends of two of them to two Moreton Bay Fig trees just outside the southern fence of the Observatory (Cooke, 1916f: 306). Nearly four months earlier, Cooke (1916a: 131) had informed the Town Clerk that

> … our wireless house has not been used since the commencement of the war, owing to instructions received from the Defence Department to disconnect our instruments.

Despite this instruction, Cooke (1916ae: 15) had previously informed the Under Secretary for Education, when he submitted the Sydney Observatory's report for 1915, that:

> Owing to the war no further developments in connection with wireless time signalling were possible on account of military regulations, but a fair amount of experimental work has been carried out.

At the beginning of July, Cooke (1916j: 309) asked the Under Secretary for Education for authority, along with a letter of introduction from the Premier of NSW, to visit Lieutenant William Rooke Creswell (1852–1933) in Melbourne, the naval head of all wireless operations in Australian waters, to obtain his consent and cooperation.

Cooke then began engaging with NZ and Fijian authorities. He wrote to John Strauchon (1848–1934), NZ Surveyor General, and Timothy Buckley, Chief Electrician of the NZ Post and

Telegraph Department, along with Cecil Charles Fisk Monckton (b. 1867), Superintendent of Telegraphs for Fiji. He echoed that

> … provided I can put this scheme into operation within the next three months or so … [but] I have yet to obtain the consent of several people ... so there is not at present any certainty of the proposition being carried out. (Cooke, 1916i: 321).

Finally, he announced that

> The N.S.W. Government has now authorised me to proceed … [and] It happens to be essential for me to start very soon, if at all, as my opportunity will slip and may not easily recur. (Cooke, 1916g: 322–323).

He added:

> I'm afraid the matter is very urgent. That is to say; I shall lose the opportunity unless I can get started within a month or two at the outside. (Cooke, 1916h: 325).

So authorised to undertake this international collaboration, Cooke still had to ask the Under Secretary to kindly issue him a first-class return railway pass from Sydney to Melbourne, and two sleeping berths, to attend to matters relating to the proposed longitude determination work (Cooke, 1916j: 326). Cooke may or may not have made his way to Victoria, but what is evident is that Governmental structures were quite centralised at the time.

After Cooke met with Lieutenant Creswell, who was visiting Sydney, he wrote to the Naval Secretary in Melbourne, apprising him of the Premier's instructions, leading to the following appeal:

> I have been instructed by the Premier of N.S.W. to undertake a determination of the difference of longitude between Sydney and an America Observatory (probably Lick) by means of wireless time signals across the Pacific. For this purpose, I shall require your consent, and I hope also to enlist your sympathy and co-operation. (Cooke, 1916l: 344).

Separately, Cooke also asked the Naval Secretary to give his consent to the carrying out of experiments with his two sons' invention that, if successful, would be offered to the British Military authorities. He gave no further details on what the invention entailed, as was proper during wartime, other than that the designs had been been submitted to the Chief Electrical Engineer of the NSW Railway Department, who had approved trials. As part of this work, it would be necessary to erect a couple of small aerials to perform a few simple wireless experiments (Cooke, 1916l: 346). Cooke secured the Naval Secretary's consent to perform the said experiments, and the Town Clerk's permission to attach wires to the fig trees was thus forthcoming (Cooke, 1916n: 366).

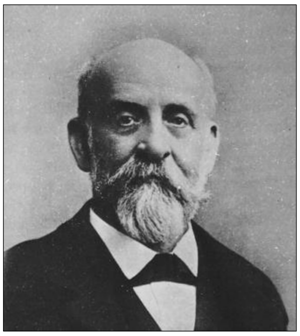

Figure 6: Dr C.E. Adams, New Zealand's first Government Astronomer (Orchiston Collection).

Cooke also extended his invitations to participate in the project to other Government Astronomers: Dr Charles Edward Adams (1870–1945; Figure 6) in New Zealand, Dr Joseph Mason Baldwin (1878–1945) in Victoria, and George Frederick Dodwell (1879–1963; Figure 7) in South Australia, reiterating that:

> Owing to readjustments in the Lands dept., I have been offered the services of a small well-equipped field party for an indefinite period, provided I can take it up almost immediately. (Cooke, 1916k: 348).

In early July, Frank Basil Cooke (1892–1967), Professor Cooke's son, who had been at Sydney Observatory for nearly three years, finally received notification of his appointment as Junior Assistant. Nevertheless, an appropriate increase of salary was not forthcoming. The file dealing with this matter is missing.

Cooke Junior was 23 at the time and received £60 per annum (Cooke, 1916j: 327). As a professional astronomer, Cooke Junior, with his advanced skill set, was poorly compensated. In Victoria, in 1910, the average yearly factory worker's wage for a male was £157 16s 8d and a female £70 17s 5d. In 1920, on average a man was earning £204 15s 9d per annum and a woman £99 1s 6d (State Library Victoria, 2017).

Figure 7: Adelaide Observatory Director G.F. Dodwell in about 1926 (https://de.wikipedia. org/wiki/George_F_Dodwell#/media/File:G_F_Dodwell_1926.png).

By mid-July, Cooke wrote to the Under Secretary for Public Instruction.[2] The Under Secretary, who Cooke never names, reported to the Minister of Education, who at the time was Arthur Hill Griffith (1861–1946). Cooke (1916m: 358) stated:

> I wish to appoint the assistant at once. I propose that the salary be £200 with a £50 allowance. That will leave £150 of the £400 authorised by the Premier for the necessary travelling and incidental expenses. Will you kindly authorise the appointment to be placed in the hands of the Public Service Board immediately

Cooke (1916q: 398) informed John M. Taylor, Chairman of the PSB and inaugural President of the Wireless Institute, when

> … deprecating any further delay in connection with the proposed wireless longitude and latitude work … [that] my son, who I suppose will be the assistant from the Observatory side. Cooke Junior has been most enthusiastically developing the technical part of the work.

Incidentally, this would have meant an increase in salary for Cooke's son from £60 per annum to £200, which was more than a threefold increase, plus a £50 expense account.[3]

Cooke Junior was the only viable contender in Australia for the Assistant's role, as there were no other applicants. However, the PSB responded by sidestepping Cooke Junior's appointment. Instead, they perpetuated the unresolved Constitutional debate regarding the Federal Government's responsibility to manage international research efforts such as astronomy. This was despite the fact that there was no central astronomical agency in place at the time and this particular collaboration was trigonometrical. It has always been a State obligation to establish its borders even if this required linking them to an international trigonometrical effort, as evidenced in *The States of a Nation: The Politics and Surveys of the Australian State Borders* (Taylor, 2006).

Furthermore, Cooke reinforced the fact that the original concept of triangulating the Pacific stemmed from a conversation he and Taylor had. The point was also made that

> … the question of referring it to the Commonwealth Government has already [been] raised and disposed of before authority was granted. (Cooke, 1916r: 407).

Cooke (1916q: 399) reported that "… the newspaper reporters have got on to the project, and it has been made known practically throughout the world."

Cooke (ibid.) closed the correspondence:

> My strong contention is that it is now too late to reconsider the matter of carrying out the scheme. The receipt of the cable from the Marconi Co. this morning practically assures the success of the undertaking, and if it were dropped, except for some new and overwhelming objection, I could never have the assurance to request outside assistance for any future undertaking. It would make the Observatory and myself a laughing stock and cause deep humiliation (after what I have already told you I think you will understand that it would be about the last straw).

The situation, about which Cooke had already told the Under Secretary for Education, was a singular exception in Cooke's manner, at least on record, dated 31 July 1916, in which he was uncharacteristically personal:

> My present position is considerably worse, financially than the one I resigned. In addition, I have lived a dog's life. All interests have been taken away. My tremendous enthusiasm for my work has been slowly strangled, and I have aged 20 years in the last 4. My wife has become a chronic invalid, and my daughter is just drifting about without any chance of domestic pleasures or the usual accomplishments that a young lady expects. She has, in fact, become a household drudge. These are cold facts, not in the least exaggerated. (Cooke, 1916o: 377–378).
>
> For four solid years which ought to have been the best four of my life, I have been wearing out my brains and nerves – not in the work for which I was appointed – but in chasing official papers from pillar to post, begging and imploring those who had the say to fulfil the promises under which I was appointed [*sic*] induced to leave my former life. And now after all this wear and tear, I have brought the undertaking to the present point. The plans are at last prepared. They have been approved from dot to finish by various officials at various times. Authority to go ahead has been given by the Minister of Education, the Premier, and the Minister of Works; and the Premier has provided £3,500 for a start (up to June 30th 1916). Any hitch now will be fatal as far as I am concerned. This is absolutely my last effort. I am utterly down-hearted and cannot make a fresh commencement. Nothing in the world can compensate me for the last four years, but at least I expect some recognition of the promises that lured me here and even belated ratification of them.
>
> My personal honor [*sic*] and that of the State is at stake. A quarter of a century ago Sydney undertook a share in the great International Photo-Durchmusterung; and so far, owing mainly to the want of a suitable site and instruments, the work has been already done, at a total cost of many thousand pounds and a whole generation of workers, has been wasted. (Cooke, 1916q: 378).

During my research I found no evidence of either a reply or a reaction to Cooke's emotional outpouring, and it appears to have been ignored.

Cooke was not above asking for advice from his international peers, such as those at the Naval Observatory in Washington, who had connected Washington with Paris with wireless time signals (see Renan, 1916; Rines, 1916; Home and Watanabe, 1990):

> I should, in any case, be grateful for any information or hints you may be able to give as a result of your experience in the work. (Cooke, 1916p: 383).

Notwithstanding the technical inexperience of Lick Observatory's Professor W.W. Campbell, Cooke hoped he would join him in triangulating the Pacific, using the same technology used in connecting Paris and Washington:

> Whether you eventually co-operate or not I should greatly value your candid (brutal if you like) criticism of my proposed methods. (Cooke, 1916s: 446).

On 16 August 1916, the day the Sydney Observatory Board of Visitors was to have its first meeting, Cooke wrote to the Premier urging him to consider reinstating his previous decision supporting the trigonometric survey. The PSB's principal objection was that they thought the scientific effort was a Commonwealth responsibility (Cooke, 1916r: 407). This position, however, did not take into account that it was up to each State to determine its borders, and the Commonwealth had no resources to undertake the work as only Cooke Junior and Hawkins possessed the skills to do this work—as previously mentioned.

Cooke (1916r: 410) listed eight reasons for continuing the trigonometric project:

> I contend Sir that it is altogether too late to withdraw. I did not move a finger in the matter until it was officially requested of me by one minister and sanctioned by the Premier. Surely this constitutes sufficient authority? If not – then there is no finality at all. Nothing further can ever be undertaken for I shall always have the feeling that after having deeply committed myself the authority will be withdrawn. That would constitute utter demoralisation and prevent any further initiative.

In the light of the evidence provided earlier, Cooke's statement thathe "… did not move a finger …" is somewhat questionable. Cooke had asked for authority in July and then immediately contacted NZ and Fijian authorities.

At the Board's first meeting

> The Government Astronomer outlined the steps he had taken concerning a determination of the longitude of Sydney by means of wireless communication. He regretted that the Public Service Board had raised objections to the carry out this work, and he informed the Board that it would involve only a temporary appointment of a Junior member of the staff in this connection. (Sydney Observatory Board of Visitors, 1916: 3).

As noted earlier, the PSB objected because they saw this as a Commonwealth matter, even though it had always been a State obligation to establish its borders. However, the original project sponsor, Fredrick Poate, had now retired, and John Broughton (1857–1925) had replaced him, not only as Surveyor General but also as a member of the Sydney Observatory Board.

In stark contrast to Poate's industriousness, Broughton invested some of his wife's money in shares in the Royal Sydney Golf Club and NSW Tennis Ltd., clubs of which he was a member (Kass, 2008: 281). Broughton held vastly different interests from those of his predecessor, and Cooke thought of him as a 'dilettante'.

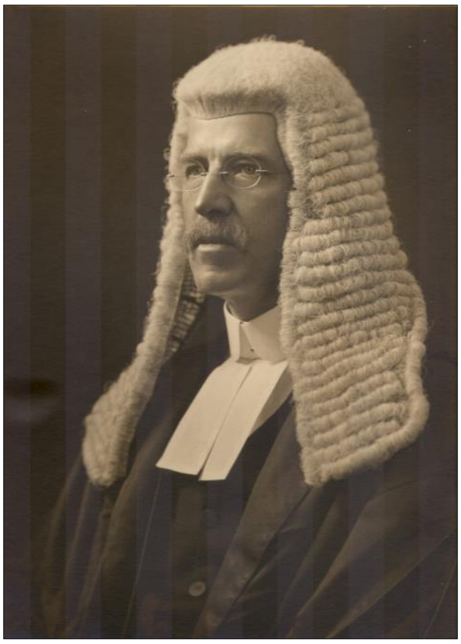

Figure 8: Frank Leverrier in 1900 (courtesy: University of Sydney Archives, G3/224/ 2039).

The Observatory's Board never recommended or supported the triangulation of the Pacific, even though sitting as their Chairman was the lawyer Francis Hewitt (Frank) Leverrier (1863–1940; Figure 8), who also was the President of the Wireless Institute of NSW and therefore would have been aware of the proposal. The Board subsequently held several meetings at the University of Sydney, deliberately excluding Cooke. Eventually, it was decided to refer the matter to the Astronomer Royal (Sydney Observatory Board of Visitors, 1916: 1, 3–4, 6, 8).

When Cooke (1916s: 444) wrote to Professor Campbell at Lick Observatory in September of that year, he not only bemoaned his Government but also forthrightly named his adversary, John Broughton:

> ... but I am afraid that I have lost the opportunity – not in any way through your inability to meet me with an immediate response – but owing to the usual departmental delays which seem to cripple all one's efforts. I have always understood, though without being definitely informed, that the necessity for haste was largely due to the resignation of our late Surveyor General, Mr Poate. It was he who offered me the field party, and who urged an immediate commencement. Both Premier and Minister for Lands were very sympathetic and authorised the necessary expenditure, and I pushed my head as hard as I could against the old stone wall, but it would not budge in time. Now I am finding quite unexpected obstacles, and fear that these indicate a difference of opinion on the part of the new Surveyor General. Just at present I do not know how the matter stands, but believe the Premier still wishes the work to proceed.

Throughout Cooke's correspondence about the scheme, he consistently reiterated that it had to be up and running before Poate's retirement. Cooke never expected to gain Broughton's support. Dr Harley Wood, a later Director of Sydney Observatory, tells a different story, that appears to diverge from the evidence. Financial aid had already been committed by the Minister for Lands to the extent of £750 per annum. The Premier, who at the time was the Acting Head of the Education Department, had approved a further £400 per annum (Cooke, 1916e: 289; 1916q: 397). Wood (1958: 21) states that "For want of financial support, Cooke was compelled to drop an extensive plan to determine longitudes in the Pacific in 1916."

Cooke, however, did not miss a stride as he corresponded with George Dodwell, the Government Astronomer of South Australia on 20 September regarding the difference in longitude between Sydney and Adelaide:

> Thanks for the clock errors. I have taken your signals on several evenings and worked out the diff. of long. between Sydney and Adelaide. It is of course a very rough test because we have taken your clock errors as the errors of the signals at emission, have had no determination of personal equation, have determined our own clock error by a complete novice using a new impersonal micrometer, and have discovered that the head of the moving wire was loose.
>
> Moreover, we did not get good sets of stars at both ends. Notwithstanding all these drawbacks the results do not come out badly. (Cooke, 1916t: 455).

Cooke found that the mean difference between Sydney and Adelaide was 50 minutes, 29 seconds and 19 tenths of a second. Thus, Cooke wrote as a postscript to his letter that he would like to arrange for a more rigorous determination of the difference.

A couple of days later, on 22 September 1916, Cooke wrote again to the Premier via the Under Secretary for Education. The Secretary of the PSB had informed Cooke that the matter of wireless longitude signals between Sydney and America was back on the Premier's desk. Cooke included with his letter a dispatch just received from the Director of Lick Observatory. It showed much sympathy for this proposed work, and such a willingness to assist as even to the installation of a wireless, equipment and the training of a member of the Sydney Observatory staff. Cooke (1916u: 461) thought that the Government ought to be ashamed to back out given that matters had progressed so far.

On 6 October Cooke wrote confidentially to the Under Secretary for Education, for transmission to the Premier. This was Cooke's final appeal for 1916, and he explained that the Commonwealth Department (which he does not name) was keeping quiet on war-time progress in wireless research that Cooke felt ought to be encouraged as reflecting credit upon the State of New South Wales. He concluded that the key people were Hawkins and his son Basil:

> In Messrs' Sawkins [*sic*] and Cooke we have two ideal people to carry out the scheme successfully, Mr Sawkins [*sic*] with his experience of astronomical field work, and Mr Cooke with his knowledge of and enthusiasm for all sorts of wireless research. The expense will not be great, and the undertaking will reflect credit upon the State. Please authorise me to go straight ahead. (Cooke, 1916v: 480).

It is plausible that Wood may have concluded that the triangulation of the Pacific did not go ahead due to the financial consideration alluded to above, but funds had by then been allocated. However, the project became convoluted when authority was sought to appoint Cooke Junior.

On 17 October Cooke wrote to Dr Adams, the Government Astronomer in NZ, and subtly disposed of Broughton, writing him out of the proposal and replacing him quietly with Frederick Slade Drake-Brockman (1857–1917), the Surveyor General of Western Australia, whereby

> From present appearances I am afraid it looks as if the Government at the last moment has decided not to go ahead with this work, but nothing is yet settled. If we do carry it out, I am hoping to act in conjunction with a small committee formed of the Government Astronomers of N.Z., Victoria, S. Australia and the Surveyor General of W. Australia. Will letyou know as soon as something definite is settled. (Cooke, 1916w: 493).

In the same post, Cooke (1916x: 494) wrote to Adelaide Observatory Director G.F. Dodwell:

> Just at present we have no wireless station

> as the Commonwealth people who have become rather interested in the whole matter are making certain alterations with a view to greater aerial efficiency.

The on 14 November Cooke (1916y: 541) queried if Dodwell had tried the Audion receiver:

> These are made by an American inventor, who is not yet bringing them forward in a large commercial sense because the De Forrest company threatens an action for infringement of the patent. It is therefore difficult to procure them, but they are coming into order in small driblets, and I think it would be possible to procure one or two of the bulbs, at 25/- each.

Towards the end of Cooke's effort to get this project off the ground, on 29 November 1916 he submitted a paper to the President of the Royal Society of New South Wales, Thomas Harry Houghton (1857–1924). He also forwarded a slightly revised version to the Astronomer Royal Sir Frank Watson Dyson (1868–1939: Figure 9), whom he first met in Sydney in 1914 during the meeting of the British Association for the Advancement of Science (see Orchiston, 2017: 498–499):

> Herewith I am sending you a paper on some suggested improvements in accurate time signalling, having in view longitude work in particular. The main principle seems so remarkably simple that one feels it must have been tried, but we have seen no reference to it: and it appears to be remarkably effective. We do not like to enthuse in a paper such as this, but we are tremendously in love with the audion we possess, and with the little we have experienced with arc work. (Cooke, 1916z: 572).

The papers were published by both Societies (Cooke, 1916af; Cooke and Cooke, 1917), even though the triangulation of the Pacific project appeared to be a dismal failure as a result of a lack of political support at the State level.

Then on 6 December 1916 Cooke submitted a paper to Sir Frank Dyson on a proposed method of differential star corrections, and this also was published in *Monthly Notices of the Royal Astronomical Society* (Cooke, 1917b). These publications are evidence that work was proceeding at Sydney Observatory on several fronts simultaneously—despite the aborted triangulation project—and Cooke knew that his international peers engaged in this effort would appreciate his suggestions, as they had in the past:

> There are, or will be, a number of observers working in zones of 2° in connection with the meridian scheme of the 1909 Astrographic Conference, and they will, I feel sure, find this proposed method a considerable simplification. I think it will also be suitable for those who are taking the intermediates, and in fact for all except fundamental observers. (Cooke, 1916aa: 582).

Cooke also wrote to the Under Secretary for Education on the same day that he received a communication from Adelaide's G.F. Dodwell who was engaged in geodetic work in connection with the Military Topographical Survey. Dodwell was using a wireless method for the determination of longitudes. At the time Dodwell and Cooke Junior were the only two people in Australia who knew much about this new astronomical development, and Cooke's (1916ab) opinion was that it was an opportune time to meet for a dicussion.

Cooke informed Dodwell on the 14 December 1916 that he was waiting for the authority to send Cooke Junior across to Adelaide Observatory. Meanwhile, Cooke sent a copy of a paper that he and his son had presented to the local Royal Society a few nights earlier, and recommended that Dodwell try their new method of determining coincidences (Cooke, 1916ac: 593).

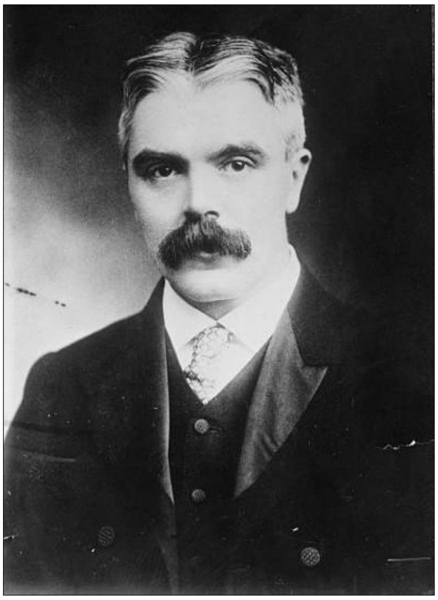

Figure 9: An undated photograph of Sir Frank Dyson (https://upload.wikimedia.org/wikipedia/commons/c/cd/Frank_Watson_Dyson.jpg).

On 22 December Cooke (1916ad: 599) wrote to the Under Secretary for Education regarding the official visit by Cooke Junior to Adelaide, asking him to kindly issue the necessary return railway pass for the journey on 24 December. However, there is no evidence that Cooke Junior ever made the trip.

On 20 March 1917, Cooke reluctantly wrote to the Under Secretary for Education recommending the acceptance of his son's resignation. Cooke (1917b: 24) suggested that

> I think the attention of the Public Service Board ought to be directed to this or any typical case which indicates a fault of some kind in the present organisation. Meanwhile will you kindly indicate your acceptance of

> Mr Cooke's resignation at once, as he wishes to start fresh University course and the term has already commenced.

The matter concluded on 2 May 1917 when Cooke wrote to the Under Secretary for Education that items under Observatory contingencies such as the 'Longitude Operations' would be eliminated (Cooke, 1917c: 765). After all this, the PSB finally replied:

> The Board are unable to understand why wire-less apparatus has been erected at the Observatory. So far as can be seen it has no connection with the ordinary functions of an Observatory. (Gilfillan, 1917).

Cooke entered the field of astronomy when great Australian professional astronomers like Henry Chamberlain Russell (Bhathal, 1991), Robert Lewis John Ellery (1827–1908; Gascoigne, 1992) and Sir Charles Todd (Edwards, 1993) reigned supreme. He served his apprenticeship under Todd in Adelaide, before accepting the Directorship of Perth Observatory. However, by mid-WWI Cooke could no longer work amiably alongside the likes of the retiring NSW Surveyor General, Frederick Poate, but instead had to contend with his replacement, the 'socialite' John Broughton. However, a more severe roadblock to realising the triangulation of the Pacific by wireless time signals was most likely the propossed appointment of Cooke's son Basil as Hawkin's Assistant in 1916. A threefold increase in Cooke Junior's salary, supplemented with an expense account, was possibly too lavish for the PSB to authorise, and an alternative approach was employed that distracted the politicians with State versus Federal responsibilities. Yet despite these setbacks, Cooke and his son still managed to publish several research papers that year. It is also significant that the Chairman of the Sydney Observatory Board of Visitors, Frank Leverrier, was also the President of the Wireless Institute of New South Wales, yet he and the Board refused to support Cooke's triangulation proposal. Had they done so, this would have led to a convergence of astronomy, geodesy and wireless, with astronomy taking the leading role in supporting the war effort.

3 THE SECOND PAN-PACIFIC SCIENCE CONGRESS

Cooke was not granted permission to attend the inaugural IAU General Assembly in Rome, so he had to wait until colleagues from abroad visited Australia to once again apply pressure on the NSW Government and further his quest to link the Pacific by wireless time signals. However, this strategy also was ineffectual, although it did set the stage for later efforts by others.

Cooke was President of the Astronomy Section of the Australian National Research Council, and he chaired the committee that organised the second Pan-Pacific Science Association (henceforth PSA) Congress in 1923 in regards to Section VIb: Pacific Radiotelegraphy and Longitude by Wireless. In these roles, he was positioned to exert his influence and set the programme.

The second PSA Congress was held in Melbourne (13–22 August) and in Sydney (23 August–3 September). The Congress aimed to advance scientific understanding across the Pacific region, including the development of institutions and organisations to encourage and support scientific research. The Congress was a multidisciplinary gathering, and the attendance of many international, as well as prominent Australian scientists, generated real interest in the development and importance of Australian science (see Conway and Philp, 2008).

The PSA was the first Asia-Pacific regional inter-disciplinary science association, and was dedicated to the furthering of science in the Pacific. The PSA has been an influential organisation in the region throughout its eight-decade history (Ward and Lewis, 2009).

This regional focus was in contrast to the earlier wartime focus. WW1 had been a crucial event in this earlier period for many and obvious reasons, and it both reinforced nationalism and at the same time signalled the need for more internationalism, not only in political but also in economic and intellectual terms. Technological changes and scientific discoveries were accelerating towards what would now be called globalisation (ibid.).

The 1923 Congress, however, was a determining moment for the PSA. In contrast to the Australian meeting of the British Association for the Advancement of Science (BAAS), held in 1914, this first post-war congress signalled the emergence of a new scientific nationalism in Australia. A new scientific relationship was developed between Australia and its great and powerful friend across the Pacific, the United States of America (MacLeod and Rehbock, 2000).

The PSA Congress was also pivotal in recognition of science as an instrument of Australian regional, national and international policy (MacLeod and Rehbock, 2000). It assisted in the creation of committees for Pacific investigation, linked through the International Research Council (henceforth IRC). The IRC was established in Brussels in 1919 by wartime neutral and allied nations, led by America, Britain and France, to replace Germany's pre-war hegemony in the organisation of international science. Each member country was required to create a national academy or research council as an 'adhering body' to the IRC (ibid.).

The role of host fell to the Australian National

Research Council (henceforth ANRC), a 'quasi-academy' of scientists from all six Australian States, which was founded in 1920 as Australia's adhering body to the IRC. The ANRC became the principal medium through which the country's small scientific community presented itself to the public. In 1922, however, the ANRC was just one year old. Its functions, as spelled out in its charter, were both broad and specific: to represent Australia in international science; to promote scientific research through its 18 discipline panels; and to serve as Australia's *de facto* National Academy of Science. It aimed to bring research problems to the attention of the universities and the Commonwealth Institute of Science and Industry, which later would become the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (ibid.).

Dominating the list of topics at the PSA Congress were questions of geology, notably Alfred Wegener's hypothesis of continental drift, which the Dutch proposed to test by taking measurements at 5-year intervals. Wegener wanted to determine whether Pacific islands were moving about the surrounding seafloor (ibid). This proposal foreshadowed the development of technology that would become Global Positioning Systems (GPS) later in the twentieth century.

International speakers at the PSA received favourable publicity. Extensive daily newspaper and radio coverage brought the Congress to a broader audience than science had enjoyed in Australia since the 1914 BAAS Congress (ibid.).

Questions of political economies, such as the establishment of international standards for radio, the future of aviation, and the prospect of tropical settlement, were featured prominently by leading Sydney writers (ibid; see also Practical science, 1923).

Sir George Knibbs (1858–1929), amateur astronomer and Director of the Commonwealth Institute of Science and Industry, believed that the Congress was more than a meeting of scientists: it was "… an event of great national and international importance." (Australia science, 1923; cf. MacLeod and Rehbock, 2000: 219).

One of the striking elements of the Congress was the sizable American presence at the Congress. As one of its instigators, Gregory, had correctly foretold, a relatively small investment produced substantial diplomatic returns. The Congress lent a new dimension to American-Pacific relations, at a significant moment in international scientific affairs. By sending a strong delegation, larger even than that of Britain, America signalled an increasing interest in the region. Notwithstanding its many attachments to Europe, American science was here-after to enjoy higher visibility and prominence in the Pacific, on both sides of the equator (MacLeod and Rehbock, 2000; Tasker, 2012).

Even beyond its importance to the Pacific, the Congress of 1923 is of particular importance to Australia. Quite apart from bringing many colleagues to Australian shores, the Congress was a massive triumph for the protagonists of Federal science. The Congress gave the ANRC its first public platform and its first significant opportunity to speak to Government with an assembled voice. It also showed the Australian public that Australian science held a respected place in the world. In 1914, in welcoming the BAAS, Australia was a loyal member of the Empire. By 1923, Australians, although not turning away from Britain, began to look toward America, and even inwardly, into the heart of their vast continent, which was still such a mystery. As such, the Congress stressed the urgency of Federal assistance to scientific enquiries that Australian scientists had been advocating since the 1870s (MacLeod, 1988; cf. MacLeod and Rehbock, 2000).

The Geodesy and Geophysics Section at the 1923 Congress urged the Commonwealth, "… no longer a colony … take up her fair share …" of the world's work in terrestrial magnetism and geophysics, from "… both economic and defence points of view." (Rivett, 1923: 636). The same Section called for the establishment of a Geodetic Survey of Australia and a Commonwealth Solar Observatory, both of which eventually came into being (re the latter, see Love, 1985).

From its highly individual beginnings in Honolulu in 1920 to its more common manifestation in Melbourne and Sydney in 1923, the Pan-Pacific movement in science gathered momentum and achieved recognition. For those who saught to cultivate a Pacific sense among nations, like geologists, Gregory from America and Andrews from NSW, the Australian Congress of 1923 was a forerunner of things to come. It gave evidence of a more precise Pacific dimension emerging in American science. It displayed and encouraged European science in the region. It heralded a strategic, federal vision for science in Australia. Above all, it "… was destined to rank as a remarkable achievement in the international cooperation of science." (Elkin, 1967: 25).

For the next 80 years, successive PSA Congresses would strive to achieve a similar combination of commitment to both national goals and internationalist ideals. The theme of unity and the dedication to the Pacific sense would be played out time and again, in the interests of peace and prosperity and the service of science and humanity (MacLeod and Rehbock, 2000).

Of particular interest at the 1923 Congres was the section relating to Pacific Radiotelegraphy and Longitude by Wireless, hosted in Sydney. The participants read like a 'Who's Who' in this field, and their topics provide a snapshot of the technology and issues of the time:

- "Australian wireless longitude determinations" (G.F. Dodwell, B.A., FRAS, Australia)
- "Application and development of wireless in Australia" (E.T. Fisk, Australia)
- "Organisation of wireless time signals in the Pacific and adjoining countries" (Professor W.E. Cooke, M.A., FRAS, Australia—see Cooke, 1924)
- "Observations of static in the Pacific" (Rev. M. Selga S.J., Philippines)
- "Aerial sciences and their possibilities in the Pacific" (Captain G.A. Taylor, Australia).
- The social and commercial possibilities of wireless communications in the Pacific" (E.T. Fisk, Australia)
- "Determination of longitude by wireless at Batavia" (Dr C. Braak, Dutch East Indies)
- "Encouragement of invention and its bearing upon the peace of the world" (Captain G.A. Taylor, Australia)
- "A few suggestions for discussion in connection with radio telegraphy" (Father E. Gherzi SJ, Hong Kong)
- "Theory of electricity as syntonic vibration" (Commander F.G. Cresswell, Australia)
- "Reception of Bordeaux and Honolulu wireless time signals" (Dr C.E. Adams, New Zealand)
- "The time service in the Philippine Islands" (Rev. M. Selga SJ, Philippines)

The *Sydney Morning Herald* ran an article on the influential radio pioneer and businessman Ernest Fisk (1886–1965), who was Managing Director of Amalgamated Wireless Australasia (AWA). This company was formed in 1913 by an amalgamation of Marconi's Wireless Telegraph Co. Ltd and the Australian Wireless Company. On 28 August 1923 Fisk was quoted as saying: "Australia was one of the few countries that had solved the problem of government control and development of the science …", although this was said somewhat 'tongue in cheek'. Cooke's attempts to conduct wireless experiments during 1916, which required permission from different levels of Government, clearly indicate that Australia had not solved this problem.

Cooke also received some favourable free press for his proposal:

> Wireless Time Signals, W.E. Cooke M.A.
>
> In the radio telegraphy section, attention was given to the proposal of Professor W.E. Cooke that there should be an organisation of wireless time signals in the Pacific and adjoining countries. There are already wireless time signals, but they are mainly in the northern hemisphere. A separate series is necessary for astronomers and geodesists in countries bordering the Pacific. They should be sent from Honolulu since the astronomers who would be in that series would be interested only in the fractional part of a second. There would be no necessity for any zero points. A long dash at the commencement and end would be a luxury, but not a necessity – a fact which wireless experimenters may understand and appreciate. The dots should be started at an assigned moment of Greenwich Mean Time and be continued without a break for about five minutes. Greenwich, 1 a.m., would be the best, and that would be approximate! 11 a.m. in Sydney and Melbourne. (Wireless time signals, 1923; cf. Editor, 1923: 9).

Cooke's proposal above reflects his 1916 plan to triangulate the Pacific by wireless time signals (and was further consolidated when he joined IAU Commission 18 (Longitude by Wireless) in 1925).

International astronomers present at the 1923 PSA Congress included Bernard Benfield (Astronomical Society of the Pacific), Alfred Moore (Director, Smithsonian Solar Observatory) and Dr Wait (Carnegie Institute, and Watheroo Magnetic Observatory—in Western Australia), all from the USA. Astronomers from Japan included Dr Shizo Shinjo (1873–1938, Professor of Astronomy at the Imperial University Kyoto), while from the Netherlands was Dr C. Braak (Director, of the Royal Magnetic and Meteorological Observatory, Dutch East Indies).

The PSA Congress proposed that accurate determination of latitude and longitude should be carried out every five years to ascertain what horizontal movement might be involved in such areas of instability throughout the Pacific by their Geology section. Unfortunately, Wegener's proposal proved to be way ahead of the technology of the day, and he would not live to see his Plate Tectonics Theory proved.

4 THE SECOND IAU GENERAL ASSEMBLY

Professor Sir Thomas Lyle FRS (1860–1944) represented Australia at the second IAU General Assembly at Cambridge, England in July 1925, only because he was in England at that time (Australian National Research Council, 1925: 8). Lyle was a retired Professor of Natural Philosophy (Physics) at the University of Melbourne University from 1889 to 1914, Chairman of the ANRC, a member of the Gravity Survey and Solar Physics Committees, and on the Board of Visitors of Melbourne Observatory. No Australian State Government astronomers had the opportunity to attend this second General Assembly, not even those who had missed the first General Assembly.

By 1925, two Australian astronomers had joined IAU Commissions (International Research Council, 1925: 28, 34, 129, 192, 273). Dr Walter Geoffrey Duffield FRAS (1879–1929), who joined C12 (Solar Physics), had also taken up a new post as the inaugural Director of the Commonwealth Solar Observatory at Mt Stromlo, near Canberra (Love, 1985), while Cooke joined C18 (Longitude by Wireless), where he was once more able to promote the triangulation of the Pacific by wireless signals.

Meanwhile, Dodwell (*Bulletin Géodésique*, 1923) had by now become a member of the International Geodesy and Geophysics Union's Longitude Committee, and he was applying the wireless longitude method to confirm State borders—with Cooke's technical assistance (Dodwell, 1921; International Research Council, 1922: 280, 287; Taylor, 2006).

5 COOKE HANDS OVER THE INTERNATIONAL TIME SIGNAL PROJECT

Before his forced retirement, Cooke wrote to the Chair of the National Committee for Astronomy on 19 May 1926, regarding the proposal by Yale Observatory for the co-operation of the Australia Observatories in the investigation of variations of latitude. Cooke had hoped that Melbourne Observatory's Dr J.M. Baldwin would be able to undertake this collaboration. Although Cooke sympathised with Dr Duffield's views that this kind of work was more suitable for a State observatory than the Federal one, he felt that it was futile to ask any State Government for additional astronomical research funding as matters stood (Cooke, 1926b).

On 23 June 1926, Cooke wrote to the French radio pioneer General Gustave-Auguste Ferié (1868–1932), informing him that Sydney Observatory was abolished as such and that it would be maintained only as a time service station. William Edward Raymond FRAS (1871–1937), Chief Transit Observer, was to remain as the sole salaried officer, and James Nangle (1868–1941), Superintendent of Technical Education and an accomplished amateur astronomer, was residing at the Observatory. Cooke suggested that, as Nangle was interested in wireless time signals and Raymond was fully capable of determining the time, the Observatory might still participate in some work. Cooke (1926c) further suggested that Ferié write to Nangle.

On 28 June Cooke also wrote to Professor Robert Meldrum Stewart (1878–1954), Director of the Dominion Observatory in Canada, thanking him for the reminder of 19 April regarding the Honolulu signals. Cooke informed Stewart that Sydney Observatory had, unfortunately, practically ceased to function, that the staff were being transferred, that he, Cooke, had been instructed to retire, but one Assistant would remain to carry on the time service. Cooke (1926a) reported that the NSW Government had taken this action in the interests of economy. However, in the end not all was lost, and Sydney Observatory would remain operational as a research facility until 1983 (State Records Archives Investigator, 1999).

6 CONCLUDING REMARKS

This paper addresses the dynamic of insufficient authority and resources that the NSW Government Astronomer Professor W.E. Cooke had to contend with in his attempt to pursue the triangulation of the Pacific using wireless time signals and establish Sydney Observatory as the the Australian prime meridian. The triangulation of the Atlantic had already been completed between France and America, and triangulation of the Pacific would close the chain, improve global accuracy, and assist military logistics.

When Cooke first proposed this project in 1916 WWI was raging, and refined maps of the Pacific region were urgently needed. This project therefore should have taken precedence over of all other astronomical endeavours at Sydney Observatory. Cooke therefore urged the NSW Government to take the lead in this important international scientific endeavour, but his relationship with his superiors proved that no amount of coercion was going to sway the bureaucracy and gain support for his project.

In 1916 Cooke strategically appointed an influential and politically astute Board of Visitors, in the belief that they would pressure the NSW State Government into delivering on its prior commitment to fund the Pacific triangulation project. It was Cooke's role as the Government Astronomer to set Sydney Observatory's research direction, but the Board wanted him to focus on other matters that they, as science administrators, determined were more important than the war effort. They went so far as to write directly to the Astronomer Royal in England seeking his support, but this back-fired when Sir Frank Dyson backed Cooke.

In the longer term what were required were national (as opposed to State) facilities, though in 1916 these were beyond the still-weak Federal system and would only come into being long after the war, with the benefit of returning expertise. Cooke therefore remained without the authority or means to undertake a project that would have benefitted Australia at State *and* Federal levels, and would also have contributed to the international scientific community.

Cooke's position as a Section President and Committee Chairperson in the Australian National Research Council meant he could take advantage of the 1923 PSA Congress—which was held in Australia—and re-activate his plan to triangulate the Pacific through wireless signals. The media received him well and Cooke's international peers respected him for publishing both methods and procedures to improve efficiency in the performance of data collection, yet once again the Sydney Observatory Board of Visitors prevented his efforts from bearing fruit.

Cooke also could promote his Pacific triangulation project through Commission 18 of the International Astronomical Union, but he never was able to attend a General Assembly and had to rely on corresponding with other members of the Commission. Strategically, Cooke supported his protégé G.F. Dodwell, the South Australian Government Astronomer, who approached the issue of State boundaries within Australia but from a different perspective: through the Longitude Committee of the International Geodesy and Geophysics Union, and by using wireless time signals from around the globe. Notwithstanding his influence, publications and politicking, Cooke still could not convince his Board or the NSW Government to fund his Pacific triangulation project.

Over the years, the Sydney Observatory Board could have offered Cooke much in the way of assistance and influence, but it did not help or support him, right up to his forced early retirement. In 1926 Cooke tried to re-activate the long-planned move of Sydney Observatory from central Sydney to a 'dark sky' site beyond the city limits, and the Government responded to this by deciding to close down the Observatory. As Malin et al. (1986: 66) poignantly observe, Cooke

> … became a scapegoat He was placed on a month's notice and finally left the observatory in August 1926 … [he was] a broken man … [Because] the university refused to pay his pension … He retired in poverty to eke out a living by conducting classes in contract bridge … before returning to his home city of Adelaide, where he died in 1947.

What this paper draws out is that personal and emotive issues, such as jealousy, turf wars, political infighting, lack of vision and national insularity (the tyranny of distance), had the potential to impede the advance of Australian science. In this instance, the triangulation of the Pacific was delayed by a decade, but more importantly, Australia lost its prominent position on the world stage in the fields of astronomy, geodesy and wireless.

More than one hundred official documents were examined in the course of the research for this paper, and Cooke remained the consummate professional throughout. Only once did he pour out his soul to those who blocked him at every turn when he reported the effect that this had on him, his wife and his daughter. Haynes et al. (ibid.) note that "… despite his very considerable abilities, Cook was not destined to have an easy time in New South Wales." Viewed solely in the light of his Pacific triangulation project, this is surely an understatement!

7 NOTES

1 For those wondering what £750 or £400 mean, prior to the introduction of decimal currency on 14 February 1966, Australia used pounds (£), shillings (s) and pence (d). There were 20 shillings in a pound, and 12 pennies or pence in a shilling. Thus, a salary of £157 16s 8d (mentioned on the following page of this paper) is 157 pounds, 16 shillings and 8 pence. Another way of expressing this is: £157/16/8. Similarly, often shillings and pence would be listed say as 16/8 (i.e. 16 shillings and 8 pence) or 16/- (16 shillings exactly).

2 Although the Department of Public Instruction (1880–1915) was renamed the Department of Education in 1915, the former title persisted.

3 The expense account amounted to 83% of his original £60 salary package.

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Ian Tasker was born in New Zealand in 1959 and began his career in telecommunications with the New Zealand Post Office before emigrating to Australia in 1984. He spent several decades in Information and Communications Technology, eventually becoming a principal consultant, working across multiple time zones from Japan through to India. Pursuing an interest in astronomy, in 2004 he published the paper "Robotic Observatories in eEducation and eResearch" in the IAU Commission 46 Newsletter. Ian returned to academia in 2007 and completed a Post-graduate Certificate in Research Studies, with a thesis on *Feasibility Study for a Planetarium at UWS: The Efficacy of Planetaria, Astronomy and Space Science Education*. He then undertook a Masters (Hons.) degree, developing a methodology to reverse engineer the viability of Sydney Observatory, as a case study defining the decline of colonial science from 1916 to 1983. Since then, Ian's research interests have matured and he is currently addressing how internationally managed science is funded. Currently, he is in the process of publishing his research for a PhD by Publication at Western Sydney University, which will be supervised by Professors Ray Norris and Brett Bowden.

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AN ACCOUNT OF THE COMET, WHICH APPEARED IN THE MONTHS OF SEPTEMBER, OCTOBER AND NOVEMBER 1807*

Captain John Warren
Acting Astronomer, Madras Observatory, Madras, India.

The Comet of which it is the object of this paper to describe the path, was noticed for the first time in Bengal, at Penang and at Sea (in latitude 10°S) about the 20th of September.

By some unaccountable over sight or accidental intervention of clouds, it was not noticed at Madras untill the 2d of October, when it appeared in the constellation of the Serpent, about 9½ degrees W of α of that asterism, of the size of a star of the first magnitude with a faint beard about 3° in length just discernible to the naked eye. Viewed thro' a Telescope, its nucleous was ill defined, with hardly any apparent diameter, and surrounded with a haze similar to that of its beard. Its size rapidly diminished and on the 8th of October it did not seem magnified when viewed through a Telescope with a power of about 80. It was seen distinctly as late as the 8th of December, but the weather having thickened previous to the memorable hurricane of the 10th and 11th of that month and kept clouded subsequently, it was but just perceived when the sky cleared up on the 13th of December.

There being no Instrument in the Madras Observatory wherewith to take at once angles of altitude and azimuth, I ascertained the position of this Comet relatively to the neighbouring fixed stars with an 8 Inch Radius Sextant made by Ramsden, I observed it from the 3d of October until it became too faint to admit of a tolerable observation by means of an instrument of so little power.

As the object of this paper is principally to investigate the orbit of the Comet, I shall only give here an abstract of such observations as I have used in working it.

On the 3d of October at 7h: 13′: 24″.7 P.M. mean time I observed the Comet 8°: 31′: 47″ E of α Serpentis and 13°: 9′: 5″ N of β Librae.

On the 14th of the same Month it was at 6h: 45″: 17″ P.M. 14°: 8′: 15″ of α Coronae Borealis and 7°: 50′: 25″ NE of α Serpentis.

On the 25th, at 6h: 42′: 15″ P.M., it was of ζ Herculis 9°: 26′: 15″ S, and 8°: 47′ :45″ SW of σ Herculis.

On the 18th of November the Comet was from α Lyrae 4°: 50′: 7″ SW and from Altair 35°: 1′: 15″ NW.

With these data and the sum or difference of the respective stars right ascensions and declinations we are enabled to compute by spherical trigonometry the situation of the Comet as seen from the Earth on each of these days; But as the detail of these computations afford nothing particularly interesting I shall only insert the results in the following General Table, which can easily be verified, and leave the operation recorded at the Madras Observatory.

Having thus obtained four longitudes and elongations of the Comet with corresponding latitudes, we are to look for a parabola which will represent its position in the heavens at these respective periods. As the details of this investigation are but little known to any but astronomers, I shall concisely state the different steps which have led me to the resolution, or rather approximation of this laborious problem.

Let SA (Fig I) be the distance of ⊙ and ⊕ at the moment of observation (A)SH, the curtate distance from ⊙ to Comet or distance reduced to the plane of the Ecliptic SHA(*c*).

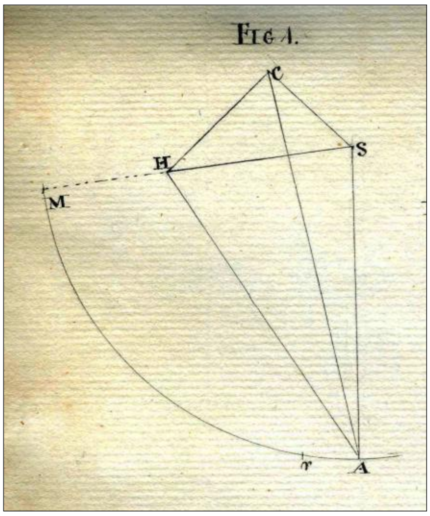
SAH the difference of ⊙ & Comet's longitude, seen from the Earth, called the angle of Elongation (*E*).

HSA the assumed difference of Comet and Earth! Heliocentric Longitude called the angle of Commutation (*n*).

SHA the angle at the Comet reduced to the plane of the Ecliptic (*m*).

Time of Observation at Madras	AR	Declin	Geocentric Longitude	Geocentric Latitude	⊙ long. Contempo.	Longitude of ⊙'s distance
D h ′ ″	° ′ ″	° ′ ″	s ° ′ ″	° ′ ″	s ° ′ ″	
Oct 3:7:13:24.7	225:35:47.0	4:32:50	7:11:42:46	20:52:17 N	6: 9:24:25.5	9.997990
14:6:45:17.5	237: 1:14.4	14:13:02	7:20:51:03	33:18: 7 N	6:20:16:02.3	9.9985320
25	247:29:42	22:34:00	8: 0:41:50	43:45:51 N	7: 1:12:32.6	9.9972190
Nov 18	272:24:58.0	36:11:44	9: 3:51:28	59:37:31 N	7:25:19:45.3	9.9946970

* Based on a MS dated 1 January 1808 now in the RAS Archives, London (RAS MSS Madras 6). We are grateful to the Royal Astronomical Society for permission to publish this manuscript and to Dr Sian Prosser (RAS Librarian and Archivist) for his help.

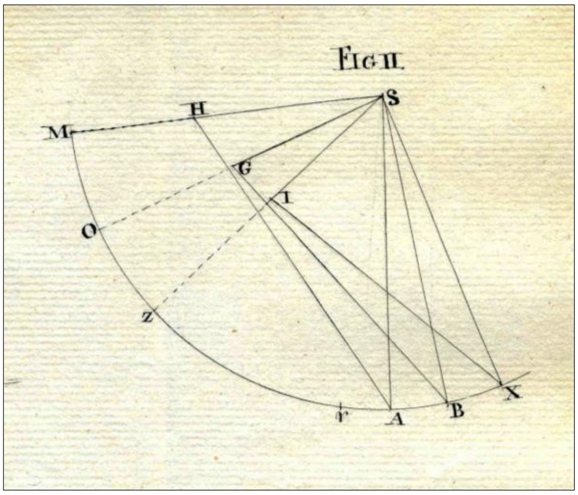


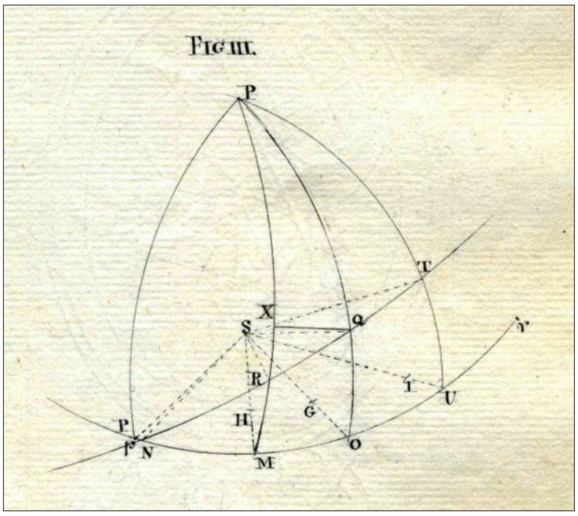
Draw CH perpendicular to the plane of the Ecliptic SHA, and let C be the place of the Comet in its orbit.

Then CAH is the Geocentric Latitude as observed (*l*) and

CSH is the Heliocentric Latitude which is to be determined (*L*)

of these different terms are only given SAH, the Elongation, and CAH the Geocentric Latitude





such further data as may be required to work the problem must be assumed; and this may be done either by assuming SH, the curtate distance, or (when the angle H at the Comet is very near 90°) to assume that angle.

As these cases belong to plane trigonometry, I shall merely state that preserving the above notation we have the angle at Comet.

$m = (\text{Sin } E \times \text{A})/c$
and the angle of Commutation
$n = m + E - 180$

which when worked and assuming SH = 0.5868 will give m = 65°: 33′: 11″ and n = 82°: 8′: 28″

We resolve the Comet's Heliocentric Longitude by taking the angle of Commutation from the Earth's Longitude adding in this case 12 signs to it, because the Earth is in ♈ and the Comet is East of it/ and the remainder leaves the Comets Longitude of which HS♈ is the supplement to 360.

In this case ☉'s long. being	12^s: 9°: 24′: 25″
and n = - - - - - - - - - - -	2: 22: 8: 28
we have Heliocentric long. Ist obs^n.	9: 17: 15: 57

(*l*)

The Heliocentric Latitude CSH is … [indistinct] and in this case, L = 35°: 15′: 1″.

C being the true place of Comet on orbit, SC will be true distance from the Sun; or the Radius Vector (*V*) which is to be determined by dividing the curtate distance SH by the cosine of the Heliocentric Latitude *L*, the log. of which in this case will be 9.8564601.

2^d Observation

Proceeding in the same manner for the 2^d observation and assuming SG (Fig II) = 53101 we shall have

∠ at Comet …………..	12°: 43″: 53″
∠ of Commutation…..	77: 0: 5
Heliocentric Long.	10^s:3°: 15′: 57″
Heliocentric Lati^{de}	51: 31: 10
Rad. Vector log.	9.9311422

difference of Longitude Ist and 2^d observation HSG (Fig I) or MO (Fig III) 16°.

We are now to determine Ist the Perihelion or focal distance Sp of the Parabola (Fig III) 2^d. The two anomalies pR, pQ. 3^d. The interval of time elapsed between the two observations which if SH, SG have been rightly assumed will be the same as the interval observed.

Let NMO (Fig III) be an arc of the Ecliptic, P its pole, Np RQ a part of the Parabola required p, the Perihelion N the Node, and ∠RNM the Inclination of the orbit with the Ecliptic.

Then RM, QO, are the two Heliocentric Latitudes, RQ is the motion of the Comet on orbit between the two observations, and MO, the difference of Heliocentric Longitudes corresponding to it.

By common spherical trigonometry we have for RQ

tang^t PX = Cos MO × co.tang^t QO

and Co-sine RQ = (Cos RX × Sine QO)/Cos PX

which in this instance is = 19°: 51′: 12″.

For the whole anomalies pR, pQ, if we put *V* for Rad. Vector SR, and *v* for SQ; we shall have by spherical trigonometry

tang^t [(½*V*/*v*) – 45]/tang^t (¼RQ) = ∠*p*′

and ∠p ± ¼ RQ = ½ { pQ greater anomaly / pR less anomaly

which being worked accordingly will in this case be

pQ = 62: 34: 10 Greater anomaly
pR = 42: 42: 50 less anomaly
diff. 19: 51: 12 as found before.

By referring to the General Table of anomalies for the comet of 109 days we will find the number of days corresponding with the greater anomaly to be 56.1038
and the lesser 33.7879
diff. 22.3159 which

difference being multiplied by the 3/2 power of the Perihelion Distance will give the number of days elapsed which belong to this Parabola.

Now we have (by conic sections) for the Perihelion Distance Sp

Sp = (cos½ pQ)^2 × SQ = .62325 and
(Sp)$^{3/2}$ = .49203 whence
(62325)$^{3/2}$ or 49203 × 22.3159 = 10^d.98 which is exactly the interval observed.

A Parabola has therefore been found which answers to the position of the Comet at the times of the first and second observation.

Therefore if by applying it to the circumstances of the 3^d observation, it is also found to answer then it will be the real path, or orbit of the Comet.

Preparatory to this investigation we must determine the following Elements, to be deduced from the preceding results

Ist the Long. of Node
2^d the time of passage of Perihelion
3^d the Obliquity of Orbit or ∠N

For this we are to compute the different parts of the triangle RNM which by spherical trigonometry (Fig III) will be done as follows

tang^t ∠R = (Sine PX × tang^t MO)/Sine RX
= 30°: 17′: 9″

tang^t MN = Sine MR.tang^t ∠R = 18:37:38

Cosine ∠N = Sine ∠R × Cosine MR = 65:40:19

Sine NR = (Rad × Sine MR)/Sine ∠N
= 39°: 18′: 3″

For the Longitude of Node

distance from Node MN	18°: 37′: 38″
Heli. Long Ist obs^n	9^s.17°: 15′: 57″
Long. of Node	8^s.28°: 38′: 19″

Reducing the days of the Tables corresponding with the smaller anomaly, to days of the Comet, by multiplying these into 3/2 power of Perihelion Distance, we have the time elapsed since passing = 16.624 days and this reduced to the preceding month by subtracting it from October 3^d 7^h: 13^m: 24.7^s gives the passage on September the 16th 16^h: 14′: 53″ or 16.67691 days.

For the Longitude of Perihelion

longitude of Node	8^s.28°: 38′: 19″
argnt. of Latitude RN	1: 9: 18: 3
Sum	10: 7: 56: 22
Lesser anomaly pR	1: 12: 42: 58

Longitude of Perihelion 8: 25: 13: 24 on orbit

3^d Observation

We have now obtained the following Elements which will enable us to compute the Geocentric Latitudes and Longitudes resulting from the 3^d observation, and which (if a right hypothesis had been assumed), ought to be the same as have been observed.

Longitude of Perihelion 8^s.25°: 13′: 24″
Longitude of Node 8 28 : 38 :19
Inclination of Orbit 65 : 40 : 19
time of passing Perihelion Sept^r 16th 16^h: 14^m: 53^s
time (observed) of 3^d observation Oct^r 25th 6^h: 42^m: 45^s or October 25.2795 days
log. of Perihelion Distance 9.7946652

For time elapsed since passage of Perihelion

3^d observation & corres. anomaly
time of passage Sept^r 16.677
30
13.323

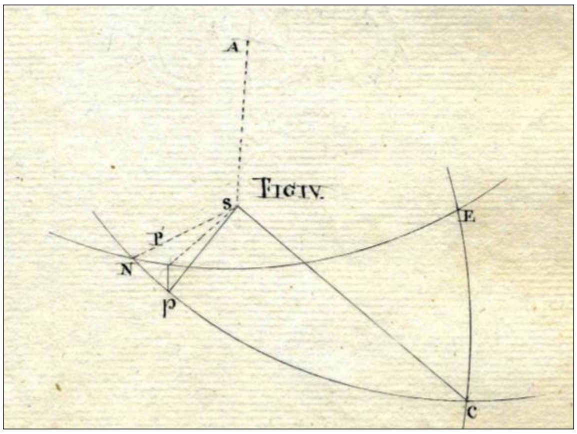
which divided by 3/2 power of Perihel^n. Distance give us days of the Table 78.455 corresponding with 76°: 36′: 46″ of anomaly = pT (Fig III).

For the arg^t. of Lat. NT

Anomaly pT	2^s: 16°: 36′: 46″
Long. of Perihelion	8: 25: 13: 24
Heli. place of Comet on orbit	11: 11: 50: 10
Long. of Node	8: 28: 38: 19
NT arg^t. of Latitude	2: 13: 11: 51

For distance of Comet from Node on Ecliptic NO

tang^t. NO = (Rad × Cos ∠N)/Cosine NT



= 53°: 45′: 38″

For Heliocentric Longitude on Ecliptic

distance from Node	1^s. 23°: 45′: 32″
place of Node	8 28: 38: 19
⊙'s Longitude	10: 22: 23: 51
	13: 1: 12: 32
∠ISX of Commutation	2: 8: 38: 41

For the Heliocentric Latitude

$\text{tang}^t\ TU = (\text{Rad} \times \text{Sine } NU)/\text{Cotang}^t \angle N$
= 60°: 32′: 57″

For the Curtate Distance
By conic sections

curtate dist $SI = (\text{Cosine } TU \times \text{per. dist.})/(\text{Co-sine}\tfrac{1}{2}\ pT)^2 = .49765$

For angle at Comet SIX, and of Elongation SXI (Fig II)

Let SX = x and SI = y, then by plane trigonometry and

$\angle p \pm \tfrac{1}{2}\ \text{Supp}^t.\ ISX = \angle SIX$ at Comet 81° 38′ 56″
= ∠SXI of Elong. 29: 42: 4

For Geocentric Longitude

Elongation	29°: 42′: 20″
⊙'s longitude	7^s: 1°: 12′: 32″
Geo. Longitude =	8: 0: 54: 52
But it was obs^d.	8: 0: 41: 50
error	13′: 2″

For Geocentric Latitude
By plane trigonometry

tangent Geocentric Lat. = (Sine IXS × tang^t. Hel. Lat.)/Sine ISX

hence computed Geo. Lat. =	43°: 18′: 57″
But it was obs^d.	43 : 45: 51
error	26: 54

I shall not detain the attention of the reader by giving him an account of the various trials which I have made to obtain, that hypothesis which would produce the nearest coincidence, with the greatest number of positions.

I have selected for an example the three preceeding observations because they were the three first taken when the Comet was most distinct and consequently when it was to be presumed the arcs were most accurately, measureed but when I came to apply the hypothesis to remoter observations I found that it gave too small a motion to the Comet. It was not untill I had made a great number of trials of observations and taken three that I brought out at least an hypothesis which (though not absolutely perfect,) yet represented sufficiently well the position of the Comet as seen from the Earth to justify the adoption of the following Elements on which I shall ground my subsequent remarks.

In order to be more concise I shall annex to these the Elements of the Comet of 1684, which is the only one that bears the least resemblance with ours; observing at the same time before we can venture any final opinion on the subject, we must look to astronomers in Europe for that information which can only be obtained by adequate means both as to talents and Instruments.

Let us now examine what must have been the position of the Comet at any given period before its perihelion, for example at 90° anomaly descending.

Let S be the Sun (Fig IV) NṔE, a part of the Ecliptic, N the place of node, Ṕ the place of perihelion on Ecliptic, p the perihelion, pC an arc of 90° anomaly, CE the Heliocentric Latitude of Comet when at C and SA the direction of the Earth.

We have then

Place of the Node	8^s. 29°: 1′: 15″
Place of Perihelion on its orbit	8^s. 26: 13: 41
Np arg^t. Lat. Perihelion =	2: 47: 34
which added to pC =	90
gives NC arg^t. of Latitude	92: 47: 34

This with the Inclination of orbit gives by spherical trigonometry

NE the dist. to Node	96: 16: 44
which taken from Long of Node	^{s}8. 29°: 1′: 15″
leaves Heli. Long. of Comet	^{s}5. 22°: 44′: 31″
also the Heliocentric Lat.	63°: 32′: 41″

Elements	Comet of 1807	Comet of 1684
Perihelion distance	0.61305	0.96015
Inclination of orbit	63°: 40′: 51″	65°: 48′: 40″
Long. of ascending node	^{s}8: 29°: 1′: 15″	^{s}8: 28°: 15′: 0″
Place of perihelion	^{s}8: 26°: 13: 40	^{s}7: 28: 52: 0
Time of pass. Per. Greenwich time	Sep^t. 16^d: 21^h: 2′: 36″	June 8^{th}:10^h: 15′: 40″
Motion	direct	direct

We are now to find the number of days which our Comet will take to move through 90º of anomaly.

For this we have in the Tables corresponding to 90° anomaly 109.67 days which divided by the 3/2 power of Perihelion Distance will give for this Comet 52.645 days or $52^{days}:15^{h}:29'$ by which quantity it may (as usual) be denominated.

Now the time of passing the Perihelion being on September 17th $2^{h}:23':50''$, we have for the day on which the Comet had 90° anomaly descending, the 26th of July at $10^{h}:56$ on which day the Suns Longitude + 6 signs was

	10^{s}. 2°: 43′: 16″
Heliocentric Long. of Comet	5^{s}. 22°: 42′: 31″
∠ of commutation	4^{s}: 9°: 58: 45

which being disposed of as usual will give for 90° anomaly descending

The Elongation	17°: 0′: 52″
Geocentric Longitude	4^{s}. 19°: 44′: 8″

and Radius Vector or dist from the Sun SC log 0.0885873.

For curtate distance of Perihelion and Radius Vector of Node, we have, Co-sine Heli. Latitude × Perihelion Dist. = curtate dist. SP of Perihelion = 60250 (log 9.7871104) and Perihelion Dist. × Co-sine (½ anomaly)^2 = Rad. Vector at Node = 6134(log 9.7877712).

Lastly for the distance from Earth to Comet on the 3d. of October and 23d. of November, we have by plane trigonometry (Fig I)

Distance AH = (Sine Comm$^{n.}$ HSA × Curt. SH)/ Sine Elongation = 1.0648

which divided by Co-sine Latitude 20°: 52′: 50″ gives the distance CA = 1,1386 from Earth to Comet on the 3d. of October, and by the same rule for the 23d. of November = 1.72250.

We may deduce from the preceeding results that had the Comet been in its Node on the 21st of June at Noon (when the Earth has $^{s}8$: 29°: 1′: 15″ anomaly) the Comet would have eclipsed the Sun, and would have been nearer to us in the proportion of 10.16 to 4.026.

The same serves also to explain the reason why the Comet was not seen at the time of its approach to the Sun; for having computed its place when at 90° anomaly descending (which happened on the 26th of July at $10^{h}:54'$) I found that its Elongation, or difference of Geocentric Longitude from the Sun was on that day only 17°: 0′: 52″ and had only increased to 32°: 20′: 14″ by the 3d. of October, from which it is evident that for a long while it was much too near that luminary, not to be lost in its rays, had not even the Comet's distance from us, been then more than double that from the Sun, that is nearly in the proportion of 10 to 22. Which alone would have prevented our seeing it, since it was barely discernible on the 23d. of November, when its distance from the Earth was only as 10 to 11 and when it had 40° Elongation.(*)

I shall now take leave of this difficult subject, which would have been investigated with infinitely more ease and accuracy, had I been suplied with more appropriate instruments; and beg on that account to submit the preceding investigation to the notice of the public more as an essay than a successful description of the orbit of the Comet of 1807.

Having been prevented by illness to observe after the 2d. of December the Bramin assistant Senivassachairy, continued to notice it. On the 8th of December at 7^{h} P.M. he took roughly its distance from α Cygnii which was about 9°:47′ N.W. and from α Aquilae 35°:11′ NE.

The last sight he had of it was on the 13th after which the light of the Moon prevented his perceiving it any longer.

Madras Observatory
1st of January 1808

[Signed] John Warren
Act^{g} Astronomer

*The Comet might have been seen when at its Perihelion; for then its Elongation was 32°: 49′: 21″ and its distance as 11.26, which is a little more than what it was on the 23d. of Nov. when it was still discernible to the naked eye.

As it passed its Node on the 17th of Sept^{r}. at 20^{h}: 5′,when its Elongation was 34°: 42′: 56″ and its distance somewhat less than the above, it must have been distinctly visible: and so it seems was the case since it was noticed at several places about the 20th of that Month.

I shall here observe that the present hypothesis gives the Elong. of Node in the last degree of Libra, that is, its Geocentric Long.

ON OBSERVATIONS OF THE GREAT COMET OF 1807 (C/1807 R1) FROM INDIA

R.C. Kapoor
Indian Institute of Astrophysics, Koramangala, Bengaluru 560034, India.
Email: rckapoor@outlook.com

Abstract: Captain John Warren, the Acting Astronomer at Madras Observatory between 1805 and 1811, observed the Great Comet of 1807 (now C/1807 R1) and computed its orbit. He wrote up his observations in a paper titled "An account of the comet, which appeared in the months of September, October and November 1807" and sent this to England, but it was not published at the time. This paper has now been published in this issue of the *Journal of Astronomical History and Heritage* (courtesy of the Royal Astronomical Society), and the present paper discusses Warren's observations and others made from the Indian Subcontinent. It turns out that Comet C/1807 R1 was first sighted on 20 September in Bengal, making this an independent discovery from India. Notably, this was the first comet observed at Madras Observatory following its inception.

Keywords: The Great Comet of 1807; Madras Observatory; John Warren; Royal Astronomical Society

1 INTRODUCTION

Captain John Warren (1769–1830) was Acting Astronomer of the Madras Observatory during 1805–1811 when the Astronomer, John Goldingham, went to England on leave. In the course of Warren's tenure, two Great Comets appeared in the sky, in 1807 and 1811. These created a sensation among astronomers internationally, and even generated concern among the general population, leaving an indelible imprint on many minds. Warren observed both comets while at Madras (now Chennai), and summarised his observations in the Madras MS Records. He wrote a detailed paper about the Great Comet of 1807, and sent this to the Royal Astronomical Society in 1809 (Ananthasubramaniam, 1991); the date of its receipt was 2 June 1809. For some unexplained reason this paper (Warren, 1808) was not published at the time, and it is now in the Archives of the Royal Astronomical Society (RAS MSS Madras 6). Its title is "An account of the comet, which appeared in the months of September, October and November 1807".

This paper supplements Warren's 1808 manuscript that we publish here for the first time (i.e. Warren, 2019). See Figure 1. However, a brief description of the early days of Madras Observatory and the equipment there is desirable because in his paper Warren regrets "… having no instrument at the observatory of sufficient powers of observation of this nature."

2 THE EARLY HISTORY OF MADRAS OBSERVATORY

Madras Observatory was the first modern astronomical observatory to be established in India. Originally it was a private facility erected at Egmore in Madras (now Chennai) in 1786 by William Petrie (d. 1816), an officer with the East India Company (Kochhar, 1985a; 1985b). Petrie's intention, expressed years later in a memorandum of 4 September 1804 to the Governor of Madras was

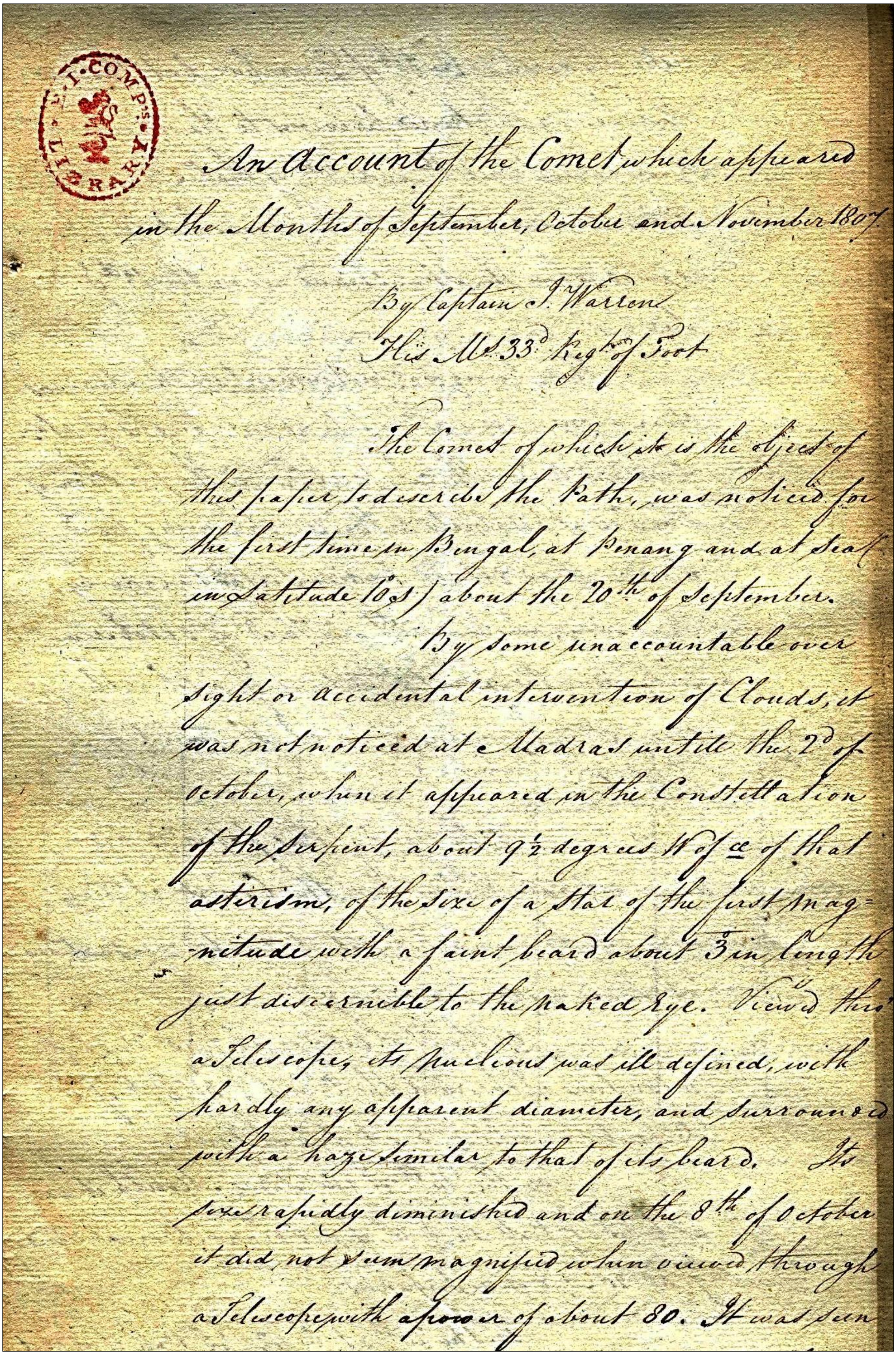
> … to provide navigational assistance to the company ships, and help determine the longitudes and latitudes of the company territories. (Madras MS Records: 76).

According to Kochhar (1985a, 1985b), Petrie possessed the following scientific instruments:

- three 2.75-inch achromatic telescopes of 42 inches focal length by John Dollond (1707–1761; King, 1979);
- an astronomical clock with compound pendulum by John Shelton (Clifton, 1995) similar to the one used by Lieutenant James Cook in his 1769 transit of Venus expedition (Howse and Hutchinson, 1969) and later, in 1900, moved to Kodaikanal Observatory—where it is still ticking (see Kochhar, 1987);
- a quadrant by John Bird (1709–1776; Hellman, 1932); and
- a 20-inch focal length transit instrument by John Stancliffe (Andrews, 1996: 231).

The longitude of the Observatory was determined from observations of eclipses of the Jovian satellites. The first observation on record, on page 164 in the MS Records at the Indian Institute of Astrophysics Archives, dates from 5 December 1786 and pertains to the determination of the coordinates of Masulipatam Fort Flagstaff from such observations.

Early in 1789, Petrie prepared to proceed on leave and made an offer to gift his observatory to the Government. Michael Topping (1747–1796) saw merit in the proposal (Phillimore, 1950) and the Observatory passed from Petrie into the hands of Topping. The Directors of the East India Company (EIC) gave consent in 1790 for "… the Establishment of an Observatory at Madras … [that] would be of very great advantage to Science." Topping was the Company's new Astronomer and Marine Surveyor. In 1792 the observatory was moved to new premises at Nungambakkam designed by Topping and renamed Madras Observatory (see Figure 2).



An Account of the Comet which appeared in the Months of September, October and November 1807.

By Captain J. Warren
His M's. 33d Regt. of Foot

The Comet of which it is the object of this paper to describe the Path, was noticed for the first time in Bengal, at Penang and at Sea (in Latitude 10° S) about the 20th of September.

By some unaccountable over sight or accidental intervention of Clouds, it was not noticed at Madras untill the 2d of October, when it appeared in the Constellation of the Serpent, about 9½ degrees N of α of that asterism, of the size of a Star of the first magnitude with a faint beard about 3° in length just discernible to the naked Eye. Viewed thro' a Telescope, its Nucleus was ill defined, with hardly any apparent diameter, and surrounded with a haze similar to that of its beard. Its size rapidly diminished and on the 8th of October it did not seem magnified when viewed through a Telescope with a power of about 80. It was seen

Figure 1: The title page of Warren's MS about the Great Comet of 1807 (courtesy: RAS Library and Archives).

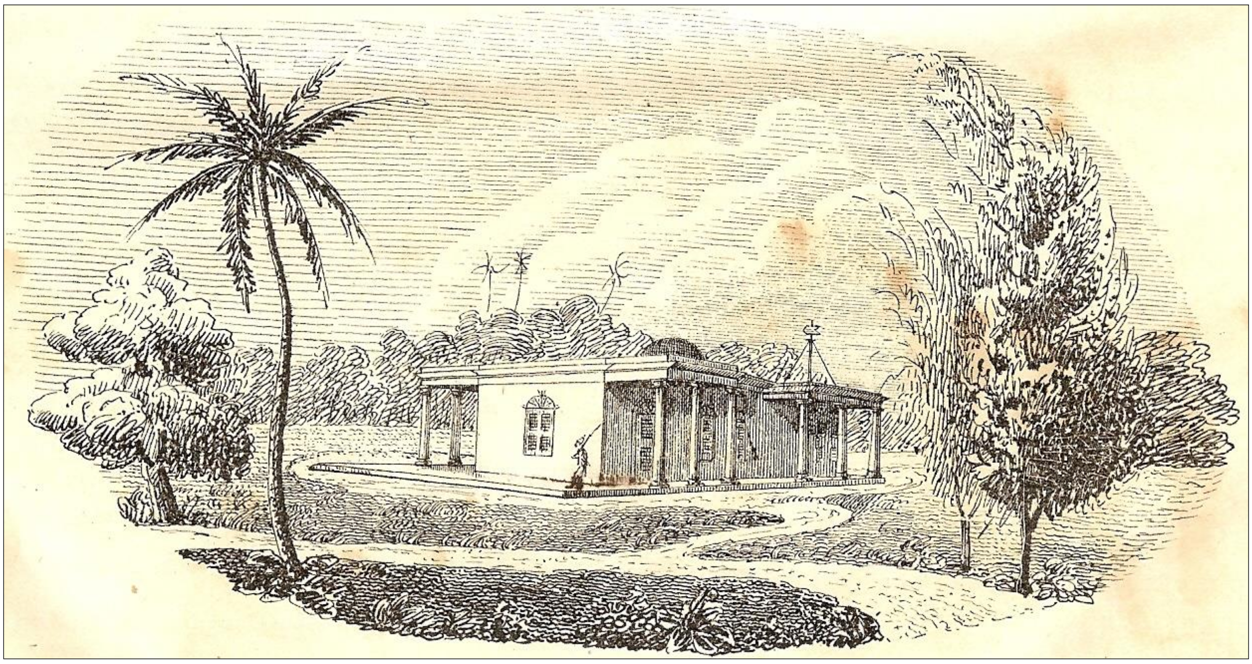


Figure 2: Madras Observatory at Numgambakkam (from the cover of Volume IV of Taylor (1838) (courtesy: Indian Institute of Astrophysics Archives).

Madras Observatory initially served as the reference meridian for the work on the trigonometric survey of southern India initiated by the East India Company. It was called the Great Trigonometrical Survey of India from 1818, and eventually would cover the entire Indian region. Thus, a precise determination of the Observatory's longitude was essential, from which longitudes in the Survey would be measured. Subsequent work at the Observatory was mainly positional astronomy: recording positions of bright stars on the celestial sphere. In 1793 Toppings' assistant John Goldingham (1767–1849) also began systematic meteorological measurements at the Observatory.

After Topping's death in 1796, Goldingham took charge as the Company's Astronomer and Marine Surveyor on the Coast. His tenure was in two phases: between 1796 and 1805, and from 1812 to 1830. In the intervening period, while he was away in England, Captain John Warren (1769–1830; Figure 3) took charge. Warren arrived in Calcutta in December 1793, and later was involved with the trigonometrical survey of the southern region (Kochhar, 1991).

Goldingham was succeeded by Thomas Glanvile Taylor (1804–1848) in 1830. He, too, maintained the meteorological measurements.

In 1804 Madras Observatory received a 12-in Troughton circular altazimuth instrument and a portable transit by Jesse Ramsden (1735–1800; Chapman, 1996; McConnell, 2007). Warren resigned in December 1811 and Goldingham resumed his duty on 17 February 1812. Phillimore (1950: 196) lists the only available instruments maintained around this time as a transit telescope by Stancliffe, a portable transit by Ramsden, three astronomical clocks, three Dollond telescopes and a circular instrument; Warren spoke very highly of this last-mentioned instrument.

Stellar positional measurements were not the only astronomical observations conducted at Madras Observatory. Solar System objects and events, and occultations of the fixed stars and planets by the Moon, also were of interest.

Madras Observatory also initiated a local time service. Since the local time (based on meridian transits of stars or the Sun) depended on longitude, for time-keeping it was necessary to choose a standard longitude for India. In 1802 Goldingham determined the latitude and longitude of Madras as 13° 5′ 24″ N and 80° 18′ 30″ E from observations of eclipses of Jupiter's satellites and culminations of the Moon. Subsequently, in 1807 Warren redefined the longitude as 80° 17′ 21″ E, and this remained the accepted value for almost a century, until 1905 (Phillimore, 1950: 195). Recall that Lambton had commenced the trigonometrical survey at Madras on 10 April 1802 when a baseline measurement relating to the longitude of Madras was made.

Warren also was concerned about the value of the latitude for Madras, and he made observations of zenith distances of selected stars from October 1806 to June 1807 with a zenith sector loaned to the Observatory by William Lambton (ibid.). As a result he refined the latitude by several arc-seconds.

For a biographical sketch of John Warren see Kochhar (1991), and for details on the development of modern astronomy in India see Kochhar and Orchiston (2017).

3 THE GREAT COMET OF 1807

According to Kronk (2003), the Great Comet of 1807 (C/1807 R1) was discovered by Castro Giovanni of Sicily in the evening twilight near the horizon in the west-southwest direction on 9 September 1807. Subsequent independent discoveries were from 21 September only, its observability being subject to the observer's latitude and interference from a brightening Moon (with Full Moon on 18 August and 16 September). The accomplished French astronomer Jean-Louis Pons (1761–1831) was the first to independently discover the comet, on 21 September. By then it was a bright comet, distinctively visible to the naked-eye, and it also was well observed by William Herschel. The comet was last observed on 27 March 1808 (ibid.). Details of the observations of the comet made elsewhere can be found in Kronk (2003) and Vsekhsvyatskii (1964).

Figure 3: John Warren, Acting Astronomer, Madras Observatory 1805-1812 (courtesy: Indian Institute of Astrophysics Archives).

The comet passed closest to the Earth on 26 September, at 1.1533 AU. In the month of October, it displayed two tails, a straight tail more than 6° long and a relatively shorter curved one. It continued to be a naked-eye object throughout the months of October, November, and even into December by which time it had dimmed.

4 JOHN WARREN AND THE GREAT COMET OF 1807

The Madras M.S. Records in the Indian Institute of Astrophysics Archives is a hand-written document of the Madras Observatory proceedings. It spans the period January 1794–October 1812, and runs to 218 pages. Included is the Report of Madras Observatory dated February 1809 by Captain John Warren, which on pages 78–79 briefly refers to the 1807 comet:

> In September, October and November 1807 the remarkable Comet appeared which had attracted so much of the attention of astronomers in Europe. Having no Instrument at the observatory of sufficient powers of observation of this nature, the acting astronomer was under the necessity to compensate by the number for the inaccuracy of his observations involving long and tedious calculations and approximations the power of which is well known to persons acquainted with those operations. The Paper on the movements and path of the Comet was submitted to Government early in 1808 was the result of two months calculations.

The soft copy of Warren's (1808) paper is spread over 21 jpeg images, and has four figures depicting the geometry of the situation. Warren begins by saying:

> The Comet of which it is the object of this paper to describe the path, was noticed for the first time in Bengal, at Penang and at Sea in latitude 10°s / about the 20th of September. By some unaccountable oversight or accidental intervention of Clouds, it was not noticed at Madras until the 2nd of October … There being no Instrument in the Madras observatory wherewith to take at once angles of altitude and azimuth, I ascertained the position of this Comet relatively to the neighboring fixed stars with an 8 Inch Radius Sextant made by Ramsden, I observed it from the 3rd of October until it became too faint to be to admit of a tolerable observation by means of an Instrument of so little power.

In the eighteenth century a Ramsden's sextant was a good navigation tool that enabled mariners to determine altitudes of celestial objects and ascertain their position at sea with accuracy. An example of such an instrument is shown in Figure 4.

Equipment apart, one needed accurate positions of fixed stars in the sky, with due corrections applied for precession and nutation. The most notable eighteenth century star catalogues were Flamsteed's *Historia Cœlestis Britannicæ* (1725); Lacaille's *Coelum Australe Stelliferum* (1742), a catalogue of 9766 southern stars; and Lalande's *Éphémérides des Mouvemens Célestes* … (1783). The latest, however, was Piazzi's first catalogue, *Praecipuarum Stellarum Inerrantium*, a catalogue of 6748 fixed stars that was published in 1803 (Lequeux, 2014; Thurmond, 2003). However, according to Kochhar (pers. comm., December 2018), at that time Madras Observatory did not possess any star catalogues, and for his part Warren (1808) does not mention using one.

Warren (ibid.) determined the orbit of the comet using spherical trigonometry and Kepler's laws. To deduce the six elements, at least three separate sets of angular observations of right ascension (α) and declination (δ) were necessary, and he used four consecutive observations, made on 3, 14 and 25 October and on 18 November. Calculations for a highly eccentric ellipse were normally quite involved, and since during the brief interval a comet was seen, the arc of an elliptical orbit had about the same curvature as that of a parabola, astronomers chose to work with that assumption (see Gregory, 1802: 393).

Using the Ramsden sextant, Warren measured the angular position of the comet with reference to two nearby fixed stars, using different reference stars on each occasion, and he duly recorded the local time of each observation. Corresponding to the date and the time of each observation, he derived and tabulated the right ascension, declination, geocentric longitude and geocentric latitude of the comet, the Sun's ecliptic longitude and elongations of the comet. Warren (1808) did not give the exact times of his last two observations. He then proceeded to look for a parabola that would represent the position of the comet in the sky at these respective epochs. Warren (ibid.) obtained a parabola from the first two observations, and stated:

> … if by applying the circumstances of the third observation, it is also found to answer then it will be the real path, or orbit of the Comet.

The deduced orbital elements are presented in the second table in Warren's manuscript. He also tabulated the orbital elements of the comet of 1684, about which he says "… is the only one that bears the least resemblance with ours." This comet is now designated C/1684 N1, and the elements are those given by Halley (1704–1705: 1886), but the time of perihelion passage differed. In fact, the given date is close to that cited later in 1874 by Neugebauer (see Kronk 1999: 378).

After fixing the orbit of the comet of 1807, Warren examined what would be the position of the comet at any given period before its perihelion, say, at 90° anomaly descending and the number of days that would elapse for it to move through this anomaly. One may read this in view of Gregory (1802: 399), who gives the time of passing from perihelion to 90° as $\sim q^{3/2}$. For the distance to the comet on 3 October, Warren deduced a figure 1.1386 AU. Apparently, he computed the absolute value and expressed it in terms of the unit of the Earth-Sun distance then in use, although he did not specify this. That value would have been the one arrived at following the most recent transit of Venus. Observations to determine the solar parallax during the 1769 transit were the most accurate then available, but the values ranged from 8.43″ to 8.80″. As the currently-accepted value for the solar parallax is 8.794148″ (Dick et al., 1998) and the Horizons software gives the corresponding figure for the distance as 1.159 (AU), we can appreciate Warren's result.

Warren (ibid.) deduced that if the comet were at its node on 21 June at noon, when the Earth had an anomaly of 8^{s}:29°:1′:15″ (which was the longitude of the ascending node), the comet would have eclipsed the Sun. The longitude was expressed in terms of signs, where $8^{s} \equiv 240°$. Warren ended his 1 January 1808 write-up by noting the observations that were made by his Indian assistant:

Figure 4: An eighteenth century Ramsden sextant (from NationalGeospatial-Intelligence Agency https://www.nga.mil/ABOUT/HISTORY/TIMEANDNAVIGATIONEXHIBIT/Pages/RamsdenSextant.aspx accessed 19.01.2019).

> Having been prevented by illness to observe after the 2nd of December the Bramin assistant Senivassachari continued to notice it. On the 8th of December at 7h P.M. he took roughly its distance from α Cygnii which was about 9°:47′ N.W. and from α Aquilae 35°:11′ NE.
>
> The last sight he had of it was on the 13th after which the light of the Moon prevented his perceiving it any longer.

Warren's regret in not having access to suitable equipment is somewhat puzzling since we know that by 1807 Madras Observatory already possessed three Dollond refractors, a Bird quadrant and a Stancliffe transit telescope. Sextant measurements are not considered very accurate, for, at very least the instrument should be securely mounted. However, given Warren's

Table 1: The orbital elements of the Great Comet of 1807.

Elements	Warren (1808)	Bessel (1810)
Perihelion Distance (*q*)	0.61305	0.64612382
Longitude of the Perihelion Distance		9.8103157,5
Eccentricity (*e*)	1.0	0.99548781
Semi-major axis		143,195
Inclination of orbit (*i*)	63°: 40′: 51″	63°: 10′: 28.1″
Longitude of the Ascending Node (Ω)*	8s: 29°: 1′: 15″	266°: 47′: 11.45″
Place of perihelion (*ω*)*	8s: 26°: 13: 40	4°: 7′: 30.49"
Time of Passage (Greenwich time)	September 16d: 21h: 2′: 36″	September 18.745366 (for Paris)
Motion	Direct	
Period		1,713.5 years
* Note that Warren's longitudes are expressed in terms of signs (where $8^s \equiv 240°$).		

involvement in the trigonometrical survey, it is not surprising that he was able to give the comet's angular separations from reference stars to the last second of an arc, and the time of the observations to one-tenth of a second. Warren's observational data may yet be useful in any future attempt to further refine the comet's orbit elements.

5 DISCUSSION

5.1 Determining Cometary Orbits in the Early 1800s

Ever since Newton published his *Principia* (1687, Book III, Problem XXI), where he devised a way to calculate a (parabolic) orbit of a comet from three successive observations and used it to compute the orbit of the comet of 1680 (that he had observed), astronomers worked hard to improve the algorithm. They also worked to incorporate the gravitational influences of Jupiter and Saturn, and later Uranus, on a comet's motion.

The first decade of the nineteenth century witnessed the most crucial development in the art of orbit computations, spurred on by the discovery of four minor planets between 1 January 1801 and 29 March 1807 (see Cunningham, 2016; 2017a; 2017b; 2017c; 2017d). The whole exercise of orbit determination used to be arduous. One would divide the orbit into degrees, and for each degree the computations performed were daunting. Then in 1801 Carl Gauss (1777–1855) presented a simple and quicker method of computing an elliptical orbit by using observations derived from an arc in the sky (Gauss, 1809). This approach soon led to the recovery of a 'lost' Ceres.

As for the Great Comet of 1807, a number of astronomers, including the German Friedrich Bessel (1784–1846), worked out their methods and calculated parabolic orbits based on observations made in October 1807 and incorporating the effects of perturbations. These led to different dates for the perihelion passage. From computations based on observations that extended to 24 February 1808, Bessel found that the orbit was elliptical, with perihelion on 19 September, and a period of 1953 years. Later Bessel (1810) refined the orbital elements on the basis of the observations made between 22 September 1807 and 27 March 1808, which confirmed that the orbit was elliptical, but with a period of 1713.5 years.

The orbital elements that Warren (1808) calculated were close to Bessel's 1810 values, differing mainly in the time of perihelion passage and in the eccentricity (*e*)—see Table 1.

When Bessel (1810: v) presented his calculations, he also made a significant claim for the Great Comet of 1807:

> This is the only comet, with the exception of Halley's Comet whose return was confirmed by its numerous apparitions, that one can assert with certainty to be moving in an elliptical orbit. (My English translation.)

That comets moved in highly eccentric orbits was an accepted norm, but at that time the only comet that was known to move in an elliptical orbit was 1P/Halley. After Edmund Halley (1656–1742), Johann Franz Encke (1791–1865) was the first to report another periodic comet. He rightly concluded that the comets first seen in January 1786, November 1795, October 1805, and November 1818 were one and the same. In 1820 he predicted its return in May 1822, determining a perihelion date of 24 May and a period of 3.32 years. The comet was first detected at Parramatta Observatory in Australia (Saunders, 2004: 185–186), and passed perihelion only about half a day earlier than predicted. The comet has the shortest known period of any comet and is appropriately named 2P/Encke.

5.2 Other Indian Observations of the Great Comet of 1807

There were a few other reported sightings of the comet in September and October 1807 made from Calcutta and Madras.

Sandeman (1868: 181–182) reported:

> THURSDAY October 8, 1807
>
> In our Extra Gazette of the 3rd instant, we had the honor to announce to our readers the appearance of a Comet, and our determination to submit, to their perusal, such information regarding the place and course

of the phenomenon, as we might be able to obtain from men of science, The Comet was undoubtedly seen on the 21st of September, and, we have reason to believe, at an earlier date, but though seen, it seems to have excited very little of the curiosity of those who beheld it, and was not generally observed before the 2nd of October, when the appearance of the star was so luminous as to attract the almost universal notice of the Settlement. On the 3rd of October the Comet was al-so visible, and on that day was observed with a view to ascertain with a reflecting sextant its angular distance from two given stars. The dimness of the specular and other causes prevented the success of the observation, and, on the 4th and 5th of October, the Comet was entirely obscured by the clouds. We have reason to believe that the place of the Comet was ascertained by the result of an observation taken on Tuesday night, but of this fact we are not certain, any more than of a vague opinion which has been stated to us, that the Comet is now receding from the Sun.

If any arguments were wanting to convince our Countrymen of the propriety of establishing a public observatory at this place, we think that the appearance of this Comet, and the unprepared state in which our men of science have (necessarily) been found on the occasion, would be sufficient to bring home conviction to the minds of our most skeptical readers. On this subject there are, however, no sceptics, and we are well aware that the want of an observatory must be ascribed, not to any disinclination on the part of the Settlement to furnish the trifling contributions which the support of such an establishment might eventually require, but merely to that simple, though common, cause of impediment to the progress of all improvement, *the disinclination of individuals to propose a measure which it belongs to the public to carry into effect*. [His italics.]

At Bombay, a public observatory has, we believe, been already projected by the Literary Society of that place. At Madras (fortunately for the interests of science) a public observatory already exists; and we shall be sorry to find our own is the only presidency in India, which can be reproached with the absence of an establishment at once so useful and so little expensive, that the charges for erecting it, as well as for furnishing the necessary apparatus, might be more than defrayed by the proceeds of one, or, at the most, of two lotteries.

Since we wrote the preceding paragraphs we have received certain information that the place of the Comet has been ascertained. The velocity and direction are still unknown.

There was also a report in *The Asiatic Annual Register* (1811: 13) in the section titled "Bengal Occurrences, 1807":

Oct. 6 - ... For some days past a comet made its appearance. It disappears from the horizon early in the evening. The natives assert, that it portends a scarcity of grain, from its baleful effects on the atmosphere.

In the same *Register*, the section on "Madras Occurrences, 1807" also carried a description of the comet on page 124. There also was a mention of the comet in a London magazine, *The Literary Panorama*:

Comet. – Madras, October 7. – For several evenings past an unusual luminous appearance, supposed to be a comet, has been seen in the west. It disappears about 8 P.M. Its progress is rapid, and it seems to be fast approaching the sun. It will be remembered that a comet appeared in Europe a few months ago. (Taylor, 1808: 359).

Note that the aforementioned Bombay Literary Society was founded in November 1804 along the lines of the Asiatic Society of Bengal (1784) to promote scientific discussions. In 1805 it started a library, a museum and an astronomical observatory (Sangwan, 2000: 19). In Bombay, the East India Company only established a facility for astronomical observations and time-keeping much later, at Colaba, in 1823. The East India Company also established an observatory at Calcutta in 1825 in the Surveyor General's Office in Chowringhee. This was championed by the Surveyor General of India V. Blacker (1778–1826), and would serve the Survey Department (see Sen, 2016: 46–53, 62–63).

5.3 The Great Comet of 1807: An Independent Discovery From India

As Kronk (2003) notes, the Great Comet of 1807 should have been spotted from the southern hemisphere weeks before it was discovered from Europe. Around the time of its discovery, the comet was a low declination object but with a solar elongation of about 35°, it would have been easier to spot from a location like Madras (Full Moon on 16 September, 16 October, etc.). In the MS Records, the date of Warren's first observation of the comet is not given, but in his manuscript Warren (1808) notes that

The Comet might have been seen when at its Perihelion; for then its Elongation was 32°:49′:21″ and its distance as 11.26 which is a little more than what it was on the 23rd of Nov. when it was still discernible to the naked eye. As it passed its node on the 17th of Sept at 20h:5′ when its Elongation was 34°: 42′:56″ and its distance somewhat less than the above, it must have been distinctly visible; and so it seems was the case since it was noticed at several places about the 20th of that month …

The Horizons System uses Bessel's refined elements of 1810 and one cannot miss noting their similarity to Warren's values. For the perihelion date of 16 September, the Horizons System gives the corresponding elongation as 33°.63 and also shows the comet having passed its node on 17 September at around 17 UT. All through the months of September, October and November, the comet trailed the Sun. The ephemeris of the comet generated for September 1807 presents an interesting perspective: its *r* and *Δ* values (heliocentric and geocentric distances in AU) changed only a little through the month, from 0.726 and 1.248 on 3 September to 0.709 and 1.158 on 3 October. On 9 September—the day of its discovery in Europe—its altitude in the Madras sky at sunset would have been ~20°; ~26° on 16 September and ~28° on 20 September. The comet then rose in altitude as days passed. Meanwhile, Venus was an evening object, and could be seen nearby. From the decreasing *r* and *Δ* values through the dates above, and the fact that it passed its closest by the Earth on 26 September at just 1.153 AU, one can infer how the comet would have gradually brightened during the month, affected only by a waxing Moon. Then through the latter half of October and November the brightness would decrease since *r* was increasing.

Phillimore (1950: 195) cites a flattering comment about Warren made by Justice Andrew Scott:

> I do not conceive that either Captain Warren's merit or his labour are so generally understood as they deserve to be. He sent me his paper on Zenith Distances & on the Comet to peruse … When the result of what he has done … comes to be known in Europe … Captain Warren will be found entitled to praise. If he were to give up his position at the Observatory at this time, I know of no one who could supply his place.

Warren and Sandeman (1868) independently refer to the first sightings of the 1807 comet being made from Bengal on 20 and 21 September respectively, which would imply that the comet was independently discovered from India. Those who observed the comet on the respective dates are nowhere named. In the days when communication with Europe happened through dispatches carried by ships, it would be months before Warren would learn about the comet's discovery in Europe, and *vice versa*.

It is important to note that at this time there was no set procedure to follow after the discovery of a new comet at a location far from Europe. Referring to a geographically isolated Australia in pre-telegraphic days, Orchiston (1997, and pers. comm., 2011) terms the situation a 'tyranny of distance' in the matter of independent comet discoveries made there. But more importantly, the disparity between amateur and professional astronomy stood out during the nineteenth century and may have played a key role in choosing whether or not to publish cometary observations. Professional astronomers were expected to do positional astronomy, not to search for, or follow, new comets—an activity reserved for amateurs—notwithstanding popular perceptions to the contrary. It is possible that this philosophy and the administrative changes then being effected at Madras (Phillimore, 1950: 299) caused Warren to refrain from making further observations of the 1807 comet. Then, a little later, he did not bother to write a paper on the Great Comet of 1811 that he observed and wrote about in the Madras MS Records.

5.4 Warren's Later Astronomical Studies

John Warren resigned from Madras Observatory in December 1811 (Phillimore, 1950: 196), and in 1814 he embarked upon a study of the south Indian astronomical chronological system. This culminated in a volume titled *A Collection of Memoirs on the Various Modes According to which the Nations of the Southern Parts of India Divide Time*, alternatively named *Kāla Samkalita* (in Warren's words, *The Doctrine of Times*), which was published in 1825 by the College Press in Madras (Warren, 1825). As Warren says, this work discusses three main subjects: (1) the Tamil solar year, that rests on Aryabhatta's *Ariyā Siddhānta* (but the latter may have based it on the *Sūrya Siddhānta*); (2) the luni-solar year, as per the *Sūriyah* Siddhānta; and (3) the the *Mahom-medan Kalendar*, as per the *Arabic* system. There is a copy of this book in the Indian Institute of Astrophysics Archives, and on page 9 it contains an interesting statement:

> *Ramissuara*m [this is now known as Rameswaram or Pamban], is a small Island, situated between Ceylon and the Continent of India, at the entrance of Palk's passage in the Streights of Manaar, *and is famous for its ancient Pagoda and Observatory*. [Our italics.]

The 'Pagoda' is the Ramanathaswamy Temple, one of the most sacred Hindu religious sites in all India and a major pilgrimage destination, but Warren's mention of an 'Observatory' is puzzling. Perhaps he was referring to Mt. Gandamadana near the town of Rameswaram. This is the most elevated site on this small low-lying island, and

> It is believed that this was the hillock from whose summit Lord Rama observed Lanka and conceived the idea of constructing a bridge between India and Lanka. A temple commemorates the exact site. (Pamban Island, n.d.).

6 CONCLUDING REMARKS

Records indicate that the Great Comet of 1807 was the first comet observed from Madras Observatory following its construction at Nungambakkam in 1792. Subsequently, John Warren also observed the Great Comet of 1811 (C/1811 F1), but his observations were very brief and were not published at the time. However, I discuss them in a separate paper (Kapoor, 2019) in this issue of the *Journal of Astronomical History and Heritage.*

The next comet that definitely was observed from Madras Observatory was the Great Comet of 1831 (C/1831 A1), which was tracked by Thomas Glanville Taylor. Going by his date of the first sighting, Taylor has been identified as an independent discoverer of this comet (Kapoor, 2011).

It is possible that one other comet was observed from Madras Observatory between 1811 and 1831. This was Comet C/1821 B1 (Nicollet-Pons), which was discovered on 21 January (Kronk, 2003: 54). John Goldingham was the Director of Madras Observatory at the time. A report dated 1 March 1821 in *The Asiatic Journal* (1821) mentions a comet seen in Madras during the previous four or five days. It was an evening object, and as the sky got dark it could be seen a few degrees above the horizon near γ Pegasi and northward of Jupiter but above it. The comet was said to be fading each day, and moving westwards. It is not clear if it was observed from Madras Observatory. Meanwhile, a report dated 10 March 1821 mentions that this comet, also "… has been seen by many respectable persons in Bombay …"

7 ACKNOWLEDGEMENTS

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Professor Ramesh Kapoor began his career in 1971 at the Uttar Pradesh State Observatory (now the Aryabhatta Research Institute of Observational Sciences, ARIES) at Nainital, India, in observational astronomy where his main interest was flare stars. From March 1974 until September 2010, he was with the Indian Institute of Astrophysics (IIA) in Bengaluru, where he worked on various topics in relativistic astrophysics centred round the observational aspects of black holes, white holes, quasars and pulsars, etc. He has participated as an observer and as an organizer in a few solar eclipse expeditions mounted by the IIA. Ramesh has published in international journals and presented papers at national and international conferences. His current research interest is history of astronomy, particularly comet sightings and observations from the Indian region. In addition, he has been active in popularizing astronomy, and he also has published on Indian systems of medicine. Ramesh is a member of the International Astronomical Union and a Life Member of the Astronomical Society of India.

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JOHN WARREN'S UNPUBLISHED OBSERVATIONS OF THE GREAT COMET OF 1811 FROM INDIA

R.C. Kapoor
Indian Institute of Astrophysics, Koramangala, Bengaluru 560034, India.
Email: rckapoor@outlook.com

Abstract: Captain John Warren was the Acting Astronomer of Madras Observatory during the years 1805–1811 when the Astronomer John Goldingham went to England on leave. At Madras, Warren observed the Great Comet of 1807 (C/1807 R1), computed its orbit, and prepared a manuscript that he sent to the Royal Astronomical Society in London (which they chose not to publish). Subsequently, Warren observed the Great Comet of 1811 (C/1811 F1), and recorded his observations in the Madras MS Records for 1812 (which are now housed in the Archives of the Indian Institute of Astrophysics). Outside Europe, Warren's Head Assistant Sanevasa Chairy was the first to independently notice the Great Comet-to-be, after rightfully sensing that the faint nebulosity near a star in Monoceros was a comet. Prompted, perhaps, by the fate of his 1807 paper, Warren chose not to write a paper about Madras Observatory observations of the 1811 comet, which I now discuss in this paper.

Keywords: The Great Comets of 1807 and 1811; Madras Observatory; John Warren; Royal Astronomical Society

1 INTRODUCTION

Captain John Warren (1769–1830; Figure 1) was Acting Astronomer of the Madras Observatory (Figure 2) during the years 1805–1811 when the Astronomer John Goldingham went to England on leave. In the course of his tenure, two Great Comets appeared in the sky, in the years 1807 and 1811 respectively. These comets are noted in history for creating sensation among astronomers, and even generated concern among the general public, leaving an indelible imprint on their minds (e.g. see Figure 3). Warren observed both comets and briefly recorded his observations in the Madras MS Records (1812).

Observations by astronomers in Europe and the U.S. are well documented but those by Warren remain unpublished. He recorded his observations of the 1807 comet in the form of a research paper (Warren, 1808) and sent this to England in 1809 (Ananthasubramaniam, 1991). This manuscript is now in the Archives of the Royal Astronomical Society (RAS MSS Madras 6) and through the courtesy the Royal Astronomical Society it has finally been published (see Warren 2019) and commented upon (see Kapoor 2019).

Warren's observations of the Great Comet of 1811 were briefly recorded in the Madras MS Records (1812), but they also were not published at the time. These are the subject of this present short paper.

A brief account of the early days of Madras Observatory and the equipment there has been given in Kapoor (2019), since Warren (1808) had regretted in his paper "… having no instrument at the observatory of sufficient powers of observation of this nature." For details of Madras Observatory see Kochhar (1985a; 1985b), while Kochhar and Orchiston (2017) provide an overview of nineteenth century astronomy in India.

Figure 1: John Warren (courtesy: Indian Institute of Astrophysics Archives).

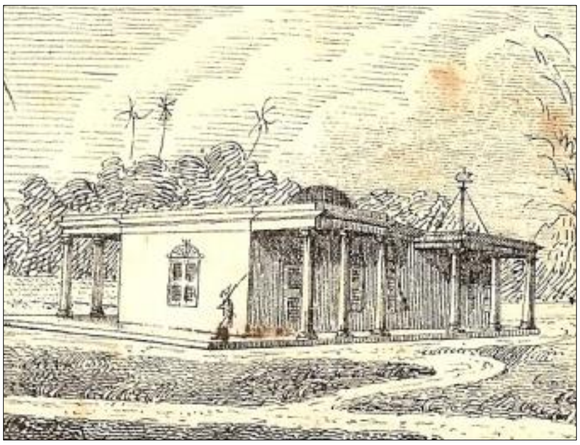

Figure 2: Madras Observatory at Numgambakkam (adapted from Taylor, 1838: cover image).

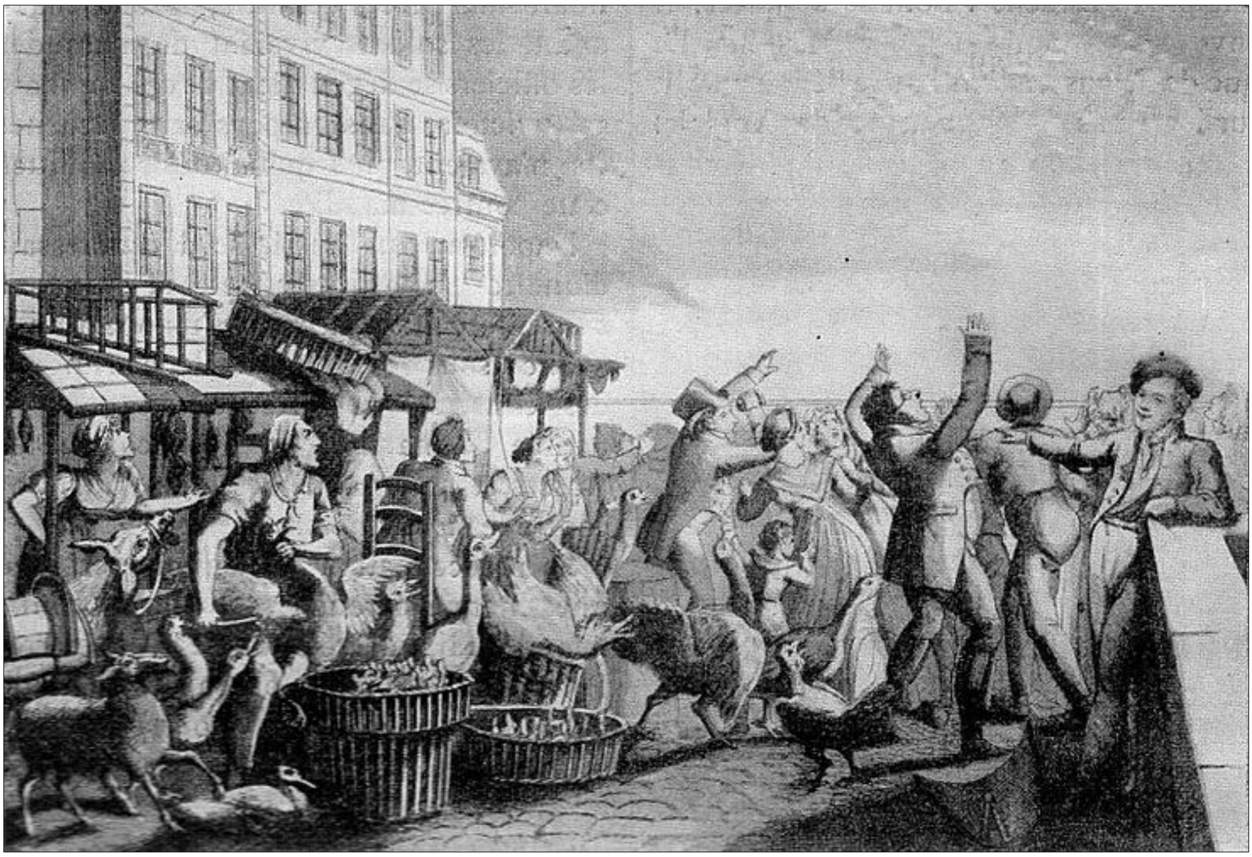

Figure 3: A charming French engraving showing public reaction to the appearance of the Great Comet of 1811 (https://fr.wikipedia.org/wiki/Fichier:Com%C3%A8te_1811.jpg).

2 THE GREAT COMET OF 1811

The Great Daylight Comet of 1811 (C/1811 F1) has an interesting history for it led to the Vintage Comet Wine of 1811. The brief entry on 'Comet wine' in Brewer's (1894) *Dictionary of Phrase and Fable* is worth reading. Comet Wine was a term of praise that was especially coined for a wine of superior quality. It came from grapes harvested in comet years that were considered to have better flavour than grapes grown in other years, for one believed that either the weather was warmer and that gave them a better quality or it was a positive chemical influence of the comet itself. This notion therefore made wines produced in the years 1811, 1826, 1839, 1845, 1852, 1858, 1861 etc. special. The finest vintage of the nineteenth century, however, belonged to the year 1811 when the harvest time September-October coincided with the presence in the sky of a Great Comet. The charm of the comet wine even led to the 1992 movie "Year of the Comet".

The Great Comet of 1811 was discovered at Viviers on the evening of 25 March by the French amateur astronomer Honoré Flaugergues (1755–1835; Lynn, 1905) in Argo Navis, the Ship of the Argonauts—a large constellation that in 1752 had been split by the French astronomer Nicolas Louis de Lacaille into Carina, Puppis and Vela. The comet was low in the south but was moving northwards and brightening. From its position given by Flaugergues for the next night the comet was located in Puppis. It was independently discovered by J.L. Pons on 11 April (Vsekhsvyatskii, 1964). The comet was visible to the naked eye for a record 260 days, a record shattered only by the comet Hale-Bopp in 1996–1997. Its tail extended to 70° in the month of December. It passed its perihelion on 12 September, was closest to the Earth on 16 October (at 1.2213 AU), and was last observed on 17 August 1812 (Kronk, 2003).

The comet left a great impression on persons of fine arts (e.g. see Figure 4), having been visible to the naked eye right from middle of April 1811 through to the first week of January 1812. It figured in the drawings of John Linnell (1792–1882), the great English naturalist, and *The Ghost of a Flea*, a miniature ca. 1819–1820 by William Blake (1757–1827) who had witnessed the comet (Olson, 1985). Blake illustrated several of his works with highly imaginative images of comets and meteors. A fiery comet also figured in Leo Tolstoy's (1828–1910) *War and Peace* (VIII, Chapter 22), but if the inspiration came from the comet of 1811, the wrong year was selected. Nevertheless, the ascription continued as recently as in 2016 when David Malloy's 2012 musical *Natasha*, *Pierre and the Great Comet of 1812*, inspired by a 70-page slice

Figure 4: A German depiction of the Great Comet of 1811 (https://fr.wikipedia.org/wiki/C/1811_F1#/media/File:Komet_von_1811.jpg).

from the great classic, premiered on Broadway in November 2016. There *was* a comet discovered by J.L. Pons on 21 July 1812 but it was too insignificant to cause such sensation and merit a place in works of art. Napoléon Bonaparte (1769–1821) was superstitious about the Great Comet of 1811 and adopted it as his guide-star and controller of his destiny. Some time earlier Charles Messier (1730–1817) had stated in his Memoirs of 1808 (1769 *Grande Comète qui a Paru a la Naissance de Napoléon-le-Grand Découverte et Observée Pendant Quatre Mois par M Messier*) that the great comet of 1769 "… preceded the birth of Napoleon the Great by 7 days …" (Meyer, 2007: 4); Messier had discovered this comet on 8 August.

According to the Jet Propulsions Laboratory (2017), the orbital elements of the Great Comet of 1811 are:

q = 1.035412 AU
i = 106º.9342
e = 0.995125
ω = 65°.4097
Ω (2000.0) = 143°.04977
Perihelion on 12.7562 September

3 JOHN WARREN'S ACCOUNT OF THE COMET

The Madras M.S. Records (1794–1812) of the Madras Observatory are hand-written records of the activity at the Observatory. Therein is a letter dated 27 April 1811 written by John Warren to the Acting Surveyor General informing him of the sighting of 'a nebulosity' on the evening of the 25 April. With the passage of time this would turn out to be the Great Comet of 1811.

The letter, in Warren's own handwriting, is reproduced below in full.

> To the Acting Surveyor General
>
> Sir
>
> I have the honor to inform you that on the evening of 25th Inst. the native head assistant at the Observatory reported to me that he had seen a faint luminous appearance near some unformed stars adjoining to the Constellation of Monocerous which he suspected might be a Comet. On the 26th in the evening I observed the same Phenomenon whose appearance was somewhat brighter than the Nebula in Andromeda close to a telescopic star in the lower part of Monocerous but observing no nucleus it was visible to the naked eye and something like a Train was discernible in a direction from the Sun. Its distance (taken with a sextant) was 18:20 (from Procyon) and from Sirius – 17:29.
>
> On the 27th about the same hour in the evening I observed again the same appearance, which had visibly altered its position, being then 1° from the telescopic star before mentioned, its brightness did not seem to have increased which I ascribe to the light of the Moon having become greater. On taking its distance from the same stars as before I found it from Procyon 17°:41′ E and from Sirius 17°:41′s which indicates a motion towards the sun of about 1° in 24 hours. The Train was discernible as before but a little fainter on account of the moonlight. No nucleus was yet formed, and untill that occurs no very accurate observation can be taken.
>
> I have now but little doubt of the appearance being a Comet. a few days more observations however will be necessary to make it quite certain.
>
> I have the honor to be Sir
> Your most obet. Sert
> M.C.Obsery.
>
> [Signed] J Warren
> 27th of April
> Actg astr

Note 'honour' and 'Monoceros', as spelt. To whom did the letter refer as the Acting Surveyor General? According to Phillimore (1950: 299) it would have been William Morison (1781–1851) who was Acting Surveyor General until end of March 1815, in place of the new appointee, Major Mackenzie, when the latter had to leave for Java in April 1811.

Notably, Warren's un-named Assistant was versant with the sky and celestial phenomena, and prescient enough to perceive of the observed nebulous form as a comet. We can only guess how the observers responded to the language barrier, but what the Assistant reported to his superior did earn him credit. Phillimore (1950: 196) mentions that there were two *Brahman* Assistants at the Observatory who had similar duties to perform, but one of them was more experienced and had an advantage in that he could speak and write English. The two Assistants would observe the transit of the Sun every noon, frequently occurring eclipses of the Jovian satellites and the transits of certain stars for the purpose of regulating the astronomical clock, etc.

In his paper on the comet of 1807, Warren (1808) mentioned his Bramin Assistant 'Senivassachari' who had observed the Great Comet of 1807 together with him. I believe he was still an Assistant in 1811 because in his report published in *Asiatic Researches* on determining the obliquity of the ecliptic in the months of December 1809 and June and December 1810 Warren (1818: 194) names his Brahmin Assistant as Sanevasa Chairy. Incidentally, he would appear to be the father of Chintamani Ragoonatha Charry

(b. 1828) who began working at Madras Observatory in 1840 and went on to create an international reputation as an astronomer (see Rao et al., 2009; Shylaja, 2012; Venkateswaan, 2018).

Based on a communication by Warren, a short note on the comet of 1811 appeared in *The Literary Panorama* also, followed by an Addendum (The Literary Panorama, 1812: 726–727). The note, titled *Detail of a Luminous Phenomenon Lately Discovered by Captain Warren, at Madras*, covers his observations over the period 25 April–16 May. The description of the observations up to 27 April largely matches that in his 'Letter' reproduced above, but also includes his observation of the 26th. The text below is reproduced in full because it is best said in Warren's own words.

> On the 25th of April last, at 8 P.M., a luminous appearance was noticed by him between the constellation of Canis Major, and Monoceros on the Eastern skirts of the Milky-way; which it was at first supposed to belong to. It was in brightness equal to the Nebula in Andromeda, but so undefined that it could not be observed with an instrument on that evening.
>
> On the 26th at 7h.30m. P.M. the same phenomenon was noticed somewhat North of East, of its former position. A faint luminous trace was discernible to the naked eye, and extended from it, in a direction opposite to the Sun. Its distances from Syrius, and Procyon were observed with a sextant as follows:-
> From Syrius 18d. 20m. E } 7h. 45m.
> From Procyon 17d. 10m. S }
> it then stood close East of a Telescope star being one of the unformed group below Monoceros.
>
> On the 27th its position with respect to the same stars was,
> From Syrius 17d. 37m. E } 7h. 50m.
> From Procyon 17d. 41m. S }
> having moved 1d. nearly towards the Sun. The body was less luminous, owing probably to the increased light of the Moon which had approached it. The train was still visible to the naked eye. It had moved through a whole diameter of the Telescope from the small star near to which it was seen on the previous day; and covered another Star of the 7th or 8th magnitude so that had it been thus placed on the 25th it would have been taken for the Nucleus of a Comet.
>
> On the 28th, the Moon shining bright, the luminous appearance was so faint that no accurate observation could be obtained. It had, however, left the small star which it covered on the preceding night, and had moved through another diameter of the Telescope towards the Sun. There was at 8 on that evening as little appearance of a Nucleus as before. On the 29th and 30th the weather being hazy and the Moon not far from the phenomenon, it could not be observed.
>
> Some more observations are required to ascertain whether this appearance be a Comet or not. Its geocentric motion towards the Sun and the faint haze which extended behind it in a contrary direction indicate it to be of that class, and if it be still discernible about the 15th of May, whatever doubt may be entertained respecting its nature will then be entirely removed. JOHN WARREN. H.C.'s Observatory, 1st of May, 1811."
>
> May 16 – The weather having cleared on the 8th of May, the Phenomenon observed by Capt. Warren at the Hon. Company's Observatory near the Constellation of Canis Major was again observed in the upper part of Monoceros in a direction somewhat east of north of its former position; exhibiting to the naked eye the usual appearance of a Comet with a distinct train, though no Nucleus was discernible with a telescope. It had moved since the 28th of April at the mean rate of 0:28½ per diem.
>
> The appearance of this Comet has hitherto been so undefined that it could not be observed with sufficient accuracy to obtain satisfactory results respecting its orbit. Several more observations will be requisite for computing its elements; which may be obtained hereafter, as it probably will be visible for some time longer. –Govt. Gazette.

4 ON THE OBSERVATIONS BY JOHN WARREN

According to Kronk (2003: 19) the comet was in Puppis when discovered on 25 March, in Monoceros on 28 April and in Canis Minor on 21 May, and so on. Warren took two accurate positions with the sextant during 25–30 April 1811—about one month after the discovery—and from these he deduced that the comet was moving towards the Sun at a rate of about 1° in 24 hours.

Unfortunately Warren's two positions of the comet cannot, by themselves, be used to determine the orbit. To deduce the six orbital elements, at least three separate sets of angular observations of right ascension (α) and declination (δ) are necessary. For the comet of 1807, Warren (1808; 2019) used a set of four consecutive observations and determined its orbit using spherical trigonometry and Kepler's laws. He did not consider perturbations from the major planets but the elements came close enough to those finally calculated by Bessel (1810). Earlier we noted:

> The first decade of the nineteenth century witnesssed the most crucial development in the art of orbit computation, spurred by the discovery of four minor planets between 1

Table 1: Location of the Comet

Date (1811)	Elongation of the Comet	
	From Sirius	From Procyon
26 April	17° 16′ (17° 29′)	17° 54′ (18° 20′)
27 April	17° 26′ (17° 41′)	17° 22′ (17° 41′)

> January 1801 and 29 March 1807 .... The whole exercise of orbit determination used to be arduous. One would divide the orbit into degrees, and for each degree the computations performed were daunting. Then in 1801 Carl Gauss (1777–1855) presented a simple and quicker method of computing an elliptical orbit by using observations derived from an arc in the sky (Gauss, 1809). This approach soon led to the recovery of a 'lost' Ceres. (Kapoor, 2019: 142).

In the present case, we can at least generate the comet's positions using Horizon software to see where it was located in the sky on the two dates of the observations. The timings 7h 45m and 7h 50m as given are local mean times since these are Madras Observatory times. For Greenwich Time we subtract 5h 21m from each, to allow for the longitude of Madras. With that, we have computed the respective elongations--see Table 1.

In this Table the values in brackets are those that Warren recorded in the Madras MS Records (and they differ slightly from those listed in *The Literary Panorama 1812*). Warren's measured elongations indicate that the comet made an approximate right-angled triangle with the two prominent reference stars on the two dates. These two stars made it easy for him to follow the movement of the comet in right ascension and declination. The elongation values in Table 1 compare well, and show that the comet moved north more than it moved east or west. As we know, sextant measurements are not considered very accurate, but because he was involved in the Trigonometrical Survey of India Warren was able to measure the comet's angular separations from the reference stars to the last minute of an arc, and record the time to the nearest minute. To gain a real feel for how the Madras astronomers would observe, one needs to go through Goldingham's (1809: 22: 153–156) account. It is an astronomer's manual in brief, but it shows how concerned the early observers were about the correct values for the longitude of Madras, the angular measurements, and the apparent and the mean time of the observations, etc.

For 26 April, the phrase that "… it then stood close East of a Telescope star being one of the unformed group below Monoceros …" leads us to the star 5 Puppis (apparent mag. $5.^{m}5$) as the probable candidate. A screen-grab from SKY-MAP.ORG of the region near 5 Pup (in the box) is reproduced in Figure 5 to recreate the situation. The star 5 Pup is located ~2°.5 south of α Monocerotis ($3.^{m}9$). The brightest star near the bottom of the photograph is Sirius and the bright star at top-left is Procyon; the Orion complex is to the right. As per Warren's description, the comet would have been near the left edge of the box, the computed elongation between the two that day being ~1°.5.

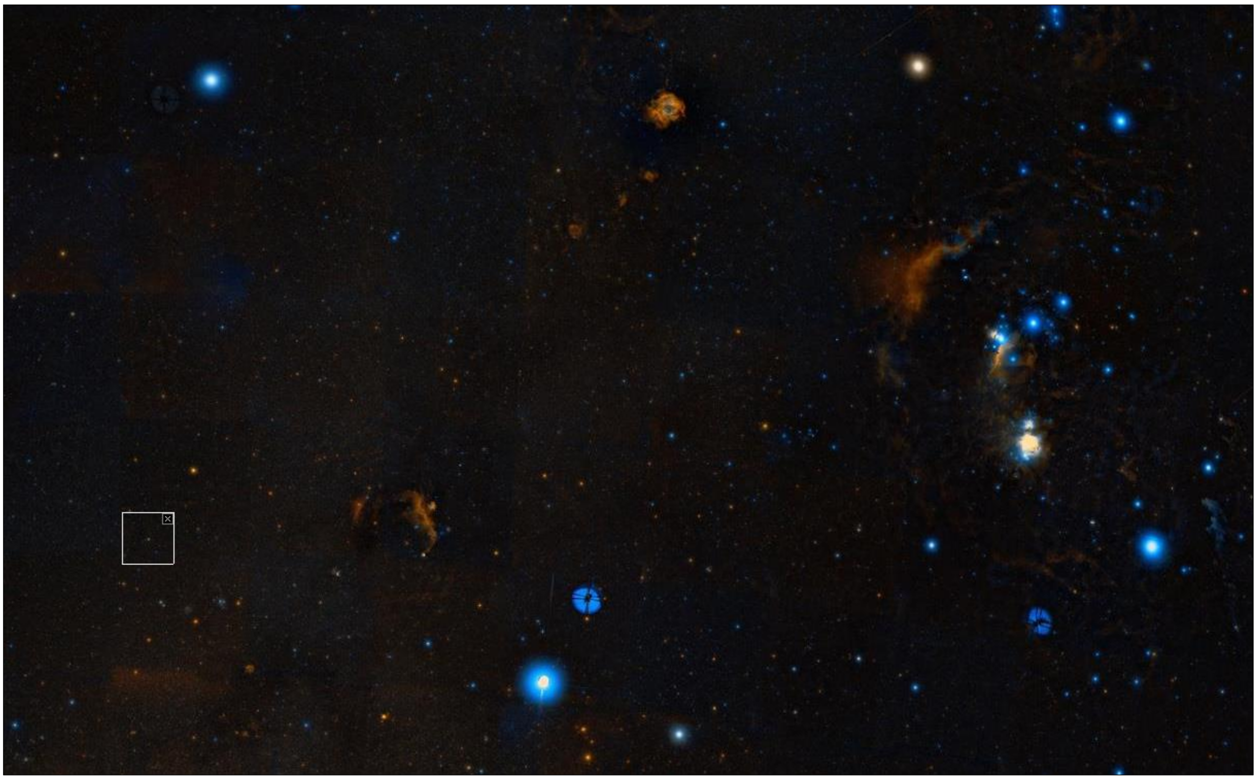

Figure 5: A screen-grab from SKY-MAP.ORG of the region near the star 5 Puppis (in the box). For details, see the text.

Ironically, Warren did not return to the comet, even when it later turned into a spectacular object months later, with a tail that extended 70° in December (Vsekhsvyatskii, 1964: 144). When it was discovered its apparent declination was about –30°, so it was easier to access from low latitudes. Meanwhile it was moving northwards mainly in declination, reaching –12° in late April when first spotted at Madras. In between, its heliocentric (*r*) and geocentric distances (*Δ*) changed a little, from 2.73 and 2.16 AU to 2.36 and 2.19 AU respectively. During this period there was a Full Moon on 8 April. J.L. Pons, who was not aware of Flaugergues' discovery, first saw the comet from Marseilles on 11 April, and Von Zach confirmed Flaugergues' discovery that same day (Kronk, 2003: 20). Later that year he summarized the observations of the comet made by several European observers between 11 April and 2 June (von Zach, 1811: 191; cf. Flaugergues and Burckhardt, 1811: 599 and Olbers, 1814: 242). The comet was in conjunction with the Sun in June, and Olbers (1814: 242) described its reappearance in the second half of August.

According to von Zach (1811), there were several early observers of the comet, and all were from Europe. Their names read like a 'Who's Who' of astronomy. Outside of Europe, Sanevasa Chairy (modern version: Srinivasa Chary) was the first to independently notice the comet, on 25 April 1811, having rightly sensed that the faint nebulosity near stars adjoining Monoceros was a comet. Previously, it was thought that the first observer of the comet outside of Europe was J.J. de Ferrer of Cuba, on 18 May 1811 (Lynn, 1898: 242).

5 CONCLUDING REMARKS

Warren did not compute the orbit of the Great Comet of 1811, but his observations of this comet and the Great Comet of 1807 qualify for inclusion in the suites of observations used in orbit determination incorporating the perturbation effect of the planets.

During the nineteenth century, professional astronomers were expected to do positional astronomy, not search for or follow new comets—an activity reserved mainly for amateurs. It is likely that this philosophy and the Royal Astronomical Society's decision not to publish his paper about the Great Comet of 1807 were the reasons why Warren chose to cease making any further observations of the 1811 comet or author a short paper based on the observations that he had made.

6 ACKNOWLEDGEMENTS

My sincere thanks are due to the anonymous referees for their meaningful comments. I thank the Director of the Indian Institute of Astrophysics (IIA) for permission to use John Warren's unpublished accounts of the comets of 1807 and 1811 contained in the Madras MS Records in the IIA Archives, and Drs Christina Birdie and A. Vagiswari, Mr P. Prabahar and Mr B.S. Mohan from the IIA Library for help in accessing various references. I thank Professor A.V. Raveendran, formerly at the IIA, for clarification of 'Madras Time', and Professor Rajesh Kochhar for useful suggestions. I also am grateful to Professor Wayne Orchiston for helping improve the presentation of this paper. This work has gratefully made use of NASA's Astrophysics Data System, the "On-Line Solar System Data Service" of the Jet Propulsion Laboratory, the websites of John Walker, Iran Chamber Society, CalendarHome.com and Juhani Kaukoranta and Raahen lukio, and several classic works and reference material on the internet.

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Professor Ramesh Kapoor began his career in 1971 at the Uttar Pradesh State Observatory (now the Aryabhatta Research Institute of Observational Sciences, ARIES) at Naini Tal, India, in observational astronomy where his main interest was flare stars. From March 1974 until September 2010, he was with the Indian Institute of Astrophysics (IIA) in Bengaluru, where he worked on various topics in relativistic astrophysics centred round the observational aspects of black holes, white holes, quasars and pulsars, etc. He has participated as an observer and as an organizer in a few solar eclipse expeditions mounted by the IIA. Ramesh has published in international journals and presented papers at national and international conferences. His current research interest is history of astronomy, particularly comet sightings and observations from the Indian region. In addition, he has been active in popularizing astronomy, and he also has published on Indian systems of medicine. Ramesh is a member of the International Astronomical Union and a Life Member of the Astronomical Society of India.

AUSTRALITES. PART 2: EARLY ABORIGINAL PERCEPTION AND USE

Philip A. Clarke
17 Duke St, Beulah Park, South Australia 5067, Australia.
Email: Philip@anthropac.com.au

Abstract: This paper reviews the Indigenous perception and use of australites as recorded in the Australian ethnographic literature. Aboriginal people perceived australites as having power derived from their Creation ancestors. There are accounts of australites being ritual objects used for healing, rain-making, hunting, sorcery and conveying messages. There are also descriptions of Aboriginal people using australites as raw material for tool-making, as their glass-like properties enabled specialised microlith tools to be made from them.

Keywords: tektites, Aboriginal Australians, Creation ancestors, ritual objects, tool-making

1 INTRODUCTION

During the nineteenth century Australian tektites, known as australites, were chiefly seen by scholars as obsidians of volcanic origin. For scientists, a problem was that many of the areas where they were found on the surface did not have a volcanic history. This lack of connection between australites and the geological areas of their distribution led to the conclusion that they must have been widely distributed by humans, and to some extent by the large birds that they hunted (Clarke, 2018b; McColl, 2017). Scholars studying the distribution of australites implicated the actions of Indigenous people living in Australia prior to the arrival of British colonists in the late-eighteenth century. Supporting this suggestion was the fact that australites were often found in places, such as old campsites and waterholes, that Europeans perceived to be associated with Aboriginal people.

Australite-researcher George Baker (1957: 1) summarised the anthropological significance of australites in Australia, which

> … are sometimes encountered, among other types of stones, on the sites of ancient aboriginal camps, and are distinctive in being remarkable, black glassy objects, mostly possessing relatively regular shapes. Many of them were treasured by certain aboriginal tribes … as medicine-stones, death-pointers, punishment-stones, hunting-stones, sacred-stones, magic-stones, amulets or charm-stones, throwing-stones, rainmaking-stones, message-stones, and a few were used as small implements. It has also been suggested they were earlier used as barter-stones.

In the twentieth century, scientists believed that australites were meteoric glass produced by a lunar strike, but more recently they have been recognised as material produced by a meteorite strike somewhere in Southeast Asia about 793,000 years ago (Lei and Wei, 2000; McColl, 2017). Australites were therefore present in the Australian landscape long before the arrival of the ancestors of modern-day Aboriginal people.

This paper is the second instalment of a two-part study that aims to explore the relationships that Australia's Indigenous people had with australites. The first-part considered the Indigenous involvement in the discovery and finding of australites (Clarke, 2018b). The focus of this paper is to explore Indigenous cultural perspectives on the origin of this category of tektite and document their use in material culture as ritual items and artefacts.

1.1 Ethnographic Sources

Those Europeans who compiled records pertaining to the Aboriginal perception and use of australites included explorers, settlers, colonists, scientists, geologists, mineralogists and anthropologists. While there is some useful cultural data available on australites for analysis, there are major biases with it. For many areas we must chiefly rely upon anecdotal accounts from settlers and colonial officials of the late-eighteenth and early-nineteenth centuries who were able to compile information from Aboriginal people as survivors of the first wave of European settlement. The spatial coverage of Aboriginal records across Australia is such that there are good records available for parts of the tropical and arid zones, but major gaps for most of the temperate zone, and particularly for Tasmania. For localities mentioned in the text see Figure 1.

For accounts of Indigenous beliefs and customs for many areas of Australia we must chiefly rely upon anecdotal accounts from those Europeans who were in contact with Aboriginal people who could remember a time before British settlement. The settlers and colonial officials who had ethnological interests in australites included James Dawson (1806–1900) in southwest Victoria, William D. Campbell (1849–1938) in the Goldfields of Western Australia, Ethel Hassell (1857–1933) in southwest Western Australia, George (Poddy) Aiston (1879–1943) in eastern Central Australia, and Anthony G. Bolam (1894–1966) on the Nullarbor Plain. Early geologists and mineralogists who documented Indigenous beliefs concerning australites were Ralph Tate

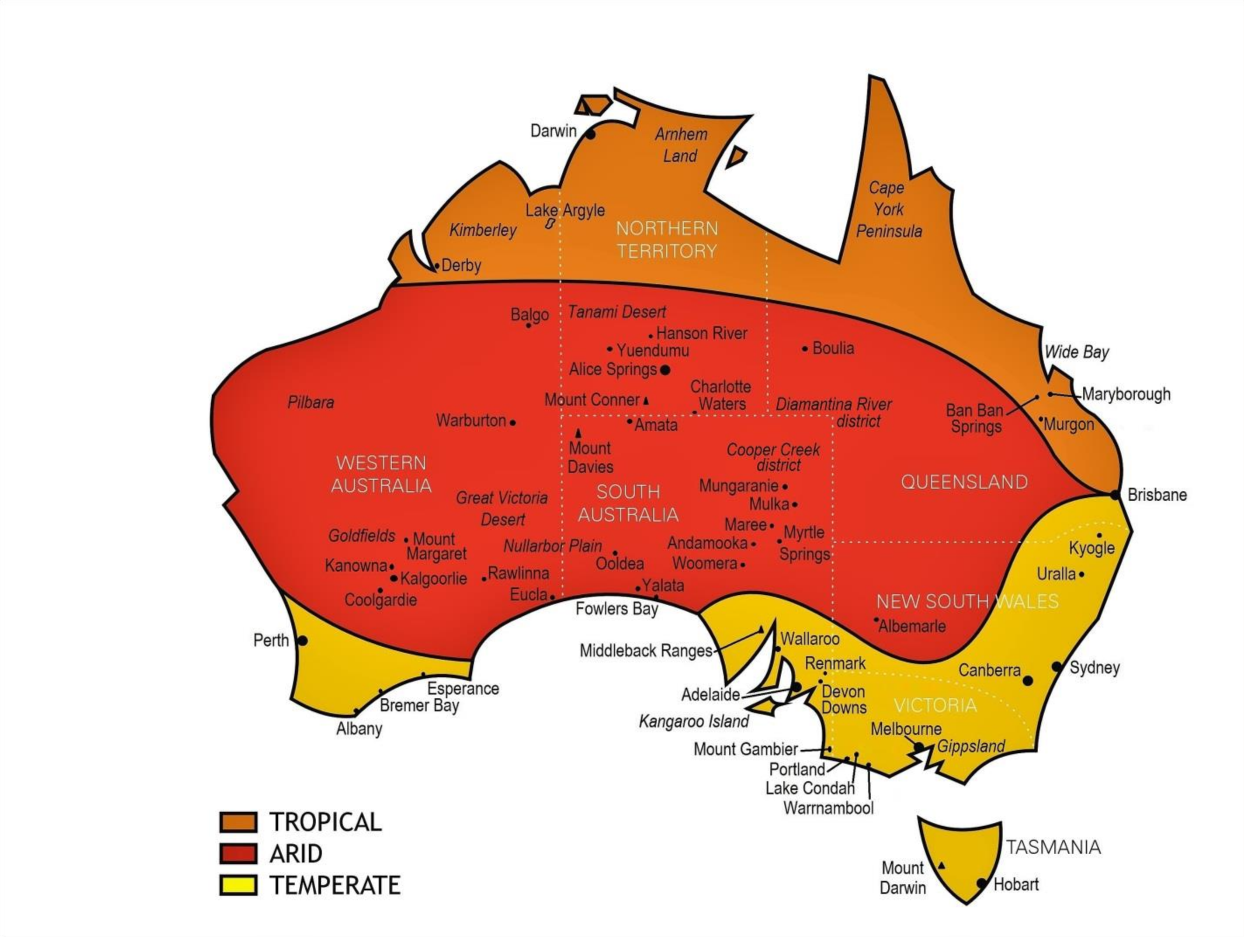

Figure 1: Australian localities and regions mentioned in the text.

(1840–1901; Figure 2), Edward J. Dunn (1844–1937), Walter Howchin (1845–1937) and Herbert Basedow (1881–1933).

Anthropologists who compiled records pertaining to the Aboriginal perception and use of australites were Lorimer Fison (1832–1907) and Alfred W. Howitt (1830–1908; Figure 3) across southeastern Australia, John Mathew (1849–1929) and Lindsey P. Winterbotham (1887–1960) in south-east Queensland, Frank J. Gillen (1855–1912) and W. Baldwin Spencer (1869–1927) in eastern Central Australia, and Daisy M. Bates (1859–1951; Figure 4) along the Nullarbor Plain.

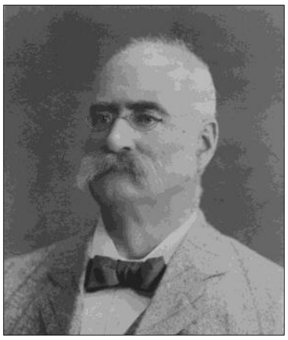

Figure 2 (left): Ralph Tate (https://en.wikipedia.org/wiki/Ralph_Tate#/media/File:Prof._Ralph_Tate_FGS_FLS.jpg).

Figure 3 (right): Alfred William Howitt (adapted from https://en.wikipedia.org/wiki/Alfred_William_Howitt#/media/File:Alfred_William_Howitt_circa_1861.jpg).

Figure 4: Daisy Bates (https://en.wikipedia.org/wiki/Daisy_Bates_(author)#/media/File:Daisy_Bates_2.jpeg).

Figure 5 (left, upper): George Baker (after Gill and Segnit, 1976: 519).

Figure 6 (right): Norman B. Tindale (centre), with some other staff from the Anthropology Division at the South Australian Museum in 1985 (courtesy: South Australian Museum Archives) [Editorial Note: Third from left in this photograph is a youthful Philip Clarke, the author of this paper.]

Figure 7 (left, lower): Charles Fenner (courtesy: Ballarat School of Mines Museum).

The field interests of Adolphus P. Elkin (1891–1979) were widespread across the continent. In the case of Herbert Basedow, who is mentioned above with the geologists, he was often considered to be an anthropologist and had also trained in medicine.

Museum-based scholars have been prominent in both the collection and research of Indigenous relationships to australites. At the Australian Museum in Sydney was archaeologist Frederick D. McCarthy (1905–1997), who documented Aboriginal material culture across the country and provided published overviews of artefacts and art (Kahn, 1993). Geologist George Baker (1908–1975; Figure 5) was a well-published australite researcher who worked on collections held in the National Museum of Victoria[1] (Gill and Segnit, 1976). The work of Baker (1957) is particularly significant for this present paper as he wrote a detailed account of the Indigenous uses of australites and provided a list of Aboriginal names for them, referenced to the 'tribes' as documented by Norman B. Tindale (1940) at the South Australian Museum. Another prolific scholar was geochemist William (Bill) H. Cleverly (1917–1997), and he was an honorary researcher at the Western Australian Museum (Bevan, 1999).

At the South Australian Museum, the ethnologist Norman B. Tindale (1900–1993; Figure 6) recorded Aboriginal traditions across Australia during a career that spanned much of the twentieth century (Jones, 1995). He was a member of several fieldtrips that were organised with a brief that included searching for australites. For instance, australites were collected by him in 1935 when he accompanied cinematographer E.O. Stocker on an expedition to the Warburton Ranges of central Western Australia (Tindale, 1935a), and then in 1964 when he was with geologist David W.P. Corbett and natural historian Hans Mincham from the Museum on a trip to Myrtle Springs in the Flinders Ranges of northern South Australia (Anon., 1964; Corbett, 1967; Tindale, 1961–1965, 1964–1965). When traveling, Tindale also inspected private australite collections (Tindale, 1964–1965; 1966).[2] By chance he came across australites in the field, at places such as Lake Victoria in western New South Wales (Tindale, 1964–1965) and at Moorook Lake near Loxton in South Australia (Tindale, 1964–1969). Also at the South Australian Museum was Charles Fenner (1884–1955; Figure 7), who prior to 1946 when he became an honorary researcher at the Museum to study australites, was a former Director of Education in South Australia (Fenner, 1954; 2006).

Archaeologists from museums have conducted research into the use of australites for artefact-making. A contemporary of Tindale who was connected with the South Australian Museum was geologist James (Jim) E. Johnson (1917–1983), who had a research interest in aus-

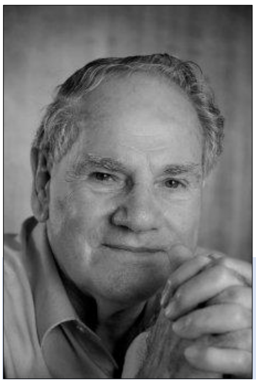

Figure 8: Dr Robert Edwards in 2009, photographed by John Elliott (https://www.portrait.gov.au/portraits/2010.1/robert-edwards/).

tralites, as well as in archaeology. Other archaeologists/anthropologists who worked on Aboriginal use of australites were Robert (Bob) Edwards (b. 1930; Figure 8) and Kim Akerman (Figure 9), who is still an active researcher.

2 ANCESTOR OBJECTS

The perceived power of australites was derived from their connection to ancestors who went up to the Skyworld after the Creation. It was a widely held Aboriginal belief that it was in the Skyworld that the ancestors, often seen as celestial bodies, created the weather for the Earth and still had an influence over living people (Clarke, 2009; 2014; 2015; Tindale, 1983). There was broad agreement between Aboriginal people and Europeans concerning the origin of australites:

> The aborigines tell us these stones fell from the sky, and are (what our American friends would call) "good medicine," in which they agree with the majority of modern geologists. (INO., 1924: 5).

On the Nullarbor Plain, the railway station master A.G. Bolam (1930: 63) described the 'sky-stones' that were found on the Nullarbor Plain and in the sand dunes at Ooldea:

> The blacks call them "Nulu,"[3] and barter them with neighbouring tribes as magic stones. They believe that the australite reached the earth from some extra-terrestrial region, and possess some magic power.

2.1 Creation Narratives

There is a recorded account of a Creation myth that involves the origin of the australites. During a South Australian Museum fieldtrip to the North West of South Australia in 1963, Tindale was at Mount Davies in the Tomkinson Ranges and noted in his journal:

> According to [Aboriginal patrol officer] MacDougall's story the Njinggar or Ice men[4] made a black hail of australites fall from the sky to kill ring necked parrot [*patilpa*, *Barnardius zonarius*] men as punishment for killing all the *waro* or wallabies [*waru*, black-footed rock wallaby, *Petrogale lateralis*]. (Tindale, 1963: 177, 179).

There may have been some syncretism of beliefs occurring in the australite mythology as recorded by Tindale, because in his same journal he noted that his Aboriginal informant, Tommy Dodd, stated: "White people say they [australites] fell from the sky." (Tindale, 1963: 178). Prior to the writing of Tindale's record above, Mountford had written about Ninya (= Njinggar) the "Ice Men", who were said by Anangu Pitjantjatjara Yankunytjatjara people of Central Australia to be spirit beings who lived under two salt lakes north of Mount Conner in the southern Northern Territory in

> … huge underground caverns, whose ice-covered walls are continuously swept by howling, wintry blasts; a frightful place ... (Mountford, 1948 [1981: 77]).

There was no mention of australites in Mountford's account, but he did go on to record that "… the Ninya can only be seen by medicine men …" and could influence the weather, as the " … piercing winds that accompany them are responsible for the cold of winter ...." (ibid.).

During a fieldtrip to Woomera in western South Australia in 1965, Tindale again interviewed Walter (Wally) MacDougall about australites and recorded a truncated version of the australite myth involving ringneck parrots and rock wallabies, that omitted Njinggar the Ice Men. He said:

> MacDougall found that the Mt. Davies aborigines called these australites *ko:di* and not *japu*.[5] In their myth the *waro* or rock wallaby quarrelled with the ring-necked parrots who were killing many *waro* without cause. A *waro* being caused black hail to fall and this killed all the ring-neck parrots while the *waro* hid safely in their rock shelters. (Tindale, 1964–1965: 683).

There is another myth narrative from the 1960s that Bob Verburgt—who was then working as Superintendent at Amata for the Department of Aboriginal Affairs—recorded when out on a trip with Aboriginal men near Mount Davies. It was on this same trip that the green gemstone known as chrysoprase was discovered,[6] and the mythological account of its creation is similar to that of the ringneck parrot given above, but without any mention of the Ice Men, rock wallabies

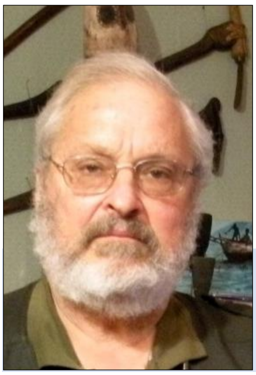

Figure 9: Adjunct Profess- Kim Akerman (https://www.Kimberleyfoundation.org.au/events/kft-lecture.perth-wed-23-sept-kim-akerman/

or australites. Verburgt (1999: 53) said:

> The old men who were with me told an interesting story as to how the green stone came to be. In the Dreamtime they said the green parrots [i.e. ringnecks] used to come to the area to drink from the rock-holes in the early morning and later afternoon. They would come in their thousands, swooping and squawking before settling down to drink. One day a fearful storm came up with strong winds, thunder and lightning. This frightened the parrots and they took to the air in panic. They were circling around the hills as a burst of hail thudded into the ground. The hail was so large that it knocked most of the green parrots onto the ground, transforming them into stone.

The association of australites and emus (Figure 10) is culturally important to Aboriginal people in the north east of South Australia. Here, the Diyari (Dieri) people of Cooper Creek had traditions concerning australites being associated with the Emu Ancestor, and as such were described as *warukati-undru*, that meant "pertaining to emus" (N.B. Tindale, pers. comm. [Baker, 1957: 3, 21]). The act of the emu losing their eyes was said to have occurred during the Creation period. Frederick McCarthy (1965: 17) from the Australian Museum in Sydney said:

> After lighting a ring of fires around a waterhole, the hunters threw "emu's eyes" (australites or tektites of meteoric origin) at the birds to confuse them and cause them to run into the water, where they were easily killed. The australites were believed to be the eyes of ancestral emus which lost them while searching for food, but imbued them with a magical control over the living birds.

Emus are major Creation ancestors across much of Australia (Clarke, 2016; Maddock, 1975; McCarthy, 1965; Spencer and Gillen, 1927). In Aboriginal tradition it is the presence of the ancestor's power that is imparted into objects, such as the flanged button-shaped australites known as 'emu-eyes', which can be accessed by knowledgeable people who are healers and sorcerers (Baker, 1957).

2.2 Charms and Sorcery Objects

Aboriginal people possessed a variety of objects as ritual tools, relying on the ancestral powers they could access through the use of them (Hassell, 1936; Howitt, 1904; McCarthy, 1976; McCourt, 1975; Mountford, 1960; Petri, 2014; Roth, 1903). It is not possible to separate ritual objects just used for healing from those used for purposes such as to entice and enthral wild birds or animals, to create weather or for making sorcery. The same object could be used by its owner for all such things. Shiny and transparent materials, particularly transparent quartz, were seen as powerful, and after Europeans arrived pieces of bottle glass were similarly used (Howitt, 1904). Objects that showed a prism were associated with the rainbow, which was the manifestation of Rainbow Serpents that were believed to live in certain waterholes on Earth and in the Skyworld (Radcliffe-Brown, 1926). Because of their unusual shape and shiny glassy interior australites often were also used ritually.

Stones that are unusual in colour and shape are often found scattered on the surface of former Aboriginal camps. In 1934 Howchin remarked:

> Among the relics picked up on the sites of old camps are such objects as might be called "pretty" stones – not adapted for chipping into shape as tools, but had evidently been carried about by the natives for some reason or other. Thus in the old camping grounds near Adelaide, such objects as "saffron-quartz" (false topaz), clear quartz crystals with pyramids, stones weathered into peculiar shapes, or stones variously striped in colours, etc., have been picked up, which no doubt meant something in the life of those who carried them. To be able to see through a hard stone, as in clear quartz, would greatly impress the native, and he would immediately attach some potent influence to this unusual object. It might bring rain, or make game plentiful, a charm against a witch doctor, or a corrective to the effects of a pointed bone. (Howchin, 1934: 78).

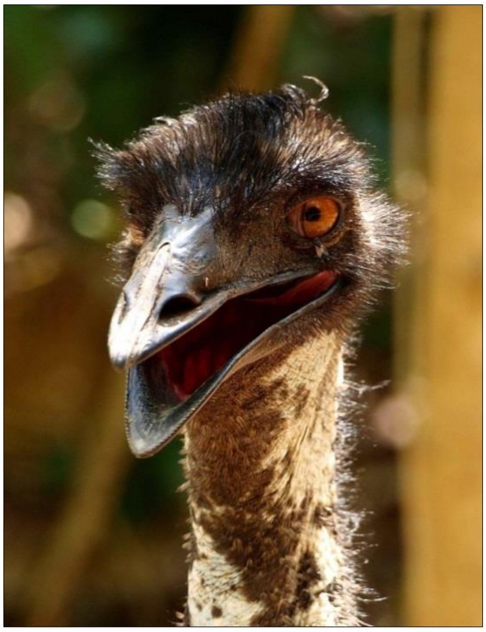

Figure 10: The head of an emu. The emu (*Dromaius novae-hollandiae*) is an indigenous flightless bird of Australia. The black iris in the eye of the emu was widely associated with the more frequently found central cores of australites (photograph: P.A. Clarke private collection).

This section describes the use of australites as charms. It is divided into large geographical regions (see Figure 1) for a discussion of the relevant cultural traditions. These regions are not ethnographically autonomous, as groups from the Western Desert culture are widely spread across the arid zone. There are many areas in Australia for which there are no records concerning the relationships that local Indigenous people may have had with australites, even though these objects were present in the landscape. In particular, it is claimed that there are no known ethnographic records of australite use in Tasmania (Scott and Scott, 1934).

2.2.1 Southwest of Western Australia

Analysis of the ethnographic record for this region indicates that australites were used for healing and sorcery. Tate (Anonymous, pers. comm. [Tate, 1879: lxxi]) reported that his correspondent from Salt Creek, King George Sound at Albany in southern Western Australia, had written:

> The black stones are very rare, and much prized by the natives, who believe the possessor bears almost a charmed life, and is able also to cure sick people of any complaint they may be afflicted with, as also to bewitch their enemies, or any one with whom they have a grievance, tormenting them with all kinds of diseases and finally destroying life itself.

Rainmaking was another perceived function of certain australites. In 1894 Howchin (cited in Anon., 1894: 7) claimed that "… these bombs [australites] are frequently carried by the natives as charms and for the purpose of causing rain …." The Wheelman people of the Bremer Bay district of southwest Western Australia used a variety of stone as ritual objects classed as *booliah*, and it was observed by colonist/anthropologist Ethel Hassell (1936: 705) that "Any stone which differed from those about was immediately accepted as a magic stone." In the case of australites, their different appearance to the majority of other local stones would have potentially added to their appeal. Here, Hassell (1936: 706) recorded the use of 'rain stones', which were hard and like green glass, and:

> These stones were not common, only about a half dozen having been seen in this tribe, and were greatly prized as rain stones. When the transcontinental railway line was built [between Adelaide and Perth], some of these curious stones were found on the Nullarbor Plain. No one seems to know what they are but it has been suggested that they are a kind of cosmic glass which may have fallen as meteorites. Since these plains are limestone in formation and non-volcanic, these stones have been a puzzle much discussed by scientists.

There is a 'charm' in a museum ethnographic collection that is a naturally broken piece of a large hollow australite found near Scadden north of Esperance in southwest Western Australia.[7] This particular object was documented as a "… magical stone – an eye … [that was] found by a Wudjari Tr. Aboriginal c.10 yrs ago [c.1919]." In a Western Australian newspaper (Anon., 1900: 5) it was reported concerning australites that "Australian aboriginals call them wappair stones, and attribute remedial properties to them, binding them on any affected part."

2.2.2 Central Western Australia

A former missionary at Kalgoorlie in the Northern Goldfields reported that

> … the aborigines believed that the black stones (australites) fall from the sky, and that only an occasional one enters a man, who then becomes ill or "possessed" ... (A.G. Mathews, pers. comm. [W.H. Cleverly, pers. comm., Baker, 1957: 3]).

At Coolgardie to the southwest, it was claimed concerning australites that

> … these buttons are collected by the aborigines and used as charms by pressing them on the part of the body which is suffering pain. (Twelvetrees and Petterd, 1897: 42).

Australites were also recorded being used as charms to heal the sick at Kanowna in the same region (F.D. McCarthy, pers. comm. [Baker, 1957: 4]).

Among the Western Desert people at Warburton Ranges in central Western Australia, as well as at Ooldea in western South Australia, the 'witch doctors' used the 'faith-healing procedure' to extract australites by sucking them from the bodies of people suffering from sickness and pain, such as brought on by 'devil possession' (A.G. Mathews, pers. comm. [Baker, 1957: 5]). In relation to 'message-stones', it was recorded that:

> Two australites from Mt. Margaret, Western Australia, now lodged in the Australian Museum, Sydney (Reg. Nos. 23531-2), were regarded by the natives of that district as being of great value in the transmission of messages. They were carried about in the beards of medicine men; this gave them a power, supposedly exuded through the navel, to receive and transmit messages long distances ... (F.D. McCarthy, pers. comm. [Baker, 1957: 7]).

There are australites among a collection of 'magic stones' (*mabbin*, 'emu-stones') that are held in the Western Australian Museum (Baker, 1957: 5, 19). These possibly included the 'mappain stones' (obsidian bombs) collected by William D. Campbell from the Kalgoorlie area (Rhodes, 2018: 66). E.S. Simpson, who was a mineralogist at the Geological Survey in Western Australia, published a paper in 1902 based on his examination of the Campbell Collection (Simpson, 1902), which was formerly accessioned into the Western Australian Museum collection in 1958 (Rhodes, 2018). Other items from Campbell may have been procured by the British Museum of Natural History in London, as they reputedly had a box of "… obsidian bombs, called by the natives 'mappain' and work applied to the stomach as medicine." (Fenner, 1939: 16), although their provenance was not recorded. In 1901, when Campbell had put his collection of 600 australites on display in Kalgoorlie township, a local newspaper reported that

> The Australian aboriginals call them mappain stones, and attribute remedial properties to them, binding them on any affected part. (Campbell, 1901: 23).

The names of *mabbin* and *mappain* given for Campbell's australites appear to be orthographic variations of the term 'moppins', which was used by members of a pastoralist family in the Northern Goldfields during the late-twentieth century, and it was thought to be derived from

> … an Aboriginal word, probably a variant of corruption of "mappin", meaning "emu stones", a word used by Aborigines for australites in Western Australia ... (Cleverly, 1995: 173–174).

Environmentalist Vincent Serventy described being shown an australite by an elderly Aboriginal man at the Warburton Aboriginal Mission in 1956. He recalled:

> First he looked about very carefully to make sure no children were watching. Then he slightly uncapped his hand and showed me what it contained. 'Mappan,' he whispered. I looked suitably impressed as I knew this meant a magic stone, useful for a variety of purposes. It was almost the equivalent of a doctor's black bag which has a curative value merely by belief. Mappan stones were the same. Sick people thought that a wise man could cure them by using such a stone. … The stone was a tektite or Australite as they are often called. (Serventy, 1972: 28).

Indigenous australite names that are variously written as *mabbin*, *mappain*, *mappan*, *mappin* and *moppin* are all cognates of the *maban*/*mabanba* terms that are recorded as the ritual objects of healers along the western coast of Western Australia, in the Kimberley and the Western Desert cultural regions (Akerman, pers. comm.; Elkin, 1977; Mountford, 1976). Across these regions, ritual objects such as small decorated pearl shells, quartz crystals and australites were all considered to be *maban*, and the name also extended to the healer. It is likely that most of these objects were perceived as having originated in the Skyworld or being associated with spirits, such as the Rainbow Serpent, which resided there.

When the archaeologist/anthropologist Scott Cane (2002) worked on a native title claim for the Spinifex People in the Great Victoria Desert in Western Australia he noted that the 'medicine men' were called *marpan*, which would appear to be related to word to *maban* mentioned above. He observed that

> Spinifex People are superstitious and rely on a range of magic items and charms. These are generally acquired from the bush and may take the form of attractively shaped or coloured rocks and crystals, such as tektites, as well as modern items, such as polished haematite, carved wood and coloured plastics. People with reputed magical and healing skills will also carry a secret cache of 'magic stones' consisting of a range of materials, but these are never seen. (Cane, 2002: 214).

The wide use of essentially the same word, *maban*, across language boundaries is probably due the fact that these 'magic stones' were extensively traded. Trade networks between the Kimberley and the Goldfields regions, and into the Western Desert, involved an exchange of a wide range of artefacts, and included ceremonial and ritual items (Akerman, 1995). In a study of contemporary healers in the south Kimberley, archaeologist/anthropologist Kim Akerman (1979: 24) noted that

> The doctors to whom I spoke obtained their powers either through dreams, or by obtaining *maban* (tektites, shell, etc.) from acknowledged living doctors.

2.2.3 Western Desert

In the early-twentieth century Daisy Bates collected from Aboriginal people on the Nullarbor Plain an 'obsidianite' that was carried in a 'nest' of emu feathers and used for healing.[8] Across Western Australia and in western South Australia, Bates found numerous specimens of 'sky-stones' in the possession of sorcerers, which they reportedly referred to as 'eyes'. She explained that

> One stone in particular was almost the exact shape of an eyeball, and rather resembled onyx, in that it had an "eye rim" of white, forming a perfect ring round a small whitish spot in the centre of the "eyeball." The owner called the object kooroo (eye),[9] and cured or killed with its aid, the kooroo either extracting the magic from a sick member of the group, or projecting fatal eye-magic into an enemy group. (There are two widely distributed names for "eye" in aboriginal dialects, "mel" (eye)[10] being mainly a coastal word, while "kooroo" (eye) ranged over a great central area from the heads of the Ashburton, Gascoyne, and Murchison Rivers in West Australia to the Mann, Petermann, Musgrave, and Everard Ranges of Central Australia, and probably further east. The specimen in possession of the Laverton (West Australia) native sorcerer may have been originally found on or within the north-

> ern edge of the West Australian portion of the Great Nullarbor Plain in (about) lat. 29 degrees 10 min., long. 126 degrees 30 min., or on the clay pans, salt lakes, or plains areas further north or east. (Bates, 1924: 11).

Bates found 'skystones' in the possession of individuals among Aboriginal groups in south-east Western Australia at Eucla, and in western South Australia at Head of Bight, Fowlers Bay and Ooldea.[11] Allowing for differences in spelling orthography, the name she gave for this category of object was the same later recorded by Bolam, as mentioned above. Bates (1924: 11) noted:

> Nooloo or nyooloo [*nulu*] was the only name given to those interesting objects of magic, this term being used throughout the area mentioned. Quaintly shaped specimens were always supposed to contain good or evil magic, and were valuable as such, and as objects of special barter between friendly groups.

In the coastal parts of western South Australia and the adjacent part of Western Australia, it was observed that those australites that had a peculiar shape were more likely to be used as 'magic stones' and bartered, particularly the "… slightly-curved club-shaped nyooloo ..." (ibid.). A *kooroo* that Bates purchased from a sorcerer from the 'Lica Totem group' was highly polished, caused she believed by years of handling. All australites were believed to have come from the Skyworld and to be still coming down. Bates (ibid.) recorded that Aboriginal people

> … not only believed that the obsidianites [australites] came from "the sky," but they also believed that when a burndila (meteor) came down from some constellation known to them as the home (heaven) of certain dead groups, many dhalgain (new) nyooloo would be found on the beena (swamp), undiri, or arruga (plain) of such group, even though the "thunder" sound of the meteor as it struck the ground came from "far away" (warn-ma).[12]

The combination of the cultural and physical properties of the australites were such that they could be used as precision ritual tools. Baker (1959: 190) recorded that:

> Occasional larger, plate-like pieces of oval outline, were used in the religious rite of circumcision, and were sometimes used in the operation of sub-incision. One from the Nullarbor Plain bears the aboriginal name of "nyooloo", but the name is not given.

From their fieldwork at Ooldea on the edge of the Nullarbor Plain with Western Desert people during the early 1940s, the Berndts published an account of how a 'native doctor' or *kinkin* (*ma:banbaa* or *nanggaringgu*) used a *ma:ban* object, which was usually a shell disc that he had received when initiated as a healer. They recorded:

> Brought before a patient he [the *kinkin*] assumes a special attitude, scrutinises him and decides on the measure to be taken. The *ma:ban* (a quartz crystal or australite may be used with equal efficacy) is pressed to the afflicted part of the patient, and it is said that it passes through that part of the body and comes out the other side bringing with it all the badness that was causing the pain. The blood is then sucked out and complete cure is imminent. (Berndt and Berndt, 1943: 56).

The Indigenous use of names for australites that translated to 'emu-eyes' appears to have been restricted to groups living in the western and central parts of Australia (Scott and Scott, 1934). In the Western Desert region, it was an Aboriginal belief that australites had some ritual power over emus. Baker (1959: 190) noted that:

> Mr. H.R. Balfour of Toorak, Victoria, who made enquiries among the natives of the Woomera region of Central Australia about the reason for their use of the term "emu-stones," informs me that these aborigines wrap up australites in balls of emu feathers which are then thrown in the direction of flocks of emus. The particular natural inquisitiveness with which the emu is especially endowed, results in a close approach to these objects for near inspection and extraction of the contained australites. While absorbed in their investigations, the emus are speared by the aborigines.

Basedow was a South Australian who had geological training and as Chief Medical Officer and Chief Protector of Aborigines in the Northern Territory he worked extensively with Aboriginal people across Central Australia. He believed that Aboriginal people and emus were both enlarging the spatial range of australites:

> Their universal distribution has, no doubt, been assisted by the agency of the native and the emu (in the form of "gizzard stones"). The natives call obsidian bombs *Pandolla* and *Kaleya korru*, the latter meaning "emu eye." They are collected by the medicine men of the tribes, and applied in the healing of sickness. (Basedow, 1905: 89).[13]

Among the Western Desert peoples of Central Australia, the australite was the main object used for healing (Mountford, 1976). For contemporary Ngaanyatjarra, Pitjantjatjara and Yankunytjatjara peoples of the NPY Lands, the word *mapanpa* means "*ngangkari* [healer] sacred tools" (K. Peters, pers. comm. 2018; NPY Women's Council, 2003: 35, 47, 49, 55, 81). A recognised *ngangkari*, Andy Tjilari, described the *mapanpa* arriving at special camps where all the healers are gathered. He explained that

> They have a lot to talk about, as you can imagine. Meanwhile the *mapanpa* are hitting

the ground with small explosions, 'boom, boom, boom'. The *ngangkuri* dash around collecting up the objects: *kanti* are sharp stone blades; *kuti* are black shiny round tektites; and *tarka* are slivers of bone. Each *ngangkuri* gathers up the pieces he or she wants. These pieces become the *ngangkari*'s own private property. (A. Tjilari [NPY Women's Council, 2003: 34]).

The *maban* term appears to relate specifically to ritual power as a property, rather than to a specific object. In the NPY Lands another *ngangkari*, senior man Nakul Dawson, said:

> I don't know how to take a person's temperature with a thermometer. I only know about *mapanpa* or special sacred tools. *Mapanpa* can look like small pieces of bone. They are kept in water or inside the hand. They are kept inside the hand and help to locate *punu* or little pieces of wood that get lodged in people's bodies. (N. Dawson [NPY Women's Council, 2003: 55]).

In 1940 C.P. Mountford conducted fieldwork among the Anangu Pitjantjatjara Yankunytjatjara people of Central Australia, who were part of the Western Desert culture, and he found that australite charms were an important part of their material culture. He said that his informant, "Old Tjalerina, the chief actor in the Wild Turkey ceremony, had always wanted to be a medicine-man …", but could not reach his goal because of a severe health issue (Mountford, 1981: 54). Tjalerina claimed that

> … he had once been a "little bit doctor," able to see the night-dwelling spirits (the spirits off the dead)", but with sickness during the drought had lost this power to "see". (Mountford, 1976: 563).

Mountford (1981: 54) also recorded that

> When he [Tjalerina] had recovered he had given one 'doctor' many spears to rejuvenate him, but without success. From another he had purchased an australite (an obsidian button of meteoric origin) which, the second doctor man had assured Tjalerina, would make him an even bigger 'black-fella doctor' than before, if he succeeded in pushing the australite into his solar plexus. The poor chap had tried to do that repeatedly, but in vain. In fact Tjalerina said his skin became so tender that he decided the extra power he would have gained was not worth the pain and trouble involved.

Mountford was given the australite spoken of by Tjalerina, which gave him the opportunity to enquiry about its significance. The object was said to have "… contained many *kungara kurans* (medicine men's spirits)." (Mountford, 1976: 563). He wrote that:

> I learned from Tjalerina that australites are the special property of their *nungari* [*ngangkuri*][14] (medicine-men), just as quartz crystals are the stock-in-trade of the aboriginal doctors of the southern tribes. Those meteoric stones have many functions in the hands of the *nungari*. They will restore his failing powers if inserted into his body, and act as a watchdog over his property when he is absent. They will also tell him the direction of an enemy, and assist him when performing healing rites on his fellow tribesmen. (Mountford, 1981: 55).

Australites were part of a category of ritual objects that were said to be kept inside the body of senior men. Bates (1947: 111) recorded that the *jeemarri*, which were circumcision knives made from hard dark flint, "… come from the stomachs of the old men …" and were widely traded. In the case of Tjalerina, he believed that if he had succeeded in inserting the australite *maban* into his body, then

> … he would have had a number of *kurans* – his own and those contained in the Australite. He would then have hoped that one dark night his *kurans*, transforming themselves into *maralis* [spirit body] … would have taken him on many adventures, perhaps even visiting Watak-jarana, the land of the medicine men ... (Mountford, 1976: 563).[15]

Evidence from Tindale, recorded during a South Australian Museum fieldtrip to the North West of South Australia in 1963, is that large australites in particular were treated as having important ritual functions. He noted that his Aboriginal informant:

> Old Charlie offered me a piece of red ochre and produced three australites which he claimed to have found at Mt. Davies. One was an unusually large dumb bell shaped one. In discussions about *ko:ti*[16] or australites after we returned to Mt. Davies I learned that the word *ko:ti* really meant doctor. They were "doctor" stones. White people say they fell from the sky. (Tindale, 1963: 177).

Tindale (ibid.) had another Aboriginal informant on the 1963 trip describe the use of an australite flake for the circumcision and cutting of the tongue rituals. Tongue cutting using a sharp stone was also described by Carl Strehlow among the Western Arrernte for making a 'Magic Doctor' (C. Strehlow, 1907 [cited Petri, 2014: 51]). For australites, Tindale (1963: 177) noted in his journal:

> Tommy Dodd says that at Charlotte Waters large ones are found; these are split and the flakes used in making young men. In making a "doctor" man a flake of *ko:ti* stone is used to cut the tongue of the Law doctor whose blood is then sucked from the tongue. This practice is said to be general in Pitjandjara [Pitjantjatjara] territory & east to Charlotte Waters.

Tindale recorded Dodd's knowledge of where australites come from and further details concerning their use in the subincision and making 'doctors' rituals. He noted that

> According to Tommy Dodd "*ko:ti* really means 'doctor' and is applied to australites because they are "doctor business". White people say they fell from the sky. At Charlotte Waters they get big ones and split them to make knives for making young men, especially in whistle cocking [subincision]. In making a doctor man they cut the tongue with a sliver of *ko:ti* and suck the blood. Similar practices come right through to Mt Davies. (Tindale, 1963: 178).

In 1964 Johnson published the results of a stone tool survey of Aboriginal campsites in the North West of South Australia and he noted that the Pitjantjatjara people referred to australites as *koordi* (Johnson, 1964: 177), which is a spelling variation of the same word, *ko:ti*, as recorded by Tindale above. The '*o:*' character as written by Tindale was spoken as an '*oo*' sound and is often written as '*uu*' in more recent orthographic systems for the Aboriginal languages of Central Australia (see Monaghan, 2009: 234; Tindale, 1935b: 264). The meaning of *kuuti* is "… black shiny round tektites of celestial origin." (NPY Women's Council, 2003: 11), which is another acceptable spelling variation for the same word.

In 1965 John Greenway was on a fieldtrip to Eucla on the Western Australian side of the Nullarbor Plain with Tindale and Yankunytjatjara (Jangkundjara) man Freddy Windlass. In his account of this trip he recorded the Pitjantjatjara names for australites as *mapunpa* and *ku:ti*, although apparently Windlass just called them 'meteorites' (Greenway, 1973: 142). These Indigenous terms appear to relate to *maban* and *ko:ti* (*koordi*, *ku:ti*, *kuti*). The reference of *maban* (*mabanba*, *marpan*) to a healer's ritual object has already been discussed above. In the case of *ko:ti (kuuti:)*, this is possibly a secular term that relates to *kuti-kuti*, which is recorded as meaning 'revolving' in the Pitjantjatjara/Yankunytjatjara language (Goddard, 1992: 48). Similarly, in the neighbouring Ngaanyatjarra/ Ngaatjatjarra language which is spoken to the west, *kurti-kurti* means "… rolling over and over, rolling down ..." (Glass and Hackett, 2003: 105). This is a different explanation to Tindale's claim that *ko:ti* translates as 'doctor'.

2.2.4 Northern Central Australia

In 1909 missionary Carl Strehlow produced an Arrernte dictionary for people living in the Macdonnell Ranges in Central Australia, within which was recorded *ngankara* as 'zauberdoctor, zauberstine', that translates as 'medicine man' and 'magic stones' (Strehlow, 1909 [2018: 286]). Although the stones are not described by him, they could have included australites. In 1931 the Adelaide-based zoologist T. Harvey Johnson was on a Board for Anthropological Research expedition to Central Australia when he collected an australite 'charm' at Cockatoo Creek, which is near Yuendumu in the Tanami Desert to the northwest of Alice Springs.[17] Here, Edwards described australites as being still in use as charms during the mid-1960s. He noted that

> While at Yuendumu Settlement – situated in the north-west of Central Australia – during August 1965, the writer [Edwards] was told of an incident showing the present day persistence of the aboriginal custom of using australites to cure sickness. The informant was an intelligent aboriginal, 20 years of age, who stated that recently when lying sick in his shelter, he was visited by an elderly woman. From a small bag she reverently took out a number of australites, rubbed them with fat and placed them in rows across his chest. During these procedures she chanted aboriginal songs which apparently were an essential part of the treatment. The next morning his condition was much improved. (Edwards, 1966: 243–244).

The morphology of the individual australite was a determining factor in whether or not it was used as a charm. A researcher noted that

> Professor [Baldwin] Spencer tells me that he never saw them worn by the natives of Charlotte Waters, where they occur plentifully, and that no notice of them whatever was taken ... (Walcott, 1898: 43).

In spite of this, some decades later Harold L. Sheard collected a set of three australite charms, described as 'obsidian bombs', from Charlotte Waters.[18] It is possible that in some areas where australites were relatively common, only the oddly shaped or especially large examples were considered special by local Aboriginal people. For instance, Spencer's partner Gillen remarked that among the Central Australian australites, "Some stones of special shape are used for magic purposes by natives ...." (F.J. Gillen, 1901 [cited Mulvaney et al., 1997: 313]). He collected a set of 'obsidianites' in a 'nest' of emu feathers from Kaytetye (Kaitish) people at Hanson River in Central Australia.[19]

In the Warlpiri language spoken by people of the Tanami Desert area northwest of Alice Springs, *pirilyi-ngarnu* means 'charcoal-eater', and it is a general term for either emu or bustard that refers to their habit of swallowing pieces of charcoal for their gizzard stones (M. Laughren, pers. comm.). And in this language, *pirilyi-pirilyi* refers to the pupil of the eye, which is black, like charcoal (*pirilyi*). The charcoal-eating habits of emus were also remarked upon by Arrernte people (Roheim, 1974: 169). The Warlpiri perceive a mythological connection between the Emu ancestor and the production of charcoal for making black paint (Anderson and Dussart, 1988). Similarly, the Wagaya people in the Barkly Tablelands of northern Central Australia have a tradition of the Emu and Charcoal Dreaming being associated with a specific black 'war paint' mine (Rankine, 2000: 26). The symbolism of the gizzard, with its hoard of 'sacred' stones, is also significant. It is recorded that Warlpiri men regarded the contents of the gizzard removed from an emu or bustard that they had killed as 'good medicine' (Rhodes, 2018: 69). The blackness of australites, which are sometimes found in emu and bustard gizzards, makes them symbolically analogous to charcoal.

Among the Djaru of the southern Kimberley and the desert people at Balgo to the immediate south in the Great Sandy Desert, *maban* refers to magic power and the *maban-jarra* are literally the people (healers) who possessed this power (R. Graham, pers. comm.). Similarly, among the Mardudjara of Jigalong on the western edge of the Great Sandy Desert, for the *mabarn* [*maban*] healers the "… magical stone or shell objects they are said to carry in their stomachs …" are also called *mabarn* (R. Tonkinson, 1978: 107). At Jigalong it was noted for the *mabarn* healers that

> Apart from the small objects of stone, shell or wood that they are said to keep within their bodies and which are sources of their power, the *mabarn* have no curing paraphernalia. (M. Tonkinson, 1982: 233).

In the Warlpiri language of northern Central Australia, stones that are psychically put inside someone to make them sick or to kill them are *yarda*,[20] and *maparnpa* refers to both the power to detect and extract them from the body and to healers (also *karrpiri*, *ngangkari*, *ngangkayi*) who possess the power (M. Laughren, pers. comm.). These definitions of *maban* (*maparnpa*) as ritual power are consistent with Western Desert traditions.

2.2.5 Eastern Central Australia

The senior men of the Diamantina River people carried australites known as *ooga* ('emu eyes') as charms, to which they credited the power of night vision (Duncan-Kemp, 1933: 72). In Diyari (Dieri) language spoken in the neighbouring Cooper Creek area australites were known as *warukati milki-tandra,* meaning 'emu eyeball', and were regarded as representative of the *mura-mura*[21] (Fry, 1937: 201). To the south the Wadikali people at Lake Frome referred to them as *mindjimindjilpara*, meaning "… eyes that look at you like a man staring hard ..." (N.B. Tindale, pers. comm. [Baker, 1957: 3, 21; Fenner, 1954: 8]). At Stuart Creek Station near Marree in South Australia, a koonkie ('tribal witch doctor') was said to have removed an australite from the breast of a patient, who later died (Mr Canham, pers. comm. [Tate, 1879: lxxi]). A set of 'obsidianite charms" was collected from Albemarle Station in western New South Wales during the late-nineteenth century.[22]

It is recorded that australites were used ritually in the northeast of South Australia for hunting emus. For instance, in the Aboriginal Ethnographic Collection of the South Australian Museum there are two sets of four 'emu eyes' collected by Ted Vogelsang. The first set was collected at Mulka; and the second came from Mungaranie and was described as "… emu eye Muramura [ancestor] stones …" that had been obtained from an elderly Diyari (Dieri) man named Dintibana.[23] In the same region, a Diyari man known as Old Piltibunna described the use of 'obsidian bombs', or australites, as charms for blinding game during an emu drive (Horne and Aiston, 1924: 135). Aiston claimed that "As a great favour Piltibunna gave me a nest containing three emu eyes, so now I can catch emus whenever I like." (Horne and Aiston, 1924: 60). It was recorded that

> Obsidian bombs were called *warroo getti milki* (emu eyes), and were supposed to be eyes that the emu had lost when walking about looking for food. These when found were smeared with fat and red ochre and were stored in a net bag full of emu feathers, kept together by being wrapped around with hair rope. (Horne and Aiston, 1924: 135).

By an account from writer Charles Barrett, Aboriginal hunters threw australites that were still contained within a 'nest', which probably made their recovery easier. He explained:

> … they believe that the small rounded objects, which they carry in a "nest" of feathers, have the power of making emus blind. It is no trouble at all to get emus if only you possess a nest of "emu eyes." The blacks throw among emus that have come to drink one of the feather nests containing two or three australites. The birds are supposed to become blinded and run into the water. Aborigines have strong faith in the power of "emu eyes" and are reluctant to part with them. (Barrett, 1938: 42).

In the northeast of South Australia region, 'obsidian bombs' were also treated as 'lucky stones' or 'charm stones' (Baker, 1957: 7), and were believed to be the product of lightning, and therefore were called 'lightning stones' (Horne and Aiston, 1924: 136). It was perceived that the power from the heavens could be placed in objects here on Earth. Similarly, a newspaper writer claimed that an Aboriginal myth, probably from the Australian east coast, "… states that the gum in the hearts of wattle trees [*Acacia* species] is made by shooting stars lodging there and breaking into bits." (Anonymous, 1904). For Aboriginal people on the east coast of Australia, sightings of meteors were associated with fire and linked to the waratah (*Telopea speciosissima*), which has a red flower (Haynes, 2009: 11).

2.2.6 Southeast Queensland

The australite distribution map drawn by Baker (1957: Figure 1) had the northern limit on the eastern coast side at about 250 kilometres north from where Fenner (1934: Figure 3) had placed it, which was at Kyogle in northeast New South Wales. This means that much of southeast Queensland is now considered to be within the strewn field. However, it is not known whether this area was within the actual distribution zone for australlites, as they could have reached the latter region through trade.

It was within southeast Queensland that Reverend John Mathew (1928: 527) recorded the Aboriginal use of

> … animated stones … that are kept in a medicine man's private dilly [bag], wrapped around carefully with much string, and perhaps moss, that are highly efficacious.

He said that there were three main types: a white quartz pebble which the Kabi Kabi people in the Maryborough district called *nganpai*; a red stone; and a black 'obsidianite'. In the case of the black 'animated stone', which from its description as an obsidian suggests that it was generally an australite, Mathew (ibid.) said that he had one in his possession which was

> … about 1in. to 1 1/8in. [2.54 to 2.76 cms] long, 3/4in. [1.91 cms] wide at widest and 1/2in. [1.27 cms] thick at thickest part, tapering to the ends.

In terms of their use he stated that:

> The doctor will apply one of them to a painful spot and remove the cause. They are at the same time deadly in their effects to the uninformed. When not carried, they are hung up on a tree near at hand, and none but the owner will dare handle them. Once when I ventured near to inspect, the camp shouted out in alarm, "Don't touch, don't touch." (ibid.).

The Kabi Kabi called these obsidianite stones *mullu* ('black') and *minkom*, while people from the neighbouring Gooreng Gooreng (Gurang) at Wide Bay and Wakka Wakka groups in the Murgon district just knew them as *minkom* (Anon., 1912: 4; J. Mathew, pers. comm. [Dunn, 1912: 14]; Mathew, 1910: 112–113; 1928: 527; Petri, 2014: 78). As with most powerful objects, the animated stones could be used for both healing and sorcery. Mathew said:

> A sorcerer was believed to have a number of these stones in his inside. He certainly carried one or more in his dilly-bag. When a man felt an acute, sudden pain, he believed that it was caused by a "mullu" being thrown at him by an enemy. They had a curative, as well as a lethal application. (J. Mathew, pers. comm. [Dunn, 1912: 14]).[24]

There are other records from southeast Queensland of what appear to have been australites. Winterbotham recorded that 'native medicine men' in southeast Queensland obtained black stones known as *mingom* (*minkom*) by diving into waterholes associated with the Rainbow Snake (L.P. Winterbotham, pers. comm. [Baker, 1957: 6]). During the current author's fieldwork in the region during 2016–2017, it was found to be part of local Aboriginal oral history that a *mingom* was a powerful stone that could make rain, and that certain of the waterholes, such as at Ban Ban Springs, were associated with a Rainbow Serpent/Eel (Hawkins and Wein, n.d.: 4–7,10–11). In the vocabulary of the Wakka Wakka language spoken in southeast Queensland, a linguist listed *mingom* as "… bad stones in the body (causing disease) ..." (Holmer, 1983: 78).

2.2.7 Victoria

Australites had similar medicinal uses in Victoria. In southwest Victoria colonist James Dawson (1881: 59) described Indigenous healers making toothache leave the body of their patient with

> … a black stone, about the size of a walnut, called karriitch. Stones of his kind are found in the old mounds [middens] on the banks of the Mount Emu Creek, near Darlington. The natives believe that when these stones are thrown into the stream at a distance from their residence, they will return to the place where they were found; and as they are considered an infallible remedy for toothache, they are carefully preserved.

In southwest Victoria these same stones were used to give enemies toothaches by throwing them in the direction of their territory, and a tree where many of the stones were found was avoided. Dawson (1881: 59–60) also said that:

> Stones of a similar description are found in the sand hills on the sea coast, and are put into a long bag made of rushes, which is fastened round the cheek. The doctor always carries these stones in his wallet, and lends them to sick people without fee or reward.

Dunn noted that "I have been told by the [Lake] Condah natives that these stones are applied by the sorcerer to the human body to remove pain." (Dunn, 1912: 14). Since the personal effects of a deceased person were often buried with the body, it is possible that australites as charms have also been buried some metres beneath the surface, a fact that needs to be taken into account when determining the likely age and origin of these stones (Baker, 1957). In this region the private collector L.R.

Kurtze made a large collection of australites, which were placed in his own local museum at Portland (Anon., 1932b). There was also reputedly a fine collection in the nearby Warrnambool Museum (Anon., 1909).

Colonist/scholar Edward M. Curr described Aboriginal sorcery practices in the Gippsland region of Victoria, and in particular the use on an object that other researchers later identified as an australite (Dunn, 1912; Petri, 2014). Curr (1887, Volume 3: 547) said:

> The mode of proceeding was to obtain possession of something which had belonged to the person whose death was desired, such as some of his hair, or excrement, or food; or to touch him with an egg-shaped piece of stone which was called bulk, and was thought to be possessed of magic powers.

Alfred W. Howitt gave Robert Brough Smyth an example of a *bulk* object that he had obtained

> … from an old man in Gippsland … [and was] believed by the natives to possess extraordinary powers, and held in great estimation by the sorcerers. (Smyth, 1878, Volume 1: 386).

It was described as 4 inches (10.16 cms) in length and 2.5 inches (6.35 cms) in breadth, and weighed 27.5 ounces (0.78 kg), which Baker (1957) suggested was excessively large and therefore probably was not an australite. It remains, though, that the Indigenous category of *bulk* would still have included australites.

In 1880 Fison and Howitt published a more detailed account of how the *bulk* was gained by a Ganai (their Kurnai) man of the Gippsland through the agency of a dream. Howitt claimed that:

> A Kurnai [Ganai] told me that, when gathering wild cattle for a settler near the Mitchell River, he dreamed one night that two "Mrarts" ["medicine men"] were standing by his fire. They were about to speak to him, or he to them (I now forget which), when he woke. They had vanished, but on looking at the spot where they had stood he perceived a "Bulk," which he kept and valued much. (Fison and Howitt, 1880: 247).

Howitt then described the ritual uses of the *bulk*:

> Every individual, although doubtful of his own magic powers, has no doubt about the possible powers of any other person. If the individual himself fails, he supposes that he is "not strong enough." There is scarcely a Kurnai [Ganai] of those who are not Christianized who does not carry about with him a bulk – a rounded, generally black, pebble. It is supposed to be of general magic power. For instance, if buried together with the excreta of any person, that person receives the magic "bulk" in his intestines and dies. The touch of it is supposed to be highly injurious to any one but the owner. I have seen girls or women greatly terrified when I have offered to place one of these bulk in their hands. (Fison and Howitt, 1880: 251).

Howitt went on to describe the power contained with the *bulk*, which they linked to the light of a fire. He claimed that

> It is believed that a bulk has the power of motion. For instance, during the writing of this essay, Tankowillun told me that he and Tulburn had, the evening before, seen a bulk, in the shape of a bright spark of fire, cross the roof of a house and disappear on the other side. Also that they ran round to catch it, but it had vanished. (Fison and Howitt, 1980: 251).

In 1887 Howitt published an account of "Australian medicine men", within which he described the use of quartz as well as the *bulk*:

> Of all magical substances the crystal of clear and translucent quartz holds the first rank in the estimation of the Australian aborigines. Yet in the central clans of the Kurnai [Ganai] tribe the black stone called *bulk* is more regarded, and as far as this particular community is concerned, it is only among the Brataua Kurnai [Bratauolung] and the eastern Krauatun Kurnai [Krauatungalung], who adjoin the Kulin and Murring tribes respectively, that the quartz crystal is held in dread esteem. (Howitt, 1887: 26).

3 AUSTRALITES AND TOOL-MAKING

For Aboriginal people, the glassy properties of australites made them desirable for tool-making (e.g. see Figure 11). In 1894 geologist Walter Howchin showed members of the Royal Society of South Australia an "… obsidian bomb which had been shaped into a cutting instrument by the aboriginals." (Anon., 1894: 7). Then in 1909 he exhibited a large obsidianite from Kangaroo Island and observed that elsewhere "… the aborigines are often found with obsidianites in their possession, which they use as charms and sometimes chip them into the form of scrapers." (Howchin, 1909: 349).[25] Mr Johns, a curator at the Warrnambool Museum, reportedly claimed that in the southwest of Victoria, australites were carried as amulets and were sometimes broken up to form splinters used to barb spears (Archibald [cited Walcott, 1898]). It has been argued that references to 'volcanic glass' being used for making weapons, such as for barbs of the *wurokiigil* spear in southwest Victoria (Dawson, 1881: 87), are actually references to the use of "… either australite glass, or else had been confused with a special type of fragmented tachylyte ..." (Baker, 1957: 10). Archaeologist Stanley R. Mitchell (1949: 93) noted that australites

> … consist of a black glass of complex miner-

al composition, have a conchoidal fracture, and in thin flakes are translucent; they are also known as obsidianites and in their physical characteristics closely resemble obsidian. Occasionally microliths, points and micro-scrapers were made from them by the Australian aborigines.

Tindale (1964–1969) appeared to be unaware of the breadth of evidence for Aboriginal use of australites to make tools, as he believed that no Aboriginal people living prior to his proposed 'Pirrian' and 'Mudukian' cultures could have used australite glass to make implements, putting the earliest date at about 4,000 years B.P. Based on his Devon Downs excavation on the banks of the Murray River in South Australia, Tindale proposed a chronological sequence of Aboriginal culture, with the Pirrian period named after a style of stone point and the Mudukian period taking its name from a type of bone point (Tindale, 1957; 1959; 1968). Tindale (1974: 85) fine-tuned the dating, but later said that

Figure 10: An australite core found by the author at an Aboriginal campsite on Middleback Station, northern Eyre Peninsula, in 1980. Left: Edge-on view. Right: underside, showing flaked edge (P.A. Clarke private collection).

What little obsidian found was from areas where a shower of glassy meteorites had fallen during the past five or six thousand years. The pieces, seldom larger than 2 inches (5 cm.) in diameter and known as *australites,* were used by the peoples of the Pirrian and the succeeding Mudukian culture phase, who were microlith implement users.

The acceptance of Tindale's linking of australite use in tool-making with his proposed Pirrian/Mudukian cultures supported the theory that the australite shower occurred sometime in the Holocene, between 5,000 and 2,000 years B.P. (Baker, 1957). In 1964 Tindale had accompanied his geologist colleague at the South Australian Museum, David W. P. Corbett, to Myrtle Springs in the Flinders Ranges of northern South Australia (Tindale, 1961–1965; 1964–1965). Based on the data associated with the 175 australites they obtained, Corbett determined that the fall of the australites had occurred some 4,000 to 5,000 years B.P., although it was said that this was based on "Limited stratigraphic and archaeological evidence …" (Corbett, 1967: 561). The last-mentioned evidence he relied upon was Tindale's sequencing of Aboriginal cultures from the Murray River in South Australia (Tindale, 1957), along with the stratigraphic findings of Gill (1965) and Baker (1956; 1960; 1963) from southwest Victoria. Modern archaeology no longer supports the idea of classifying cultures due to supposedly unique elements of their material culture, as Tindale had done above (Mulvaney and Kamminga, 1999). Given the rejection of Tindale's model, Corbett's dating of the australite fall is unreliable.

From examples drawn from the collections of several museums, Baker (1957) has provided a detailed description of a wide variety of Aboriginal tools from south-eastern Australia that were made from australites, which I will not repeat in full here. According to him, many of these australites recovered from the field have signs of wear, both through the natural processes of weathering and by other means. Baker (1959: 184) observed that:

A few of the australites could possibly have been abraded and cracked during utilization by large native birds as gizzard-stones, and some show "carry polish" attributed to constant handling by aborigines in the practise of their customs and rites. One or two from the Port Campbell district of Victoria, were accidentally fractured by cart wheels or horses' hooves, such specimens having been found on old roads last used in 1933. Others from sundry parts of Australia, have been deliberately fractured by aboriginal man in the manufacture of stone weapons and implements ...

Using the South Australian Museum archaeological collections, Edwards (1966) conducted a survey of australite specimens obtained from known Aboriginal campsites in South Australia.[26] From his sample of 443 specimens he found that they were from four distinct categories: 130 complete specimens possibly used as charms (29%); 161 fractured specimens without trimming (36%); 56 trimmed pieces, but still of indefinite shape (13%); and 96 implements that had secondary trimming and were similar to stone microliths (22%). Edwards suggested that the use of australite glass was favoured because of its property of readily breaking with a clear fracture that is distinctly conchoidal. Limiting factors for the use of this material were its lack of structural strength, and its relatively small size in comparison to most other stone sources such as porcellanite, agate and jasper. Edwards (1966: 246) concluded that "Australites obviously held a very minor place as a suitable material for implements, but nevertheless, a number of interesting examples have been found."

In 1973 archaeologist and anthropologist Kim Akerman obtained a collection of 385 australites that had been offered for sale by a gem dealer in Kalgoorlie (Akerman, 1975).[27] They had been collected from near Rawlinna Siding on the Trans-

Figure 11: A collection of australites with flaked edges from Rawlinna Siding, Goldfields, Western Australia (K. Akerman, private collection, no. 972).

Australian Railway line at a site that was probably both a campsite and a tool-making place, and in close proximity to a gnamma hole. The result of Akerman's analysis of the Rawlinna collection was that all of the 385 items were Aboriginal artefacts: 295 struck flakes (77%), 60 utilised flakes (16%), 17 backed flakes (4%), 12 micro-adzes (3%) and 1 micro-burin (<1%). He compared this with other collections held by the Western Australian School Mines in Kalgoorlie, which were from areas such as northeast of Wiluna in central Western Australia, the vicinity of Kalgoorlie and on both sides of the Trans Australian Railway line (Akerman, 1996: Map 1). There were similar tool types in these additional collections, although it is possible that their numbers for each category may have been the result of selective collecting. In 1973 Akerman documented the finding of a worked australite among other stone tools at Lake Hope west of Norseman in southern Western Australia (see Figure 11).

In summary, Akerman's study indicates that in certain areas of Western Australia, australites were well suited as a source of material for making small implements. Akerman was involved with the finding of other australites, such as specimen from Jidirr near Balgo in northern Western Australia that had been originally found by Aboriginal man Richard Tax, and passed on to the Western Australian Museum (Megirian and Mason, 1996). Akerman later found artefacts made from australites in the northern Tanami Desert region of the Northern Territory (ibid.).

In the absence of major sources of volcanic glass in Aboriginal Australia, outside the volcanic plains of southwest of Victoria, australites were a source of small flakes that were the sharpest of cutting tools (Cotterell and Kamminga, 1987), albeit with limitations on their use, as outlined by Edwards (1966). The use of australites as tools appears to have had a discontinuous range within the documented strewn field, but it was particularly noted as an aspect of the Aboriginal material culture in southern Australia (Mulvaney and Kamminga, 1999). Edwards observed that:

> The main australite implement finds in South Australia extend over a region between the River Murray and the Peterborough-Broken Hill railway line … where good quality stone for implements is practically non-existent and usually obtained by trade. In the Lake Torrens and Lake Eyre regions, abundant supplies of suitable stone are readily available. Australite specimens collected from campsites in such areas are generally intact and untrimmed and were possibly used by the aboriginal in his practice of "magic" … It may

> be that the availability of stone for implements influenced the use of australite glass. (Edwards, 1966: 248).

In support of Edwards' statement about the distribution of australite use there is a collection of thumbnail scrapers made from this material that were recovered from Oakvale Station north of Renmark in South Australia at a campsite that had been used by the Nanya people in the late-nineteenth century.[28] Australite researchers engaged in fieldwork during the early-1970s in Western Australia have largely confirmed Edward's view about high australite use in areas with poor sources of tool-making stone:

> Our own experience confirms this; we found aborigine-worked australites common only on the Nullarbor Plain and on Earaheedy Station, areas where the silicified rocks preferred for implements are totally lacking. (Chalmers et al., 1976: 15).

Australites in the form of flaked cores and flakes have been regularly located at former campsites, which are often near water sources such as soaks, gnamma holes, rock holes, pools and swamps (Akerman, 1975; Cleverly, 1988; 1991; 1994; Cleverly and Cleverly, 1985; Johnson, 1963; 1964; Rowland, 2014). Johnson (1963; 1964) surveyed Aboriginal campsites in the North West of South Australia, and several places where australites were found had Aboriginal names. At least some of the australites he found appear to have been in use shortly after European settlement, as they were contained within a mixture of stone and exotic material at a campsite at Lake Wilson. This was also the case at an Aboriginal campsite on coastal dunes near Wallaroo on Yorke Peninsula in South Australia, where

> Australites and australite microliths are found, as well as odd coins, one an 1818 shilling, musket balls and claypipe stems. (Johnson, 1963: 67).

For australites in collections, the dull patina on fractured surfaces provides an indication that they were made by Aboriginal tool-makers, rather than the result of recent collectors testing to see if they were glassy inside (Akerman, 1975). Since only relatively small stone tools can be made from them, there is some misunderstanding of their likely function. Akerman described australites as chiefly blades for Western Desert adzes and as wood engravers. This is supported by the documentation of an australite 'engraver' collected by James E. Johnson in 1960 from Pitjantjatjara people at Wingelina in central Western Australia.[29]

In the Aboriginal collections of the Western Australian Museum there is an australite fragment from Red Hill near Perth in Western Australia that is labelled as a "Chip of australite worked and used as a knife by an aboriginal." (Baker, 1957: 14). At the National Museum of Victoria, curator Aldo Massola is said to have identified a flaked australite found by Cleverly in the Kalgoorlie area as a 'circumcision knife' (Baker, 1957: 14).[30] It is not clear how such an object could be identified as a surface find, which led Akerman (1975: 117) to observe that

> Those artifacts made of australite that have been recognised, invariably seem to be classed as circumcision knives, as assumption that reflects more on the romantic nature of the finder than on the possible range of use that the flake may have been subjected to.[31]

Aboriginal use of australites to make tools was regarded as an impediment by geologists who were searching for large complete examples of them in the field (Baker, 1967). For instance, it was stated that

> Australites from near Hughes on the Nullarbor Plain include numerous flakes but no large specimens because of destructive use by Aborigines. (Cleverley, 1991: 371).

It was suggested that "… the survival of larger australites may be dependent upon a lack of Aboriginal interest in them as raw materials." (Cleverley, 1991: 380). There is some evidence to suggest that large australites were highly attractive for making tools. In 1963 on a South Australian Museum fieldtrip, Tindale and his zoologist companion Peter Aitken collected a flaked tool at Malupiti at Mount Davies in the Tomkinson Ranges in north-western South Australia, which had been made from a large australite.[32]

Overall, in spite of Aboriginal tool-makers having a preference for large australites, the amount of their past use for this purpose does not appear to have significantly reduced their numbers in the field. A Western Australian study of the destruction of australites by early Aboriginal people though tool-making concluded that

> … from a consideration of the forms of flaked australites, it is estimated that less than 1% of australites have been used destructively by Aborigines. This level of destruction can have no significant effect upon the australite distribution pattern. (Cleverly and Cleverly, 1985: 1).

In addition to the fabrication of stone tools from australites, there is some evidence to suggest that their use as charms may also have resulted in some physical change to them. In 1978 it was reported that on display in the Geological and Mining Museum in Sydney there was a large elongated boat-shaped australite that had been acquired in 1916 from Mr W.T. Brown from Central Australia (Cleverly and Scrymgour, 1978). The label claimed it had been used by Aboriginal people as a 'medicine stone', and upon inspection by geologists it was remarked that

> … there is some support for it in the artificial abrasion of the specimen, apparently accomplished by rubbing it back and forth parallel to the length so that slight ridges remain between adjoining facets. (Cleverley and Scrygmour, 1978: 328).

4 DISCUSSION AND CONCLUDING REMARKS

It is a major temptation for European scholars to take a celestial or environmental event from a Creation myth narrative, such as the 'black hail' example from MacDougall above, and treat it as a factual account of something that had happen in the past. Tindale (1938) often portrayed myth as memory, for cataclysmic events such as meteorite strikes (Hamacher and Norris, 2009) and volcanic eruptions. For instance, in the case of the latter he proposed that the ancestor's campfires mentioned in the Eagle-hawk and Crow myth narrative of the Mount Gambier area in South Australia were symbolic of the volcanic vents, and that this was a memory passed down through Aboriginal tradition of an actual volcanic eruption, commencing at 4,710 B.P. and with the last minor recurrence being 1,410 years B.P. (Tindale, 1959; 1974). If Tindale was correct, this would mean that the myth had been orally passed down, largely intact, some 188 generations to the present,[33] which if so is a remarkable achievement. Superficially this proposal appears to be well meaning by acknowledging that elements of Aboriginal myth are equivalent to historical fact, but unfortunately it does lock Aboriginal tradition into what Europeans have in the past considered to be its 'primitive' form.

Tindale's approach of treating myth as memory is in line with the highly controversial statement from his contemporary Adelaide-based researcher, the anthropologist and linguist Theodor G.H. Strehlow. In his ethnography, *Aranda Traditions*, Strehlow (1947: 6) argued that:

> It is almost certain that native myths had ceased to be invented many centuries ago. The chants, the legends, and the ceremonies which we record today mark the consummation of the creative efforts of a distant, long-past age. The present-day natives are on the whole merely the painstaking, uninspired preservers of a great and interesting inheritance. They live almost entirely on the traditions of their forefathers. They are in many ways, not so much a primitive as a decadent race.

In contrast to Strehlow's statement above, modern anthropology considers that Aboriginal culture and tradition is, and has always been, changing in response to the shifting social and physical environments (Kolig, 1984; Sutton, 1995). In a review of *Aranda Traditions*, a senior anthropologist remarked that while Strehlow had produced an important ethnography, he had nonetheless suffered from a

> … lack of understanding of the dynamic quality of Central Australian culture, which even today continues to exert itself forcefully in areas further north where aboriginal culture is still intact ... (Davidson, 1950: 85).

My own opinion is that while accepting that the content and structure of myths conveys important information down the generations, as part of a living culture they are constantly being augmented and altered in line with their changing situations (Clarke, 1995; 1996; 2018).

The above example provided by Tindale of the australites being portrayed by desert people as 'black hail' illustrates the point that Indigenous people are able to explain the origin of environmental phenomena that existed long before the arrival of their biological ancestors according to their own world view and with reference to their Creation traditions. In some parts of Australia, quartz crystals were also believed to have come from the Skyworld as 'hail' (Radcliffe-Brown, 1926: 22). In relation to the origin of australites, Tindale believed that they fell no more than 5,000 years B.P.—not the 793,000 years B.P. that scientists have more recently calculated (Lei and Wee, 2000).

The recording of an Aboriginal myth narrative concerning a fall of australites by Tindale demonstrates how easy it would be to assume that the ancestors of modern Aboriginal people witnessed a past geological/celestial event and recorded it in their traditions, particularly when it was assumed to have taken place since their arrival on the Australian continent. In the case of the 'black hail', the ability and creativity of Indigenous people in explaining phenomena in their environment must be acknowledged, without assuming that it was a perspective that could only have been handed down through the millennia. Recent studies have demonstrated that early Aboriginal experience and knowledge of their environment, which scholars today term Indigenous Biocultural Knowledge or Traditional Ecological Knowledge, is dynamic with redundant information quickly replaced with new experiences and knowledge that hunter-gatherers have gained (Cahir et al., 2018).

Stone, both raw and fabricated into tools, was a major element of the trade conducted across Aboriginal Australia and as such had symbolic importance in forming connections between widely separated peoples (Brumm, 2010; McBryde, 1978; McCarthy, 1939a; 1939b). Trade may explain the presence of australites in areas where they were naturally rare or absent. For instance, in the far north of Western Australia, archaeologist Charles E. Dortch found six australites in pre-European rock shelter occupation sites within the area that is now largely inundated by Lake Argyle in the Ord Valley (Cleverly and Dortch, 1975). Five of these specimens were flaked artefacts. It was reasoned that their presence was possibly due to late Pleistocene trade with people from the south where australites are more plentiful. Lake Argyle lies on the extreme edge of what is generally considered to be the extent of the australite strewn field (McColl, 2017). In contrast to australites, true meteorites do not appear to have been utilised at all in the Aboriginal material culture (Bevan and Bindon, 1996).

It has been suggested that in Aboriginal Australia charms made from australites were part of the trade cycle (Cleverly, 1976). Edwards (1966: 248) stated that:

> The australites in use at Yuendumu in Central Australia were said by the aboriginals to have come from a great distance and were possibly transported by them from the Musgrave Park or Mount Davies-Lake Wilson areas where numerous specimens have been recovered. The dispersal of australites from their original strewn-fields can be attributed to many agencies. There is insufficient evidence to indicate whether their use by the aboriginals had any significant effect on their distribution.

Individuals in possession of australites were capable of taking them long distances, and therefore north of the Kyogle-Derby line (Fenner, 1934) and outside of their natural distribution (McColl, 2017). For instance, it was recorded by australite researchers doing fieldwork in the 1970s that

> Some years ago the owner of Marion Downs, a station 35 miles south of Bouila [sic. Boulia] in northwest Queensland (23° 20′, 139° 40′), reported that an aboriginal there had a large round australite core, chipped at the edges; he stated that he had carried it for long distances over many years and obviously treasured it. (Chalmers et al., 1976: 15).

Due to major cultural changes occurring over the millennia within Aboriginal Australia, which are reflected in the archaeology (Lourandos, 1997), it cannot be assumed that Aboriginal use of australites has remained the same throughout time. Therefore, apart from the spatial differences with the Indigenous use of australites as tools, there are possibly temporal aspects to their use. It has been suggested that the use of australites collected on the Nullarbor Plain from about 10,000 B.P. may have been due to an expansion of foraging ranges due to a more benign climate, rather because of a sudden appearance of the material (Smith, 2013).

From the available evidence, it appears that while australites were possibly widely traded across Aboriginal Australia, particularly as charms, it is unlikely that this had occurred in sufficient numbers to have obscured the distribution of the strewn field. The use of australite glass to make artefacts was probably restricted to those areas where they occurred that also had a deficiency of good local stone for making tools. In spite of their usefulness in this regard, australites were not generally classed with ‘rocks’, as were the various cherts that were used for making stone tools. That these small, glassy, emu eye-like objects were not thought of as such, but considered as *maban* despite their usefulness as scrapers, is significant. Aboriginal people did not see the tektites land, but nevertheless they perceived their presence in the landscape as special. The australites, as a category of object, were utilised for both the magical and the mundane—being too good to give up use as a scraper.

5 NOTES

1. The current name of the National Museum of Victoria is Museum Victoria.
2. The collections included the following, all from South Australia: Barry Lindner from the Yalata area; Mrs W.B. MacDougall from the Mount Davies area; and Bob Verburgt from the Coober Pedy area.
3. In the Pitjantjatjara/Yankunytjatjara language *ngulu* (= *nulu* ?) means “… warily, cautiously, wanting to avoid something bad happening.” (Goddard, 1992: 88–89).
4. In the Pitjantjatjara/Yankunytjatjara language, *nyinnga* (= *njinggar*) means “ice, frost” and “… frost season, cold time of the year, winter.” (Goddard, 1992: 97). Tindale (1974: 71) translated *njenga* to mean “snow” in this language.
5. In the Pitjantjatjara/Yankunytjatjara language, *kuti-kuti* (= *ko:di* ?) means “revolving” (Goddard, 1992: 48). Also, in the Pitjantjatjara/ Yankunytjatjara language the term *tjapu* (*japu*) refers to “small. Especially used of living things that are small because they are young.” (Goddard, 1992: 146–147).
6. Greenway (1973) provided an account of Bob Verburgt’s attempts at getting the Department of Aboriginal Affairs to support the mining of chrysoprase at Mount Davies. In the early 2000s I noticed that chrysoprase was still being intermittently mined near Pipalyatjara in the northwest corner of the Anangu Pitjantjara Yankunytjatjara Lands in South Australia.
7. A27532, received circa 1929 from Mr E.J. McCarthy at Scadden via N.B. Tindale (South Australian Museum Aboriginal Ethnographic Collection).
8. A1362, early-twentieth century (South Australian Museum Aboriginal Ethnographic Collection). Other australite ‘charms’ in the Mus-

eum collected by Bates include A1357 and A1363.
9. In Western Desert languages, such as Pitjantjatjara/Yankunytjatjara, *kuru* (*kooroo*) is "eye" (Goddard, 1992: 46).
10. In the Wirangu language of the West Coast of South Australia, *mil* (*mel*) is "eye" (Miller et al., 2010: 57).
11. There is a collection of ten australites (A32509) that D.M. Bates collected at Ooldea, South Australia (South Australian Museum Aboriginal Ethnographic Collection).
12. In the Pitjantjatjara/Yankunytjatjara language, *wanma* (*warn-ma*) means "far away", "… not close, at a distance." (Goddard, 1992: 185).
13. In Western Desert languages, such as Pitjantjatjara/Yankunytjatjara, *kalaya* ('*Kaleya*') is "emu" and as we have seen (Note 9) *kuru* (*korru*) is "eye" (Goddard, 1992: 27, 46). Tindale (pers. comm. [Baker, 1957: 19, 20]) suggested that *pandolla* could mean "… pertaining to limestone places", as *parnda* and *parndala* mean "limestone".
14. For a contemporary perspective of the *ngangkuri* refer to NPY Women's Council (2003).
15. Note that Mountford has Anglicised the spelling of the Aboriginal names by putting a 's' on the end of the words to denote a plural. The term, *marali*, means "spirit body" (NPY Women's Council, 2003: 60).
16. The term *ko:ti* appears to be a variation of Tindale's writing of *ko:di*.
17. A27197 (South Australian Museum Aboriginal Ethnographic Collection). Refer to Jones (1987) for details of the Board for Anthropological Research Expeditions.
18. A16038, early-twentieth century (South Australian Museum Aboriginal Ethnographic Collection).
19. A3776, early-twentieth century (South Australian Museum Aboriginal Ethnographic Collection).
20. The term *yarda* is possibly a cognatic term to *yarida*, meaning a 'magic object' (Berndt, 1987: 20), in the Ngadjuri language of the mid-north of South Australia (R. Graham, pers. comm.).
21. In the Diyari (Dieri) language of northeast South Australia the *muramura* (mooramoora) were the 'ancestors' (Horne and Aiston, 1924: 110; Howitt, 1904: 475).
22. A6043, received from L. Hole (South Australian Museum Aboriginal Ethnographic Collection).
23. A16601, Mulka, Cooper Creek, South Australia, early-twentieth century; A16619, Mungaranie, South Australia, early-twentieth century (South Australian Museum Aboriginal Ethnographic Collection). Other collections from this region in the Museum from the same period are A14351, 'obsidian charms', Cooper Creek, J. Reuther; A21087, comprised of 7 australite 'charms' from Uruwalina, 25 miles (40 kms) northeast of Cooper Creek, northeast South Australia, collected by Dr A.M. Morgan.
24. This information was repeated in "Magic Stones. Aboriginal Superstitions." (*Ballarat Star*, 28 October 1912, p. 2).
25. Baker (1957) misinterpreted Howchin's statement to mean that Aboriginal people on Kangaroo Island had used the australites as charms and scrapers.
26. The South Australian Museum examples of Aboriginal implements made from australites cited by Edwards (1966: Figure 1) included the following: 37 implements found by Mr and Mrs K. Treloar on Waiwera Station, South Australia; numerous specimens collected by J.E. Johnson from Yorke Peninsula, South Australia and from the North West of SA (see Hale, 1956; Johnson, 1963, 1964); 81 complete australite implements and 9 fractured pieces found by M. Mudie on Arcoona Station, South Australia; and various australite implements found by Edwards at 11 localities in northeast South Australia. Edwards also inspected private australite collections, that were owned by the following persons: Mr and Mrs R.D.J. Weathersbee; Dr G. Gregory; Brian Sawers, Andrew Bailey and B. O'Connell.
27. According to Akerman (1966), the australite collection had been made in a relatively short time by Mr Norman Irons and his family.
28. A14333-14346, received from F.W. Gilbert, 3 January 1929 (South Australian Museum Aboriginal Ethnographic Collection). According to Baker (1957) there is collection of australite artefacts from this location obtained from Mr F.A. Cudmore in the Geological Collection of the University of Melbourne.
29. A52758, 27 January 1960 (South Australian Museum Aboriginal Ethnographic Collection).
30. Registered as 49299 (Museum of Victoria).
31. The observation is consistent with my own, having several times during fieldwork heard contemporary Western Desert people refer to small stone flakes found on the ground at Aboriginal sites as probably circumcision knives, referred to as *djimeri* (= *jeemarri*, Bates, 1947: 111), in spite of the fact that they appeared to be simple microliths.
32. A54805, 17 November 1963 (South Australian Museum Aboriginal Ethnographic Collection). Refer to Tindale (1963: 177–178, 187). From the same broad region, the Museum has A14351, an 'obsidian charm' from the waterhole Opparinna in the western Musgrave Ranges, collected by Williams in the early-

twentieth century.

33. The estimated number of generations is based on an average of 25 years of age for each parent. Note that the Eaglehawk and Crow mythology and its tracks extend much further than the Mount Gambier area, and also that knowledge of it appears to have been subjected to movement in the historical period (Clarke, 2016; 2018).

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Dr Philip A. Clarke has an academic background in biology, geography and anthropology. He started working on the Aboriginal ethnographical collections at the South Australian Museum in 1982, where his initial research interests were chiefly focused on Aboriginal use of plants as foods, medicines and materials for making artefacts. This eventually expanded to Aboriginal perception and use of the land, with a particular focus on the cultural geography of southern Australia. During 1998 – 2000, Dr Clarke's major task was curating the Australian Aboriginal Cultures Gallery Project at the South Australian Museum. Since permanently leaving the Museum in late 2011, Dr Clarke has worked in private practice as a consultant anthropologist. He took up a half time Senior Research Fellowship at Griffith University from February 2012 to February 2013, in order to study Indigenous adaptation to climate change in south-eastern Australia. In February 2013 he was appointed to an Adjunct Senior Research Fellowship by Griffith University, and in April 2015 by the Federation University. In December 2015 he became an Honorary Research Associate (Anthropology) at the South Australian Museum. He continues to do consultancies for government agencies, corporations and Aboriginal organisations.

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ASTRONOMY OF THE PARDHI TRIBE OF CENTRAL INDIA

Ganesh Halkare
Indrayani Colony, Badnera Road, Amravati, Maharashtra 444607, India.
Email: ganeshhalkare@gmail.com

Purushottam Dahedar
'Antariksh', Narsih Sarswati Nagar, Gopal nagar area, Amravati, Maharashtra, 444607, India
Email: dahedar@gmail.com

Wayne Orchiston
National Astronomical Research Institute of Thailand, 260 Moo 4, T. Donkaew, A. Maerim, Chiang Mai 50180, Thailand, and Centre for Astrophysics, University of Southern Queensland, Toowoomba, Queensland 4350, Australia.
Email: wayne.orchiston@gmail.com

and

M.N. Vahia
Narsee Monjee Institute of Management Studies, V.L. Mehta Road, Vile Parle (W), Mumbai, 400056, India.
Email: mnvahia@gmail.com

Abstract: We report on the astronomical ideas and beliefs of the Pardhi tribe of central India. Pardhi tribesmen were classified as a criminals by the British during the colonial era, and even though this label was scrapped after independence, the stigma remains. Consequently their lives often are based on scavenging, which gives them a unique perspective of the heavens. Their images of the sky are preoccupied with imagery of plants, animals and birds, far more so than with any other Indian tribe. While they do have some beliefs in common of other tribes in their region, there is a significant degree of originality that is commensurate with a community that has long traditions. One unique feature of the Pardhi is a bird trap that is based on the configuration of stars in the constellation Taurus, and they view the entire Orion region as a hunting scene.

Keywords: India, Pardhi tribe, astronomical systems and beliefs, bird trap

1 INTRODUCTION

In a series of papers, we have reported the astronomical beliefs of a variety of tribes of central India. The tribes we have studied are the Gonds (Vahia and Halkare, 2013), Banjaras and Kolams (Vahia et al., 2014), the Korku (Vahia et al., 2016) and the Cholannaikans (Vahia et al., 2017a). The principle results from these studies are summarised in Vahia and Halkare (2017) and Vahia et al. (2018) and their relevance to the general development of our understanding of nature is discussed in Vahia et al. (2017b).

In general, all these tribes have traditions about the Sun, the Moon and some stars and asterisms (Vahia and Halkare, 2017; Vahia et al., 2018). The complexity of their astronomical beliefs correlates well with their periods of settlement, suggesting that beyond the basics of the Sun, the Moon and stellar observations, astronomy was principally a leisure-time activity.

While many Indian tribes do not recognise constellations (in the Western sense), they do divide stars into small groups or asterisms. For example, the Big Dipper portion of Ursa Major is seen by many as a bed, with thieves or groups of people trying to steal that bed (see e.g. Figure 1). Meanwhile, the Milky Way is considered to be a pathway for animals, or human ancestors. Most Indian tribes are aware of comets and meteors. Comets are generally referred to as brooms or stars with tails, while in most Indian communities meteors (shooting stars) are seen

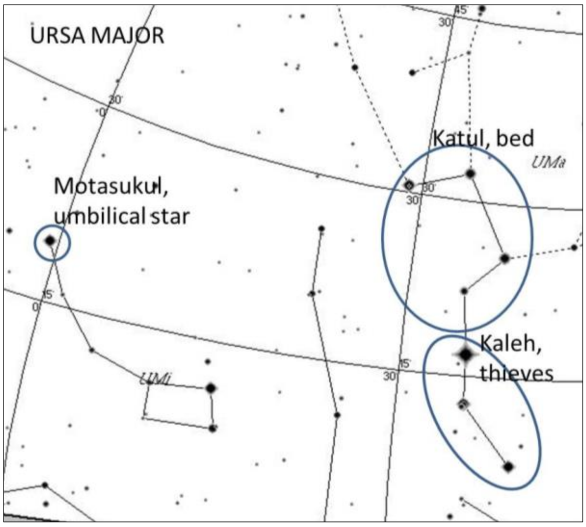

Figure 1: The Big Dipper according to the Gonds (after Vahia and Halkare, 2013: 41).

stellar excreta (and it is quite embarrassing to mention them.)

The afore-mentioned Indian tribes comprised a mix of Austro-Asians and Ancestral Indo-Europeans who had been settled in different regions of Central India as farmers over several millennia (Vahia et al., 2017b). Some, like the Gonds, had a long history of settlement, while others, such as the Banjaras, are only now settling down and acquiring agricultural skills and experience—and this is clearly reflected in their astronomical beliefs (Vahia and Halkare, 2017; Vahia et al., 2018). Many of these tribes have an intimate knowledge of local plants and their uses (Jain et al., 2010).

In this paper we report on the astronomical knowledge and beliefs of the Pardhi tribe of Central and Western India (see Figure 2).

2 THE PARDHI TRIBE

A brief description of the tribe can be found in 'Pardhi in India' (2019). In British India, the Pardhi was classified as a criminal tribe in 1871, and even though this label was formally removed (de-notified) after independence (Bokil, 2002), a mutual distrust of the overall Indian population has remained, resulting in relatively poor development of the Pardhi community (ibid.; D'Souza, 1999). The Pardhi therefore have not been studied in the same degree of detail as many other tribes, but their general characteristics are given in Table 1.

The Pardhi still bear the stigma of originally being branded as criminals, and so they tend to live in isolated, economically disadvantaged areas. Their communities find refuge in remote regions of Maharashtra, particularly in central Maharashtra, on the outskirts of towns and villages (see pardhisamaj.blogspot.in/2012/01/pardhi-samaj.html)

The Pardhi are known by various names in different regions. In Pardhi language they are called Waagharis. Most Pardhi sub-castes—including the Bhil Pardhi, Chiche Pardhi, Dhangar Pardhi, Faase Pardhi, Gaay Pardhi, Ghisaadi Pardhi, Ghod Pardhi, Haran Pardhi, Lamaan Pardhi, Langot Pardhi, Maang Pardhi, Paal

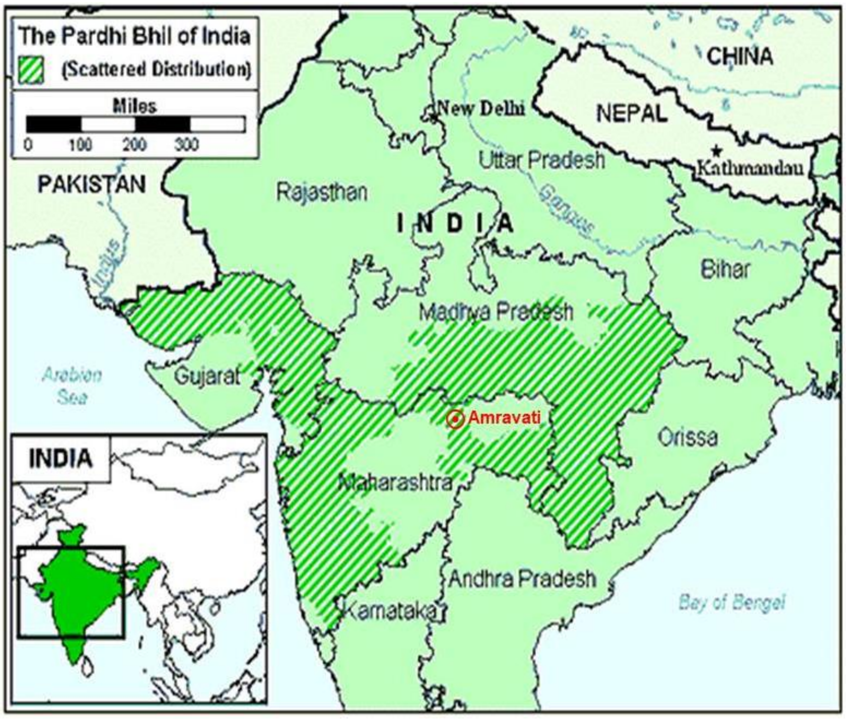

Figure 2: A map showing the geographical distribution of Bhil Pardhi in central and western India (after Pardhi in India, 2019).

Table 1: Principle characteristics of the Pardhi Tribe.*

Alternate Names	Bahelia, Chita Pardhi, Langot Pardhi, Paidia, Paradi, Paria, Phans Pardhi, Takankar, Takia
Population	49,300 (2001 census).
Location	Maharashtra: Solapur, Satara, Sangli and Kolhapur districts; Karnataka: small border areas, Bijapur and Belgaum districts; widely scattered in Gujarat and Madhya Pradesh.
Classification	Indo-European, Indo-Iranian, Indo-Aryan, 'Central zone', Bhil
Dialects	Haran Shikari, Neelishikari, PittalaBhasha, Takari. Probably more than one language (Lango). Possibly a dialect of Bhili.
Other Comments	A 'Scheduled Tribe' in Gujarat, Karnataka, Madhya Pradesh and Maharashtra, and a 'Scheduled Caste' in Madhya Pradesh. They differ from the Paradhi, who speak Kachchi. They have their own traditional religion.
* Data taken from https://www.ethnologue.com/language/pcl	

Pardhi, Raj Pardhi, Rajput Pardhi and Shika J. Pardhi—still lead nomadic lives. Only the Gav Pardhis took to farming and settled well during British rule, and they now have a sizable population in the Amravati District.

Due to discrimination, extreme poverty, and lack of education, employment and social ethics, some Pardhi were—and still are—compelled to hunt for food or lead a life of crime. This social rift has forced the tribe to remain entrenched in practicing traditional customs.

The Pardhi worship nature and goddesses rather than gods. They worship 'dhani' and 'jarane' by sacrificing goats. They claim descent from Rana Pratap and Prithwiraj Chauhan, with an original home in Gujarat and Rajasthan.

In view of the strained relations between the Pardhi tribe and the rest of the Indian community, the Pardhis are aggressive and possessive of their identity and resent any contact that may lead to their being misunderstand. As a result, genetic and other data about the tribe are difficult to come by, but limited genetic studies do suggest that they are Indo-European in origin (Clark et al., 2000; Cordaux et al., 2003). This is reinforced by a study of their language. The Pardhi's home language is akin to Hindi that is spoken in rural Gujarat and Rajasthan. It is a corrupt guttural mixture of dialects in which Gujarati predominates. It has a strong family likeness to 'Baori-bhasha' (Ghodke, 2016; Grierson, 1907), and seems to be a crude mix of Gujarati and Bhil languages plus a little Marathi. This suggests that the Pardhi belong to the Bhil tribal community, with roots in Gujarat.

Because they refuse to become part of the Indian caste system the Pardhi remain isolated.

> They prefer hunting, begging, or even stealing for a living, rather than submitting to a social system that they consider demeaning and degrading. Those who make a living by thievery steal items that they can trade or sell. (Pardhi in India, 2019).

The Pardhi interest in nature around them is unique in many ways, but while they are known to be users of plants for medical purposes (Jain et al., 2010) their perspective is limited to survival. Accordingly, in the context of astronomy, their knowledge derives from a casual interest rather than any attempt to either extract information from the skies or to use astronomical information for philosophical or cosmogonical purposes.

3 FIELD DATA

Our studies were conducted in Central India near the city of Amravati (for the location see Figure 2). Isolated tribal villages were identified and visited and detailed interviews were conducted. Information about the villages is given in Table 2, and Figure 3 shows Pardhi from the village of Ajanti Beda (number 10 in Table 2). The person middle centre in the blue shirt is the first author of this paper and the person on his right (with the white shirt) is the paper's second author.

Principal Pardhi astronomical beliefs are listed in Table 3 along with the number of villages in which the stories were reported. Note that those living in Saur, Hartala and Hiwara BK (i.e. villages 1–3) were cultivators, whereas Pardhi in all other villages visited were hunters and gatherers (and we have colour-coded them accordingly in Tables 2 and 3). It is important to explore whether the astronomical beliefs of these two ecologically-disparate populations differ significantly or if they are similar and therefore date from an era when *all* Pardhi practised hunter-gathering. This interesting topic is discussed below in Section 4.1. In this context, it is pertinent to note that the name 'Pardi' comes from the Marathi word 'paradh', which means "hunting" (Pardhi in India, 2019).

Pardhi terms relating in one way or another to the environment are listed in Table 4, and the principle astronomical beliefs of the Pardhi are summarised in Table 5. Some of their beliefs, such as Ursa Major being a cot or the Milky Way a pathway, are common to other tribes of Cen-

Table 2: Locations of farming (green) and hunter-gather (blue) Pardhi villages visited by us.

No.	Village	Location	
		Latitude	Longitude
1	Saur	21.13128	77.66459
2	Hartala	20.92794	77.55524
3	Hiwara BK	20.76909	77.63295
4	Wadura Beda	20.73698	77.63948
5	Daryapur	20.92244	77.33165
6	Darapur	20.95990	77.54480
7	Shinganapur	20.94254	77.48958
8	Khairi Donoda	21.12697	77.53389
9	Mangarul Chavhala Beda	20.60211	77.81094
10	Mukinpur Beda	20.45000	77.83654
11	Ajanti Beda	20.50772	77.81672
12	Zombadi Beda	20.53931	77.83636
13	Jagatpur Beda	20.55201	77.75824
14	Wadgaon	20.74462	77.60653

Figure 3: A photograph showing two of the authors of this paper together with people from a typical Pardhi village, in this case Ajanti Beda (No. 11 in Table 2) near Ner town in the Yeotmal district of Maharashtra (photograph: Ganesh Halkare

Table 3: Astronomical beliefs of the Pardhi (farming villages in green and hunter-gatherer villages in blue).

No.	Belief	Village														Total
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
1	Ursa Major															
	Cot of an old lady															13
	Three dead men															1
	Three thieves															6
	A person of the Pardhi Tribe															2
	Three birds: Teetar, Bater and Lawada															1
2	Orion															
	Three deer (Orion's Belt)															7
	As a Trikand (Orion's Belt)															8
	A person of the Pardhi Tribe															3
	Two hunting dogs															1
3	Taurus region															
	Triangular-shaped net for trapping birds															7
4	Pleiades															
	Flock of Juggle Babbler birds															13
5	Two stars near the Pleiades, κ2 Tau and υ Tau or η Aur and ζ Aur															
	Two eggs															6
6	Scorpius															
	Cobra or snake															12
7	Milky Way															
	As a path															10
8	Comet															11
	Omen (G = Good, B = Bad)						B	B	B	B			B	B	B	7
9	Meteors															14
	Omen (G = Good, B = Bad)	B	B		B	B	B	B	B	B			B	B	B	11
10	Sun															14
11	Moon															14
	Halo around the Moon															5
	Weather forecast using the Moon halo															2
12	Venus															14
13	Mars															9
	Conjunction of Venus and Mars															9
14	Solar eclipse															10
15	Lunar eclipse															10
	Story about eclipses															6
	Omen (G = Good, B = Bad)	B	B	B	B		G	G	G	B			B	B	B	11
16	Rainbow															11
	Mushroom-like object															8
17	Directions															9
18	Calendar															5

tral India. However, several beliefs are unique to the Pardhi, and reflect their own isolated intellectual development.

In particular, their imagery of birds and animals is far more prevalent than in other tribes, as might be expected if the ancestral population was solely dependent on hunting and gathering for its survival. They identify the Belt of Orion with three deer, the Orion Nebula with two hunting dogs, Taurus as a trap for catching birds, the Pleiades as a flock of birds, stars in Taurus as birds' eggs, and four stars with different birds that are common in the Amravati region. Their beliefs are either completely original or rarely found in other tribes. The Kolams identify the Pleiades as a flock of birds and the Gonds see a bird's egg and nests in Taurus. However, the Padhi association of Orion with deer, the rainbow with mushrooms and Taurus as a bird trap are all unique. This is the only tribe we have studied where the design of a bird trap was inspired by a constellation (see Figure 4).

4 DISCUSSION

4.1 Hunter-Gathers Versus Farmers

As indicated in Section 3, above, the Gav Pardhis in the Amravati District are farmers whereas all other Pardhi groups studied still rely on hunting and scavenging for their sustenance. It therefore is illuminating that the only entry in Tables 4 and 5 with possible farming associations is the presence of a halo around the Moon to forecast the weather. But knowing the onset of the monsoon would not only be of value to farmers but also to hunter-gatherers (see Korisettar and Ramesh, 2002). The entries in Tables 4 and 5 suggest that Pardhi astronomical terminology was standardised in an era when *all* Pardhi practised hunting-gathering. The various birds mentioned in Table 5, along with bird's eggs, deer, snakes and hunting dogs all indicate a hunter-gatherer ecology. That there are no words directly relating to farming perhaps is not surprising given that those Pardhi who practise farming adopted this lifestyle less than a century ago, and we know from other studies (e.g. see Orchiston and Orchiston, 2018) that it takes several hundred years for astronomical systems to evolve and new terminology to be introduced following a major ecological change.

4.2 Human Ecology and Birds and Animals in the Pardhi Skyworld

Ethnoastronomical studies in other parts of the world have revealed a close correlation between astronomical beliefs and ecological precepts (e.g. see Clarke 2014; 2015; Fuller et al., 2014; Leaman et al., 2016).

Tables 6 and 7 list animals and birds of dietary importance to the Pardhi recorded during our fieldwork. Only a relatively small number of animals are hunted frequently, and only one of these—the Spotted Deer—was deemed important enough to feature in the Pardhi night sky—along with dogs that are used in the hunt.

On the other hand, birds would appear to make a major contribution to the diet, with thirteen different species hunted regularly, and an equal number taken seasonally (subject to availability). All are captured in nets, with several different varieties of net reserved for small birds and for medium-sized birds. Where information exists, the names of the nets associated with specific birds are listed in the right hand column in Table 7.

Figure 4: A type of net known as Mangari, which was used by the Pardhi for catching small birds. The top image shows the net folded up ready to transport, and below, fully laid out in order to clearly illustrate its design and structure. The Pardhi named the triangular-shaped Hyades asterism in Taurus after this net (Photographs: Ganesh Halkare).

Table 4: The environmentally-related vocabulary of the Phase Pardhi.

	Pardhi Word	Marathi Meaning	English Meaning
1	सूर्यासंबर /खुर्याखंबर / हेटल्यावई /वंद / वंध / निकलतो / *Suryasambar / Khuryakhambar / Hetlyawai / vand / Vandh / nikalato*	पूर्व	East
2	उपल्यावई / डूबतो /बाइंड /upalyawai / *Dubato / baend*	पश्चिम	West
3	डोंगरी / ओलाऊ / डोंगरावू / *Dongari / olau / dongarau*	उत्तर	North
4	राक्षसबाकू / दखनी / दखनाऊ / माहुरी / हेटवास / *rakshasbaku / Dakhani / dakhanau / Mahuri / Hetawas*	दक्षिण	South
5	वई / *Vai*	दिशा	Direction
6	बाकू / *Baku*	मुख	Mouth
7	खऊ / खळू / *khau / khalu*	खळे	Glow around the Moon
8	हिलगोई / *Hilagoi*	भोरपक्षी	Ring Dove
9	ब / *ba*	दोन	Two
10	इंडा / *inda*	अंडी	Eggs
11	हम्बेल / कावडता / *hambel / Kavadata*	नाग	Cobra / Snake
12	चईतमहिनो / *chaitmahino*	चैत्रमहिना	First month of Hindu calendar
13	मसोटी / *masoti*	स्मशान	Graveyard
14	मचवा / *Machava*	स्मृतीदगड	Memorial stone
15	भारतल्ली / *Bhartalli*	स्मशानविधी	Ritual performed at the graveyard
16	माथो / *Matho*	डोक	Head
17	भतरा / *Bharata*	दगड	Stone
18	दन / *Dan*	दिवस	Day
19	रात / *Rat*	रात्र	Night
20	चलन / *Chalan*	तारकाभ्रमण	Rotation of stars
21	गिराण / *Giran*	ग्रहण	Eclipse
22	तरण / त्रण / *Taran / Tran*	तिन	Three
23	बाधीराखो / *badhirakho*	बांधूनठेवलेला	Tied
24	गाठळू / *Gathalu*	खाट	Cot
25	बाम्बलो / *Bambalo*	वारूळ	Ant house
26	पातालतुमंडी / *Pataltumadi*	जडी / आळबी	Mushroom
27	बोहारो / *Boharo*	अपशकून	Bad omen
28	हल्या / *Halya*	हेला	Male buffalo
29	बोकड्या / *Bokadya*	बोकुड	Male goat
30	मेढा / *Medha*	मेंढा	Male sheep
31	डोंडो / *Dondo*	शेपूट	Tail
32	मांगडी / *Mangadi*	दायी	Midwife
33	बेडा / *beda*	वस्ती	Place of temporary shelter
34	असन्यान / *Asanyan*	स्नान	Bath
35	आडी / *Aadi*	तिरपे	Tilted

Table 5: Pardhi astronomical terms.

No.	Pardhi Word in Deonagari and Roman Alphabets	Description	Astronomical Reference
1	बुडीनू खाटलू / बुढिनू खाट / बुडीनू गाठळू / *budinu khatalu / budhinu khat / budinu gathalu*	A cot of old lady	The Big Dipper in Ursa Major
2	चावंड्यों / *chavandeyo*	A person from the Gaon Pardhi tribe with the surname Chauhan who worshipped the goddess Chavanda	Alioth (ε UMa)
3	खोड्यान्यो / *Khodyaryo* / पिंपळाज्यो / *Pimplajyo*	A person from the Gaon Pardhi tribe with the surname Solanke who worshipped the goddess Pimpalaj / Khodyar Devi	Mizar (ζ UMa)
4	कोरोब्यो / *korobyo*	A person from the Gaon Pardhi tribe with the surname Pawar who worshipped the goddess Korobyo	Alkaid (η UMa)
5	तितर / *Teetar*	Teetar bird, i.e. Grey Francolin (*Francolinus pondicerianus*)	Alioth (ε UMa)
6	बटेर / *Bater*	Bater bird, i.e. Black-breasted Quail (*Coturnix coromandelica*)	Mizar (ζ UMa)
7	लावडा / *Lawada*	Lawada bird, i.e. Rock Bush Quail (*Perdicula argoondah*)[1]	Alkaid (η UMa)
8	मेलेला माणस / तरण चोर / *Melela manas / Taran chor*	Three dead men / Three thieves	The three tailing star of Ursa Major i.e. Alioth (ε UMa), Mizar (ζ UMa), Alkaid (η UMa)

9	तिरा हरिणे / तिन हरण / तरण हरन्या / त्रन हरन्या / *Tira harine / Tin haran / Taran Haranya / Tran Haranya*	Three deer	Orion's Belt
10	त्रिरकांडू / *Trirkandu*		Orion's Belt
11	पारधी / *pardhi* (बावरी or वाघरी / *Bawarior Waghari*)	A person from the Pardhi tribe	Rigel (β Ori)
12	बो कुत्र्या / दोन कुत्रे / *Bo kutrya / Don kutre*	Two hunting dogs	The Orion Nebula
13	मंगरी / *Mangari*	A triangular-shaped net for trapping birds	Taurus region
14	लावडानू खालू /लावडानी खाडू / लावडानू खाडू / लावडानी झुंड / *Lawadanu khalu / Lawadani khadu / Lawadanu khadu / Lawadani zund*	A flock of Jungle Babbler birds (*Argya striata*)	Pleiades
15	होलगी / हिलगोई / *Holagi / Hilagoi*	Hilagoi bird, i.e. Ring Dove (*Streptopelia decaocto decaocto*)	Not identified exactly, but somewhere in the Pleiades-Taurus-Auriga region
16	सापनी फनी / फनो निकळ्यो / नागनु फनु / नागनु फन / नागनी फनी / *Sapani fani / Fano nikalyo / Naganu fanu / Naganu fan / Nagani fani*	A cobra or snake	Scorpius
17	ब इंडा / *Ba inda*	Two bird's eggs	Two stars near the Pleiades: either κ2 Tau and υ Tau or η Aur and ζ Aur
18	खगर / सडक / रस्ता / दांडी / जावानु दांडी / *Khagar / Sadak / Rasta / Dandi /Javanu Dandi*	Path	The Milky Way
19	सुकर / सुक्कर / शुक्रर चांन्नी / पादरी चांन्नी / पायटनी चांन्नी / हागऱ्या तारा / जगीन तारा / *Sukar / Sukkar / Shukrar Channi / Padari Channi / Payatani Channi / Hagarya Tara / Jagin Tara*	Morning Star / Evening Star	Venus
20	सुकरी / सुक्करी / *Sukari / Sukkari*		Mars
21	सुकर / सुक्कर / शुक्रर चांन्नी / *Sukar / Sukkar / Shukrar Channi*	Morning star / Evening Star	Sirius (sometimes)
22	डोन्डो फुटी ग्यो / डोन्डो फुट्यो / इगन तारा / *Dondo futi gyo / Dondo futyo / Igan Tara*	Star having Tail	A comet
23	तारो तुट्यो / तारा तुटी गी / चान्नी तुटी / *Taro tutyo / Tara tuti gi / Channi tuti*		A meteor
24	चांद / दादाजी / वडो / *Chand / Dadaji / Wado*		The Sun
25	चांद / चांदर / *Chand / Chandar*		The Moon
26	सुकर / *Sukar*		A star

Table 6: Animals hunted by the Pardhi.

No.	Animal			Frequency of Hunting
	Appearance	Common Name	Pardhi Name	
1		Wild boar (*sus scrofa*)	*dukar*	Frequently
2		Indian hare (Lepus nigricollis)	*datti*	Frequently
3		Monitor lizard (Genus Varanus)	*ghorapad*	Frequently

4		Spotted Deer (*Axis axis*)	*cheetal*	Frequently
5		Black Buck (Antilope cervicapra)	*aakharik*	When available
6		Sambar (*Rusa unicolor*)	*sambar*	When available
7		Indian wild dog (*Cuon alpinus*)	*nori*	When available

Table 7: Birds hunted by the Pardhi.

No.	Bird			Frequency of Hunting	Name of Net Used
	Appearance	Common Name	Pardhi Name		
1		Common Quail (*Coturnix coturnix*) [Small bird]	*Ghagas* or *ghagri bati*	Frequently	Kandalo or Mangari
2		Grey Francolin (*Francolinus pondicerianus*) [Medium-sized bird]	*Teetar*	Frequently	Khandari

3		Common Bustard-Quail (*Coturnix suscitator*)	*Tooru* or *Tiboti*	Frequently	
4		Rock Bush Quail (*Perdicula argoondah*) [Small bird]	*Kalu lawadi*	Frequently	Kandalo or Mangari
5		Grey Partridge (*Perdix perdix*)	*Goretro*	Frequently	
6		Black-breasted Quail (*Coturnix coromandelica*) [Small bird]	*Bater*	Frequently	Khandari
7		Common Buttonquail (*Turnix sylvaticus*)	*Tooru* or *Tiboti*	Frequently	
8		Yellow-legged Buttonquail (*Turnix tanki*)	*Titur* or *Kaletroyo*	Frequently	
9		Ring Dove (*Streptopelia decaocto decaocto*) [Medium-sized bird]	*Holagi*	Frequently	Khandari
10		Jungle Babbler (*Argya striata*) [Small bird]	*Gaghau*	Frequently	Mangari
11		Painted Sandgrouse (*Pterocles indicus*)	*Batto*	Frequently	

12		Red Junglefowl (*Gallus gallus*)	*Kombodo*	Frequently	
13		Painted Francolin (*Francolinus pictus*)	*Kaletroyo*	Frequently	
14		Rufous Turtle Dove (*Streptopelia orientalis*)	*Chitrong*	When available	
15		Blue Peafowl (*Pavo cristatus*)	*Panano*	When available	
16		Common Pigeon (*Columba livia*)	*Pareva*	When available	
17		Indian Pond Heron (*Ard eola gayii*)	*Chir Banglu*	When available	
18		Indian Nightjar (*Caprimulgus asiaticus*)	*Chibla*	When available	
19		Indian Spot-billed Duck (*Anas poecilorhyncha*)	*Badak*	When available	

20		Great Stone-curlew (*Esacus recurvirostris*)	*Teraki*	When available	
21		Yellow-wattled Lapwing (*Vanella malabaricus*)	*Teraki*	When available	
22		Indian Courser (*Cursorius coromandelicus*)	*Gedam*	When available	
23		Black Ibis (*Pseudibis papillosa*)	*Chamkho*	When available	
24		Eastern Great Egret (*Ardea alba modesta*)	*Bagala*	When available	
25		Great Indian Bustard (*Ardeotis nigriceps*)	*Badekhyo*	When available	
26		Black-winged Stilt (*Himantopus himantopus*)	*Tultulo*	When available	

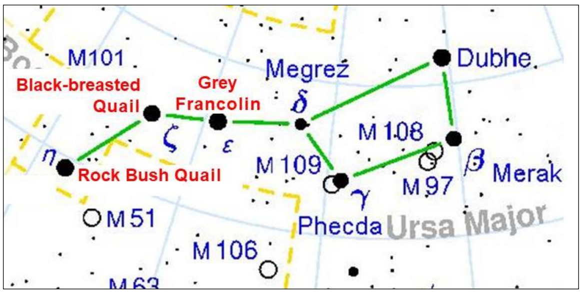

Figure 5: The 'Big Dipper' region of Ursa Major, showing three birds in the Pardhi skyworld (map: Wayne Orchiston).

It is notable that of the 26 birds listed in Table 7, the Grey Francolin, Black-breasted Quail, Rock Bush Quail, Ring Dove and Jungle Babbler all are important elements in the diet of the Pardhi and they also feature in their night sky. The first four birds are associated with individual stars in Ursa Major (Figure 5) or Taurus, while the Jungle Babbler is related to a prominent asterism, the Pleiades. But the Pardhi sky contains further avifaunal links, with two stars near the Pleiades identified as bird's eggs, while the Hyades is seen as the Mangari style of net (Figure 4) that is used to capture Ring Doves and Jungle Babblers. Its celestial positioning in such close proximity to the Jungle Babblers is illuminating (see Figure 6).

In various parts of the world, ethnoastronomers have documented clear associations between celestial birds and animals and the lifestyles of their terrestrial counterparts. Thus, in an elegant study of the Aboriginal Australians from Ooldea, Leaman et al., (2016) found that breeding habits (e.g. mating/breeding, laying/birthing, fledgling/whelping) of different birds are linked to the heliacal or acronychal rising or setting, or meridional transit, of their respective celestial correlates. Leaman et al. (2016: 72–73) concluded that

> … Aboriginal people from Ooldea deliberately selected certain prominent stars and asterisms to match the breeding cycles of the terrestrial animals they represent.

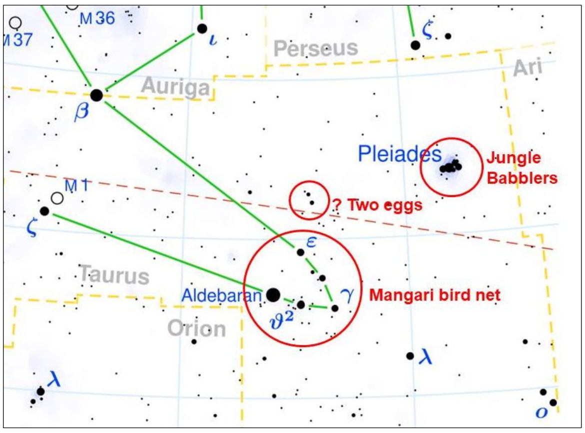

Figure 5: The Taurus region, showing a flock of Jungle Babbler birds, the net used to catch them, and possible bird's eggs in the Pardhi skyworld (map: Wayne Orchiston).

Consequently, "These traditions serve, in part, as a guide for noting the time of year to access particular food sources." Leaman et al., 2016: 61). However, in India the Grey Francolin, Black-breasted Quail, Rock Bush Quail, Ring Dove and Jungle Babbler are hunted by the Pardhi *throughout* the year—regardless of their particular breeding cycles—so unfortunately there are no grounds for associating the capture of these species with the heliacal or acronychal rising or setting, or meridional transit, of specific constellations in the Pardhi skyworld.

However, it is easy to see why the Pardhi decided to identify these five types of birds in the sky, as all would have been conspicuous features of the prehistoric Pardhi environment, just as they are today in the Amravati District and throughout Central India.

But why did the Pardhi decide to name the Pleiades after a small group of Jungle Babblers, in preference to any of the other bird species? Jungle Babblers are small birds—just like both species of Quail mentioned above—and would have supplied less edible meat per bird than the medium-sized Grey Francolin or Ring Dove, so clearly their dietary contribution was not a factor. Jungle Babblers, Ring Doves and Rock Bush Quail are all gregarious species and like to congregate in flocks, while Grey Francolins and Black Breasted Quail typically are solitary birds or found in pairs (Hume and Marshall, 1880), but what sets the Jungle Babbler apart is surely its conspicuous presence and active, vocal social behaviour:

> The jungle babbler lives in flocks of seven to ten or more [hence their popular Indian name, the 'seven sisters']. It is a noisy bird, and the presence of a flock may generally be known at some distance by the harsh mewing calls, continual chattering, squeaking and chirping produced by its members … (Jungle babbler, n.d.; cf. Ali and Ripley, 1996: 224–230).

The 'public persona' of the Jungle Babbler is perhaps best summed up by this illuminating account from the nineteenth century:

> Some years back, a new Viceroy was being shown the wonders of his temporary kingdom, and among these the Taj at Agra held, of course, an important place. Arrived before the glorious monument of Eastern love and pride, "the artless Aide-de-Camp was mute; the gilded staff were still" as Kipling says, in anxious expectation of the comment of His Excellency. But this, alas! when it came was merely the remark: "What are those funny little birds?" The shock must have been the greater for the fact that the mean fowls thus honoured were it seems, of that singularly disreputable species which is commonly known in India as the "Seven Sisters" or "Seven Brothers," or by the Hindustani equiv-

> alent of *sat-bhai*. In books it gets called the Jungle Babbler. (Finn, 1903: 15).

While the little Jungle Babbler may have been seen as 'disreputable' by nineteenth century British colonials, it clearly was held in high esteem by those Pardhi who decided to place it in their skyworld many thousands of years ago!

5 CONCLUDING REMARKS

In this paper we report the astronomical beliefs of the Pardhi tribe of Central India. Originally classified as a Criminal Tribe by the British, it continues to suffer the stigma of that listing and has therefore struggled to settle down and find fruitful employment without attracting unnecessary attention.

This shows up in their astronomical beliefs in several ways. While they have some concepts that they share with other tribes, their impression of the sky is far more animistic, and includes deer and hunting dogs in Orion, and four different species of birds and two bird's eggs in the Taurus or Ursa Major. They also use a net inspired by the Hyades in Taurus to catch two of these four bird species, and the net is conveniently positioned in their skyworld near to these birds. This celestial bird net does not feature in the astronomical systems of any of the other central Indian tribes that we have studied.

Some Pardhi now practise agriculture, while most villagers continue to survive through hunting and gathering, but all of the ecological terms found in the Padhi astronomical record relate to hunting and gathering. This indicates that the current astronomical base of the Pardhi was established at a time in the past when *all* Pardhi were hunters and gatherers. Precisely when was this?

It is estimated that there are about 460 tribal communities in India (see Singh, 1992), and during the 1991 census these comprised 8.08% of the total Indian population (Singh, 1994). Individual tribes vary in size from a few hundred to a few million. They

> … speak languages belonging to all four of the major language families represented in India (Austro-Asiatic, Dravidian, Indo-European and Tibeto-Burman) … [and] are generally thought to be the aboriginal inhabitants of the Indian sub-continent that were present in the region before the arrival of Indo-European speakers. (Cordaux et al., 2003: 254).

Although there is evidence that *Homo erectus* hominids occupied the Indian subcontinent during the Early Pleistocene (e.g. see Pappu et al., 2011; Sonakia and de Lumley, 2006), groups speaking Austro-Asiatic and Tibeto-Burman languages are believed to have been the first 'modern humans' (*Homo sapiens sapiens*) to settle in India, around 50,000–60,000 years ago (Barnabas et al., 2006; Basu et al., 2003; Kumar and Reddy, 2003). Dravidian-speakers arrived later, followed by the Indo-Europeans, possibly around 3,500 years ago (Cordaux et al., 2004)—though this date is hotly debated.[2]

Therein lies the problem: whereas the genetic evidence points clearly to the Pardhi (and other tribes) evolving from the original Austro-Asiatic settlers (Clark et al., 1999; Cordaux et al., 2003), the Pardhi and most other Central Indian tribes now speak Indo-European languages. This indicates that they deliberately abandoned their ancestral language and adopted the language of the newly-arrived Indo-European speakers once the latter settled in Central India. This wholesale language switch is termed a 'language shift', and clear-cut Indian examples have been documented by Chaubey et al. (2008). Long before the arrival of the Indo-European-speakers in Central India the Pardhi had related their 'skyworld' to hunting and gathering—and especially the avifaunal opulence of their terrestrial environment—and when they elected to speak an Indo-European language it was merely a matter of adopting substitute terminology. Fortunately, they did not have to change their entire astronomical knowledge base.

Yet this change illustrates that indigenous astronomical systems are not static: they are dynamic, and—as with other elements of culture—can evolve with the passage of time. This being the case, we may wonder if those Pardhi who are now farmers will eventually try to re-invent their sky-world so that it reflects their current ecological situation. We suspect that this will never happen. Such a change will require several hundred years (cf. Orchiston and Orchiston, 2017), and in the interim the Pardhi will continue to suffer acculturation; the young will be exposed to 'modern' astronomical concepts and terminology (through schooling, television, newspapers, magazines, etc.); and the elderly will die without passing on their traditional astronomical knowledge to the next generation.

We believe that if the Pardhi astronomical base does evolve over the coming centuries it will be to reflect changing relationships with particular birds, but specifically their capture and their dietary role in Pardhi society. If the emphasis in hunting shifts from the Jungle Babbler and Ring Dove to other birds, will any of the nets used to take these birds also end up in the Pardhi night sky?

6 NOTES

1. Although our informants in Village 12 identified the Lawada bird as the Jungle Babbler (*Argya striata*), we question this. Admittedly,

the Pardhi refer to a flock of Jungle Babbler birds as *Lawadanu khalu*, *Lawadani khadu*, *Lawa-danu khadu* or *Lawadani zund* (Table 5) but a single Jungle Babbler is *Gaghau* (Table 7), whereas the Pardhi name for the Rock Bush Quail is *Kalu lawadi*. Given that a small flock of Jungle Babblers is already represented in the Pardhi night sky, we prefer to identify the Lawada bird as the Rock Bush Quail, a bird that also was important in the Pardhi diet.

2. This 'standard scheme' relies on a combiation of archaeological, linguistic and genetic evidence, and refers only to major large-scale migrations. Given the specific focus of this paper, we have not included possible later small-scale migrations of Muslims from the Middle East (see Gutala et al., 2006; Terreros et al., 2007).

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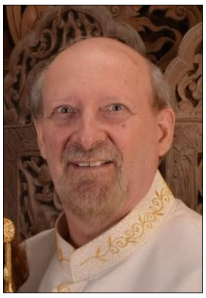
Ganesh Halkare is an advocate in Amravati, a town in Maharashtra. He also has a post-graduate degree in Archaeology and Anthropology from Nagpur University. He has a deep interest in tribal education, particularly in the removal of superstition among tribe members. He also is deeply interested in tribal anthropology and is highly respected amongst the tribesmen for his work in ensuring that they are aware of and can exercise their rights within the nation state. Ganesh has published more than a dozen research papers on the archaeology of the Nagpur region. He is now working on the astronomy of various tribes in the Nagpur region.

Purushottam Laxmanrao Dahedar is a teacher in Zilla Parishad School (i.e. Government school), Village – Sirsoli in Washim district of Maharashtra. He holds a Master's degree in archaeology and a post graduate Diploma in Anthropology and Tribal Development. He is the district co-ordinator, Center India Sky Watch Group, Chandrapur, and he also works with anti-superstition groups. He has a special interest in painted rock shelters and has presented four papers on the subject at the Indian history congress. He is also an amateur astronomer and astronomical telescope maker. He is now involved in the study of the astronomy of Indian tribes.



Professor Wayne Orchiston was born in Auckland (New Zealand) in 1943, and has BA Honours and PhD degrees from the University of Sydney. He formerly worked in optical and radio astronomy in Australia and New Zealand. He is now at the National Astronomical Research Institute of Thailand in Chiang Mai, and is an Adjunct Prof-essor of Astronomy in the Centre for Astrophysics at the University of Southern Queensland in Australia. Wayne has supervised a large pool of graduate students in history of astronomy. He has wide-ranging research interests, and has published on aspects of Australian, Chinese, English, French, German, Georgian, Indian, Indonesian, Iraqi, Italian, Japanese, Korean, New Zealand, South African, Thai, Turkish and US astronomy. One of his research fields is Indian, Maori and Thai ethnoastronomy.

Wayne's recent books include *Eclipses, Transits, and Comets of the Nineteenth Century: How America's Perception of the Skies Changed* (2015, Springer, co-authored by Stella Cottam); *New Insights from Recent Studies in Historical Astronomy: Following in the Footsteps of F. Richard Stephenson. A Meeting to Honor F. Richard Stephenson on His 70th Birthday* (2015, Springer, co-edited by David A. Green and Richard Strom); *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits* (2016, Springer); *John Tebbutt: Rebuilding and Strengthening the Foundations of Australian Astronomy* (2017, Springer), *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe* (2017, Springer, co-edited by Tsuko Nakamura); *The History of World Calendars and Calendar-making. Proceedings of the International Conference in Commemoration of the 600th Anniversary of the Birth of Kim Dam* (2017, Yonsei University Press, co-edited by Nha Il-Seong and Richard Stephenson); and *Growth and Development of Astronomy and Astrophysics in India and the Asia-Pacific Region. Proceedings of the 9th International Conference on Oriental Astronomy* (2018, Tata Institute of Fundamental Research and the Hindustan Book Agency, co-edited by Aniket Sule and Mayank Vahia).

Wayne has been very active in the IAU for several decades, and was responsible for founding the Transits of Venus and Historic Radio Astronomy Working Groups. In August 2018 he became President of Commission C3 (History of Astronomy). He co-founded the *Journal of Astronomical History and Heritage* in 1998, and is the current Editor. He also serves as the Editor of Springer's Series on Historical and Cultural Astronomy. In 2013 the IAU recognised Wayne's international contributions to astronomy by naming minor planet 48471 'Orchiston' after him.

Professor Mayank Vahia was until recently a scientist at the Tata Institute of Fundamental Research, Mumbai, and is now Dean of Mathematical Sciences at the Narsee Monjee Institute of Management Studies in Mumbai. He completed his PhD at the University of Mumbai in 1984 and began his career at the Tata Institute of Fundamental Research with an interest in cosmic rays. He was involved in an experiment that was flown on NASA's Space Shuttle Space Lab 3 mission in 1986. After that he widened his interests and worked on high energy (X-ray and Gamma Ray) telescopes that were flown on Russian and Indian satellites. For the past fifteen years or so he has been interested in the origin of astronomy in India and has studied the astronomical aspects from early rock art, megaliths, coins, architecture, ancient texts and the astronomy of some of Indian's oldest tribes. He has published about 260 papers, around 60 of which are in the history of astronomy and history of science. He also has published two books: *History of Indian Astronomy: A Handbook* (2016, Indian Institute of Technology and Tata Institute of Fundamental Research, co-edited by K. Ramasubramanian and Aniket Sule), and *Growth and Development of Astronomy and Astrophysics in India and the Asia-Pacific Region. Proceedings of the 9th International Conference on Oriental Astronomy* (2018, Tata Institute of Fundamental Research and the Hindustan Book Agency, co-edited by Wayne Orchiston and Aniket Sule).

Mayank also spearheaded India's participation in the International Astronomy Olympiad, a programme that he initiated in India and that has guided about 30 students to pursue their studies in science for a career.

BOOK REVIEWS

Mercury, by William Sheehan (London, Reaktion Books, 2018). Pp. 183. ISBN 978-1-7891-4012-5 (hardback), 175 × 225 mm, US $40.

This book on Mercury by William Sheehan is part of the Solar System series currently being published by Reaktion Press. Titles on the Sun and the Moon were reviewed in the last issue of the *JAHH*. As an historian of astronomy Sheehan gives us a thorough survey of the early telescopic observations of Mercury. This is an unrelieved tale of hope and delusion related in such an engaging way that much of the book is a genuine page-turner.

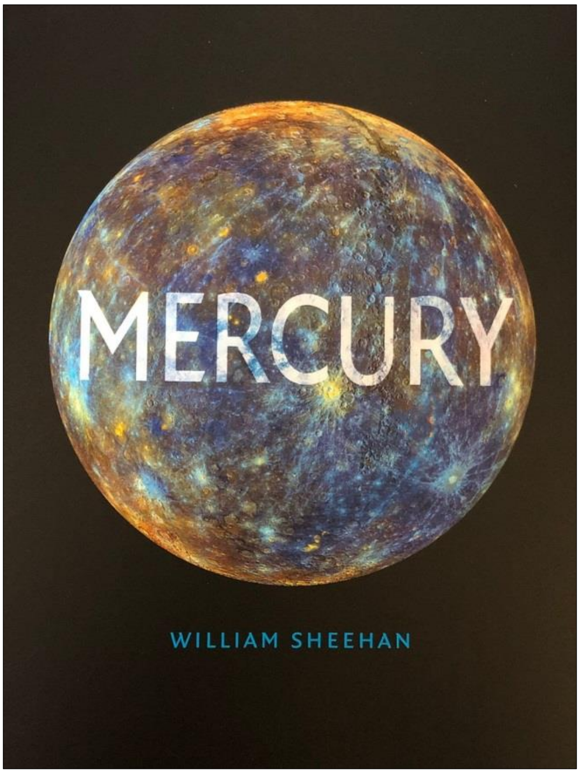
Sheehan begins with rare transit observations in the seventeenth century and Johann Schroeter's study of Mercury which did not get published until 1881, long after his death in 1816 (note that he spelled his own name 'Schroeter', not 'Schröter' as in Sheehan's book). The real missed opportunity of the nineteenth century came when the study of Karl Zöllner was overlooked. He wrote that Mercury, like our Moon, is an airless body, in contradicttion to the widely held view that it had an atmosphere. But "Later observers would pay dearly for their failure to take heed of his findings," laments Sheehan (p. 40).

After more than a century of Mercurian studies, the telescopic era culminated in the work of Eugene Antoniadi who approached his study of Mercury with the belief that Schiaparelli's Martian canals had "… a basis in reality." (p. 69). After five years of observing Mercury, Antoniadi published his results in 1929. He confirmed the results of Schiaparelli (who also studied Mercury) on the rotation period of Mercury, its libration and the existence of clouds. "Since, as we now know, all of these conclusions were wrong, it was a remarkable performance …" deadpans Sheehan (p. 73). A perfect way to express a total rout of the best telescopic observations of Mercury!

With decades of study relegated to the waste bin of history (but not before misleading the public in its perception of Mercury), it was left to radio astronomy to give us our first real data on Mercury. "The clincher came in 1965 …" Sheehan writes (p. 77). That is when a good value for the period of rotation of the planet, 59 days, put the 88-day period believed until then in the best-forgotten file. In 2018 Europe launched the BepiColumbo spacecraft to study Mercury. It was named after an expert in celestial mechanics who realised from this early radio data that Mercury was in a 3:2 resonance with the Sun, making its rotation period 58.65 days.

This "… rotation period came as a complete shock to planetary astronomers." (p. 79). Sheehan describes his own forensic study of what he terms the 'Schiaparelli case', by tracking down Schiaparelli's original logbooks at Brera Observatory in Milan. He teamed up with John Boudreau who spent several years obtaining CCD images that could be matched up with the 150 sketches of Mercury found in the archives. I would like to have seen more detail on this fascinating piece of detective work, which is condensed into just 2 pages.

A chapter on spacecraft observations of Mercury is very finely illustrated, with numerous colour images. The author gives us an excellent idea of our current physical understanding of the



planet, including its internal iron core, weak magnetic field, and existence of ice in some crater floors where the Sun never shines to heat it up.

A final 21-page chapter deals with trying to explain the precession of Mercury's orbit that violated the Newtonian law of gravitation. Starting with an image of a statue of LeVerrier and ending with a description of planetary migration, this is an all-encompassing explanation of how the great problem was solved by Einstein. Sheehan aptly describes LeVerrier's final work on the problem in military terms as a "… ten-year siege." (p. 133). Unable to solve the problem, he was forced in 1859 to postulate "… additional mass inside the orbit of Mercury …" and thus began one of the most quixotic episodes in the history of astronomy: the search for the planet Vulcan. Here Sheehan draws on his 1997 book with Richard Baum, *In Search of Planet Vulcan*.

The book concludes with three appendices: a glossary, basic data comparing Mercury with Earth, and a 4-page list of craters with their diameters, coordinates and origin of each name. It is an intriguing list, as we see the Indian poet Vyasa from 1500 BCE mingling with the likes of Sophocles, Rembrandt, Tolstoy and Mark Twain.

I noticed just three small glitches. On page 124 a Messenger photograph of the crater Raditladi has a caption indicating the image is color coded, but it is reproduced in B&W. On page 158 the equatorial inclination of Mercury is given as 0°, whereas the current NASA Solar System website gives a figure of 2°. On page 159, the (highly rarified) constituents of Mercury's atmosphere are missing.

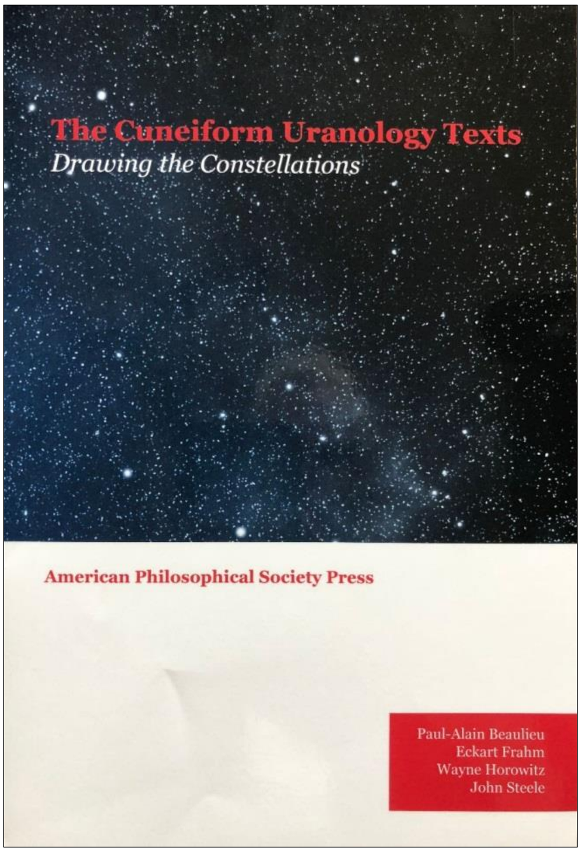
With its up-to-date results and historical perspective, this is certainly the finest and most readable book available on our innermost planet.

Dr Clifford J. Cunningham
Centre for Astrophysics, University of Southern Queensland, Toowoomba 4350, Australia.
Email: Cliff.Cunningham@usq.edu.au

The Cuneiform Uranology Texts: Drawing the Constellations, by Paul-Alain Beaulieu, Eckart Frahm, Wayne Horowitz, and John Steele. Transactions of the American Philosophical Society 107, Part 2. (Philadelphia, American Philosophical Society Press, 2017). Pp. x + 122, 17 plts. ISBN 978-1-60618-072-3 (paperback), 254 × 171 mm, US $37.

The Mesopotamian fixed star heaven is far less understood than its Greek successor. While records of astronomical practices involving the sun, moon, and planets are much more proliferate in cuneiform sources, our understanding of the fixed stars mostly revolves around schematic constructs of risings and settings as well as using the fixed stars as points of reference in the sky. The identification of many stars still remains uncertain or even unknown. In particular, the imagery and composition of the constellations have proven elusive. This is partly due to the Mesopotamian designation of celestial objects, written with the logogram MUL, which can refer to stars, planets, constellations, parts of constellations, and other celestial objects such as comets.

Despite the many thousands of astronomical texts from Mesopotamia, up until recently only one text was known to describe how to draw the constellations. Published by Ernst Weidner (1927), for nearly a century it was a unique text. The choice of the verb "draw," as it appears in the subtitle of the book under review, is intentional. It reflects a long Mesopotamian tradition that refers to the constellations as being drawn in the skies by the gods (p. 2–4; see also Rochberg, 2009: 64–69). Recently, however, four more texts describing the constellations in a similar fashion were discovered, three at Yale University and one at the British Museum. Originally the result of work done independently by Paul-Alain Beaulieu and Wayne Horowitz, they later collaborated and were joined by the late John Britton. With Britton's passing, John Steele joined Beaulieu and Horowitz to provide his expertise in astronomy. Eckart Frahm later joined the group and provided contributions, particularly on the tablets at



Yale University. This book provides a full textual edition of the five texts, referred to as the Uranology group. It includes photos and copies (found in the plates at the end of the book), transliteration, translation, and commentaries, with the exception of the text originally published by Weidner, which lacks a copy.

Chapter 1 introduces the texts, dates them, and examines the possible connections between the five texts as well as their relationship to other astronomical texts that refer to constellations, such as MUL.APIN, Enūma Anu Enlil, the Astrolabe tradition, and the microzodiac texts containing graphic representations of the constellations. When comparing the repertoire of stars mentioned in the Uranology group to other known listings of stars, the authors ascertain that “[t]here is good reason to believe that the repertoire of constellations in our group ultimately derives from Mul.Apin.” (p. 12). Out of the five texts, three of them are near parallels and together are called the Simple Group. Source A, the text published by Weidner, is the most well preserved of the three as well as the earliest, dating to the Neo-Assyrian period. Sources B and C, whose stars partially overlap with Source A but not with one another, are dated to the Neo-Babylonian or Late Babylonian period and Late Persian or Early Hellenistic period respectively. The Late Babylonian Source D offers a much more intricate and elaborate description of the constellations and is dubbed the Expanded Version. Lastly, the poorly preserved Source E is also Late Babylonian. Geographically, with the exception of Source A from Assur and Source B from Babylon, the other texts can be traced to Uruk (p. 6–11). Source B and E contain uranology text only on one side of the tablet. The other side of both sources are unrelated to ways of drawing the constellations and their editions are given in appendices B and C respectively. The authors

> ... admit that at present we know very little about the genesis and history of our group, although we can say that the group must have been popular, at least in limited circles. (page 20),

given the long chronological and wide geographical distribution of the texts.

Chapters 2, 3, and 4 consist of the text editions of the Simple Group, Source D, and Source E respectively. Each chapter provides a transliteration, translation and commentary in a consecutive manner. As opposed to having the translation opposite the transliteration, the layout of the book as it is makes it occasionally difficult to examine the authors' work, as one has to page to three different locations in the book, if one also reviews the commentary simultaneously. Since chapter 2 encompasses Source A, B, and C, the transliteration is offered as a score, with no composite. By and large, the authors' edition of source A is similar to Weidner's, but they were able to restore some of the missing sections based on the parallels in the other Uranology sources,[1] as well as a better understanding of the vocabulary associated with these texts, developed since Weidner's1927 publication.[2]

The book concludes with chapter 5, in which the authors contemplate the impact the Uranology texts have on the wider understanding of Babylonian astronomy. They note that the group

> … provides a bridge between the mainstream astronomical cuneiform text traditions of the Neo-Assyrian period … and the small group of drawings of constellations on the later micro-zodiac texts ... [and] that the basic outline of the Mesopotamian sky as known in the Persian and Hellenistic period was already in place centuries before regular contact is documented between the cuneiform writing and the Greek-speaking worlds. (page 67).

The Uranology texts also confirm tentative identification of several star groups, such as the Wagon and the Wagon of Heaven as the Big Dipper and the Little Dipper respectively. The authors refer to the recent publication by Kurtik (2007) on star names multiple times, a work that has been critiqued to be incomplete and outdated by the time of its publication (Soltysiak, 2009). Yet this does not impede the valuable insight gained in analyzing the constituent elements of the constellations. The authors leave off with questions for future research, such as the unclear terminology used to describe some elements of the constellations and the exact modern equivalents of the Mesopotamian star names.

Three appendices help navigate the book. The first lists the Sumerian and Akkadian star names (when available), their translation, modern equivalents, and listof attestation in the Uranology group. It also includes a glossary of the technical terms used to describe parts and elements of the constellations such as different body parts or various items that are carried by or set next to the constellations. Appendix B is a text edition of the other side of Source B, since only one side of the tablet is related to drawing the constellations. The authors suggest that the side presented in Appendix B is a collection of observations of the heliacal phenomena of an inner planet, though due to the fragmentary nature of this side, it is not possible to date the observations (pages 82–83). Lastly, Appendix C discusses Source E, presenting its likely provenance and providing a textual edition of the side of the tablet that does not deal with drawing the constellation. Instead, the text seems to deal with the topography of the city of Uruk, its temples and watercourses. While the connection to the uranology text found on the opposite side of the tablet is unclear, it is important to remember that the chief deity of Uruk was the sky-god Anu, who experienced a major cult revival during the Late Babylonian period. Not surprisingly, the temple of Anu in Uruk was also a locus of production of astronomical knowledge (Rochberg, 1993).

The book excels in providing high quality editions of texts that, with the exception of Source A, have been previously unknown. While the authors contemplate the interconnection with other astronomical cuneiform texts, they do not delve deeper into the Uranology group's place within Mesopotamian scholarship in general. For example, the book notes the order of presentation of the constituent elements that make up the constellations, such as human figure constellations described from top to bottom, or the preference of first describing the right side and then left (page 12). Yet how that relates to similar concepts of ordering found in other Mesopotamian sources such as lexical lists or divinatory literature lies beyond the scope of the book. Nonetheless, this volume serves as a substantial contribution to the study of Babylonian astronomy, particularly due to the lack of sources that deal with the fixed stars and the perception of the starry skies in Mesopotamian thought. It is a useful tool for Assyriologists and other scholars who are interested in the history of astronomy alike, especially those who wish to investigate the transmission of astronomical knowledge between the Mesopotamian world and the Greek. In particular, Source D provides new evidence for the transformation of the constellation "The Hired Man" into the Greek Aries by means of sign play (pages 45–46).[3]

Notes

1. E.g., Source A obv. 11-12 and obv. 14.
2. E.g., Source A rev. 9 for the authors' *i-ma-šá-al* instead of ... *-maš-šá-* ... which is found in Weidner's edition.
3. Source D, column i, line 13: MUL.LÚ.LU. HUN.GÁ MUL.LU.HUN.GÁ ... The first sign sequence is the traditional way of writing the constellation's name, albeit with a superfluous, yet homophonous LU sign. The second omits the LÚ sign, the determiner for human beings or professions. Another reading of the LU sign is UDU, Akkadian *immeru*, "sheep." Note also the associations of this constellation in line 14 and the different spellings of the name in lines 14 and 15.

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Gil Breger
Near Eastern Studies Department,
University of California, Berkeley
GilBreger@berkeley.edu