JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE

Christiansen Memorial Issue #2

Vol. 12 No. 1 MARCH 2009

JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807

The *Journal of Astronomical History and Heritage* (*JAH*^{2}) was founded in 1998, and from 2007 has been published three times yearly, in March, July and November. It features review papers, research papers, short communications, correspondence, IAU reports, and book reviews.

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.

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Centre for Astronomy,
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The annual subscription rates for Volume 12 (2009) are:

AU$200:00 for institutions
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COVER PHOTOGRAPH

This is the second of two issues celebrating the major contribution that Professor Wilber N. (Chris) Christiansen (1913-2007) made to international radio astronomy. The cover image is a view looking west at sunset, showing some of the antennas in the central part of the Chris Cross at the Fleurs field station near Sydney (Australia). This innovative crossed-grating interferometer was designed by Professor Christiansen and during the late 1950s and through the 1960s was used to produce daily isophote maps of solar emission at 1423 MHz. The insert shows Professor Christiansen in his later years. The papers by Davies, Orchiston and Mathewson, and Wang on pages 4, 11 and 33 in this issue of *JAH*^{2} discuss Christiansen's H-line work at Potts Hill and Davies involvement in solar work there (when he worked with both Christiansen and Piddington); the Chris Cross at Fleurs, and its later development as the Fleurs Compound Interferometer; and Christiansen's seminal role in the early development of radio astronomy in China.

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VOLUME 12 NUMBER 1 MARCH 2009

CONTENTS

Published by the
Centre for Astronomy, James Cook University, Townsville, Queensland 4811, Australia.
(www.jcu.edu.au/astronomy)

Journal of Astronomical History and Heritage, 12(1), 2-3 (2009).

JOURNALS UNDER THREAT: A JOINT RESPONSE FROM HISTORY OF SCIENCE, TECHNOLOGY AND MEDICINE EDITORS

We live in an age of metrics. All around us, things are being standardized, quantified, measured. Scholars concerned with the work of science and technology must regard this as a fascinating and crucial practical, cultural and intellectual phenomenon. Analysis of the roots and meaning of metrics and metrology has been a preoccupation of much of the best work in our field for the past quarter century at least. As practitioners of the interconnected disciplines that make up the field of science studies we understand how significant, contingent and uncertain can be the process of rendering nature and society in grades, classes and numbers.

We now confront a situation in which our own research work is being subjected to putatively precise accountancy by arbitrary and unaccountable agencies. Some may already be aware of the proposed European Reference Index for the Humanities (ERIH), an initiative originating with the European Science Foundation. The ERIH is an attempt to grade journals in the humanities—including "history and philosophy of science". The initiative proposes a league table of academic journals, with premier, second and third divisions. According to the European Science Foundation, ERIH "… aims initially to identify, and gain more visibility for, top-quality European Humanities research published in academic journals in, potentially, all European languages." It is hoped "… that ERIH will form the backbone of a fully-fledged research information system for the Humanities." What is meant, however, is that ERIH will provide funding bodies and other agencies in Europe and elsewhere with an allegedly exact measure of research quality. In short, if research is published in a premier league journal it will be recognized as first rate; if it appears somewhere in the lower divisions, it will be rated (and not funded) accordingly.

This initiative is entirely defective in conception and execution. Consider the major issues of accountability and transparency. The process of producing the graded list of journals in science studies was overseen by a committee of four (the membership is currently listed at http://www.esf.org/research-areas/humanities/research-infrastructures-including-erih/erih-governance-and-panels/erih-expert-panels.html). This committee cannot be considered representative. It was not selected in consultation with any of the various disciplinary organizations that currently represent our field such as the European Association for the History of Medicine and Health, the Society for the Social History of Medicine, the British Society for the History of Science, the History of Science Society, the Philosophy of Science Association, the Society for the History of Technology or the Society for Social Studies of Science. Journal editors were only belatedly informed of the process and its relevant criteria or asked to provide any information regarding their publications. No indication has been given of the means through which the list was compiled; nor how it might be maintained in the future.

The ERIH depends on a fundamental misunderstanding of conduct and publication of research in our field, and in the humanities in general. Journals' quality cannot be separated from their contents and their review processes. Great research may be published anywhere and in any language. Truly ground-breaking work may be more likely to appear from marginal, dissident or unexpected sources, rather than from a well-established and entrenched mainstream. Our journals are various, heterogeneous and distinct. Some are aimed at a broad, general and international readership, others are more specialized in their content and implied audience. Their scope and readership say nothing about the quality of their intellectual content. The ERIH, on the other hand, confuses internationality with quality in a way that is particularly prejudicial to specialist and non-English language journals. In a recent report, the British Academy, with judicious understatement, concludes that "… the European Reference Index for the Humanities as presently conceived does not represent a reliable way in which metrics of peer-reviewed publications can be constructed." (*Peer Review: the Challenges for the Humanities and Social Sciences*, September 2007: http://www.britac.ac.uk/reports/peer-review). Such exercises as ERIH can become self-fulfilling prophecies. If such measures as ERIH are adopted as metrics by funding and other agencies, then many in our field will conclude that they have little choice other than to limit their publications to journals in the premier division. We will sustain fewer journals, much less diversity and impoverish our discipline.

Along with many others in our field, this Journal has concluded that we want no part of this dangerous and misguided exercise. This joint Editorial is being published in journals across the fields of history of science and science studies as an expression of our collective dissent and our refusal to allow our field to be managed and appraised in this fashion. We have asked the compilers of the ERIH to remove our journals' titles from their lists.

Wayne Orchiston & Hilmar Duerbeck (*Journal of Astronomical History & Heritage*)
Hanne Andersen (*Centaurus*)
Roger Ariew & Moti Feingold (*Perspectives on Science*)
A. K. Bag (*Indian Journal of History of Science*)
June Barrow-Green & Benno van Dalen (*Historia Mathematica*)
Keith Benson (*History and Philosophy of the Life Sciences*)
Marco Beretta (*Nuncius*)
Michel Blay (*Revue d'Histoire des Sciences*)
Johana Bleker (*Medizinhistorisches Journal*)
Cornelius Borck (*Berichte zur Wissenschaftsgeschichte*)
Geof Bowker and Susan Leigh Star (*Science, Technology and Human Values*)
Massimo Bucciantini & Michele Camerota (*Galilaeana: Journal of Galilean Studies*)
Jed Buchwald and Jeremy Gray (*Archive for History of Exacft Sciences*)
Vincenzo Cappelletti & Guido Cimino (*Physis*)

Cathryn Carson (*Historical Studies in the Natural Sciences*)
Mark Clark and Alex Keller (*Icon: Annual Journal of the International Committee for the History of Technology*)
Roger Cline (*International Journal for the History of Engineering Technology*)
Stephen Clucas & Stephen Gaukroger (*Intellectual History Review*)
Hal Cook & Anne Hardy (*Medical History*)
Leo Corry, Alexandre Métraux & Jürgen Renn (*Science in Context*)
Brian Dolan & Bill Luckin (*Social History of Medicine*)
Moritz Epple, Mikael Hård, Hans-Jörg Rheinberger & Volker Roelcke (*NTM:Zeitschrift für Geschichte der Wissenschaften, Technik und Medizin*)
Steven French (*Metascience*)
Willem Hackmann (*Bulletin of the Scientific Instrument Society*)
Robert Halleux (*Archives Internationales d'Histoire des Sciences*)
Bosse Holmqvist (*Lychnos*)
Paul Farber (*Journal of the History of Biology*)
Mary Fissell & Randall Packard (*Bulletin of the History of Medicine*)
Robert Fox (*Notes & Records of the Royal Society*)
Jim Good (*History of the Human Sciences*)
Rod Home (*Historical Records of Australian Science)*
Michael Hoskin (*Journal for the History of Astronomy*)
Ian Inkster (*History of Technology*)
Marina Frasca Spada (*Studies in History and Philosophy of Science*)
Nick Jardine (*Studies in History and Philosophy of Biological and Biomedical Sciences*)
Trevor Levere (*Annals of Science*)
Bernard Lightman (*Isis*)
Christoph Lüthy (*Early Science and Medicine*)
Michael Lynch (*Social Studies of Science*)
Stephen McCluskey & Clive Ruggles (*Archaeostronomy: the Journal of Astronomy in Culture*)
Peter Morris (*Ambix*)
E. Charles Nelson (*Archives of Natural History*)
Ian Nicholson (*Journal of the History of the Behavioural Sciences*)
Iwan Rhys Morus (*History of Science*)
Liliane Pérez (*Documents pour l'Histoire des Techniques*)
John Rigden & Roger H Stuewer (*Physics in Perspective*)
Julio Samsó (*Suhayl: Journal for the History of the Exact and Natural Sciences in Islamic Civilisation*)
Simon Schaffer (*British Journal for the History of Science*)
Norbert Schappacher (*Revue d'Histoire des Mathématiques*)
John Staudenmaier SJ (*Technology and Culture*)
Claire Strom (*Agricultural History*)
Paul Unschuld (*Sudhoffs Archiv*)
Peter Weingart (*Minerva*)
Stefan Zamecki (*Kwartalnik Historii Nauki i Techniki*)
Huib Zuidervaart (*Studium. Tijdschrift Voor Wetenschaps- en Universiteitsgeschiedenis*)

Journal of Astronomical History and Heritage, 12(1), 4-10 (2009).

RECOLLECTIONS OF TWO AND A HALF YEARS WITH 'CHRIS' CHRISTIANSEN

Rodney D. Davies
Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL, U.K.
E-mail: rdd@jb.man.ac.uk

Abstract: I spent the period February 1951 to August 1953 in W.N. (Chris) Christiansen's group in the C.S.I.R.O.'s Division of Radiophysics in Sydney and at the Potts Hill field station. This was a particularly fruitful period of Chris' scientific career. It included the first detection of the 21-cm hydrogen line in the Southern Hemisphere and strong confirmation of the detections made at Harvard and Leiden. This, incidentally, became my own research area at Jodrell Bank beginning two years later. For Chris this was but an interruption to his group's major effort of building a solar grating interferometer. During the period from early 1951 to late 1953 we were intensely busy building, commissioning and operating this new solar instrument. I was involved in most phases of this work, admittedly in a junior capacity—ranging from digging the post holes for the supports of the 32 antennas of the east-west array through to identifying the main source of radio emission with the H-alpha plages associated with sunspots using the Mt Stromlo spectroheliograph that I operated at Potts Hill. This was an exciting time to be at Radiophysics; being a member of Chris' group was inspirational to myself and the other young team members as I shall describe in this short paper.

Keywords: W.N. (Chris) Christiansen, CSIRO Division of Radiophysics, Potts Hill, solar grating interferometer, H-line emission, solar bursts.

1 SOME BACKGROUND

During World War II Australia and the United Kingdom had a number of co-operative links in their radio and radar development programmes. These links led to appreciable transfer of personnel between the two countries after the War when the potential contribution of radio to the astronomical spectrum was realized.

Upon graduating in 1935, E.G. (Taffy) Bowen joined the Radio Research Station at Slough and was immediately recruited by Robert Watson Watt's team at the Bawdsey Research Station on the East Coast where they had already clearly demonstrated the strategic importance of radar in the future war effort. Bowen was soon to become the leader of the air-borne radar group. Hanbury Brown joined this group in 1937. At the outset of WWII young scientists from a range of disciplines—although mainly physics—were directed to radar research. Among these were A.C.B. (Bernard) Lovell, who developed the 3-cm air-borne radar used by Coastal Command for submarine detection, and Martin Ryle, who worked on other aspects of radar. J.S. (Stanley) Hey was in the Army Operational Research Group dealing with problems of anti-aircraft defence and assessing the performance of radar systems (and in the course of his radar work he detected radio emission from the Sun and later fluctuating noise from the constellation of Cygnus). At the end of hostilities they, along with a large number of other scientists, returned to academia. Bernard Lovell went back to Manchester and Martin Ryle to Cambridge, each establishing a thriving radio astronomy research group; Stanley Hey returned to the Royal Radar Establishment (RRE) at Malvern and headed a radio astronomy group there until 1969. L.G.H. (Len) Huxley, a wave-guide specialist, had acted as leader of the Radar School at RRE during the War; in 1949 he was appointed Professor of Physics at Adelaide University in South Australia.

In immediate pre-War Australia, the Radiophysics Laboratory was established by the Council of Scientific and Industrial Research[1] in the grounds of the University of Sydney with the aim of developing radio and radar for use in the Pacific area and wherever Australian service personnel operated during the War. The staff members were mainly Australian graduates. Several had research experience overseas. J.L. (Joe) Pawsey, for example, did his Ph.D. at Cambridge. At the end of the War a major decision had to be made about the future role of the Laboratory. The fact that extraterrestrial radio waves had been found by staff members during operational activities[2] played a not inconsiderable part in the final assessment of the possibilities. In 1946 Taffy Bowen was appointed Chief of the Radiophysics Division, succeeding D.F. (David) Martyn (a cousin and the dead spit image of our family doctor in Wilmslow, Cheshire) and F.W.G. (Fred) White. The UK ex-servicemen, J.G. (John) Bolton and J.P. (Paul) Wild both had extensive radio and radar experience and were recruited to the team. W.N. (Chris) Christiansen joined Radiophysics from Amalgamated Wireless (Australasia) Ltd. in 1948.

In 1947 I left the family farm at Mallala in the Adelaide Plains, some 40 miles north of Adelaide, to study physics at Adelaide University. In May 1948 A.P. Rowe was appointed Vice-Chancellor of the University. He had been Director of the RRE in England during the War, and was a strict disciplinarian according to Hanbury Brown (who had been subject to his strict rule). Rowe found the freedom expected by university staff unmanageable and he retired to Malvern, but one of the positive outcomes of his Vice-Chancellorship was the appointment in 1949 of Len Huxley as Professor of Physics at the University. In 1960 Huxley became Vice-Chancellor of the Australian National University in Canberra.

In Adelaide, Huxley established a flourishing research environment in the Physics Department, and his undergraduate lecture course on waveguides was to be extremely useful to me in later life, particularly as I was able to make good use of his textbook entitled *Waveguides*. Apart from myself, after graduation two of Huxley's other students, Alan Weiss and Bob Duncan, also were appointed to the Radiophysics Laboratory. It is sad to reflect that these two colleagues are no longer with us.

In 1951 the Radiophysics Laboratory began recruiting new Scientific Officers directly from the universities. The intake in early 1951 included R.X. (Dick) McGee, J.A. (Joe) Warburton and myself, and we were all appointed to the Radio Astronomy Group under Pawsey's leadership. As part of our induction period we spent a few weeks at the different field stations—at Dover Heights with John Bolton and at Potts Hill with Chris Christiansen. I also remember that Pawsey was keen to improve our electronic skills. He did this by having us build and test 30 MHz IF amplifier units, a skill that in my case, at least, was to prove very useful in subsequent years. After our induction, Joe Warburton and I were allocated to Christiansen's group (Davies, 2005) and we joined the bus which made the daily trip from the Radiophysics Laboratory out to Potts Hill, a 40-minute drive away.

Pawsey, as Assistant Chief of the Division of Radiophysics, was a constant presence in the radio astronomy researches. He not only supervised the construction projects but also constantly fed the research groups with ideas for consideration. This happened at the weekly radio astronomy meetings and during his visits to the field stations.[3] These visits were also accompanied by a supply of lamingtons, cake cubes covered with chocolate and coconut, which I acquired a taste for. As well as working with Chris, Joe had me analyzing the large stacks of paper recordings of solar bursts (Davies, 1954). Interpretation of this material took me into the domain of J.H. (Jack) Piddington, the Division's leading theorist, so in a sense I had three masters, but Chris was the senior one, and he managed this situation with wisdom.

At Potts Hill, priorities during the first few months of 1951 were (a) construction of the 32-element solar grating array and (b) confirmation of the existence of the 21-cm line of neutral hydrogen. Unbeknown to me at the time, I had joined Chris' group at a high point in its history, and this was to be the beginning of a formative period in my own research career.

2 H-LINE WORK AT POTTS HILL

A detailed account of the early 21cm H-line research at Potts Hill has recently been published by Wendt, Orchiston and Slee (2008b), but I will now set down my own recollections of these pioneering southern hemisphere observations, which were to have more significance than I realized at the time for my future work at Jodrell Bank two years later.

At the end of March 1951 F.J. (Frank) Kerr was at Harvard[4] and he sent Joe Pawsey a letter saying that 'Doc' Ewen and Edwin Purcell had detected 21cm hydrogen line emission from the Galactic Plane. Before publication, they were waiting for confirmation by the Leiden group. At the end of April Pawsey sent a note to Purcell saying that his group would attempt a confirmation in the southern sky; Purcell replied that he was prepared to wait a short time before publication in order to allow this further confirmation. It was agreed that Chris would undertake this challenge with the assistance of Jim Hindman, and that they would construct a receiver system and attach it to the 18 × 16-ft radio telescope that was used for solar monitoring at Potts Hill (Figure 1).[5]

In my first weeks at Potts Hill the work by Chris and his technical staff to construct a 1420 MHz receiver was progressing apace. As a result, the solar work took back stage, except for the daily recording of the solar flux density. The development of a technique for measuring narrow spectral lines required considerable expertise. Firstly, the superheterodyne receiver had to have a narrow enough bandwidth (~50 kHz) to resolve the spectral line. Furthermore, the frequency stability of the local oscillator had to be better than this value over time scales of days; this was a particular challenge given the signal generators of the time. The frequency of the receiver was then swept through the spectral line frequency in a carefully-controlled manner.

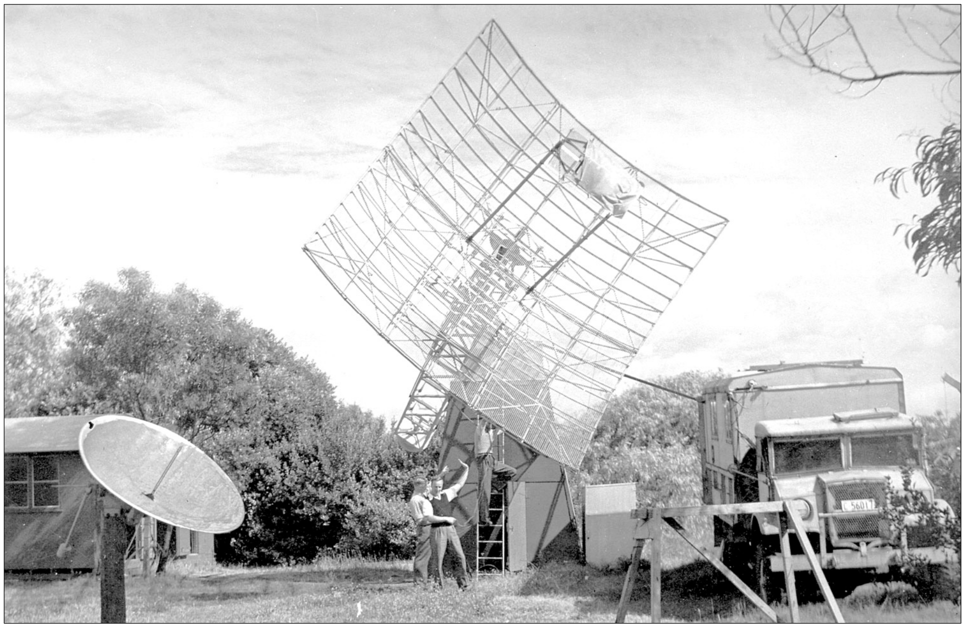

Figure 1: The 16 x 18-ft telescope at Potts Hill in use during the first detection of HI in the Southern Hemisphere. Chris Christiansen is on the left, Jim Hindman is on the ladder and Joe Warburton is in the foreground. A cm-wavelength antenna is on the left (photograph by the author).

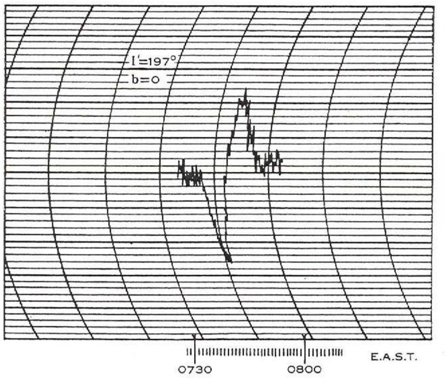

Figure 2: A spectrum of HI in the Anticentre region taken during the survey of the southern sky (after Christiansen and Hindman, 1952).

In what was a real *tour-de-force* Chris and his team pulled together a viable H-line receiver in two months and confirmed the Harvard detection. I was essentially an onlooker in this effort, my part merely being to make sure that the pen recorder kept inking properly during observations and to note the local oscillator frequency. A brief report of the confirmation was submitted by Pawsey (1951) to *Nature* and published alongside the Harvard (Ewen and Purcell, 1951) and Dutch (Muller and Oort, 1951) papers. It is interesting to note the respective submission dates of the three contributions: Ewen and Purcell on 14 June, Muller and Oort on 26 June and Pawsey on 12 July.

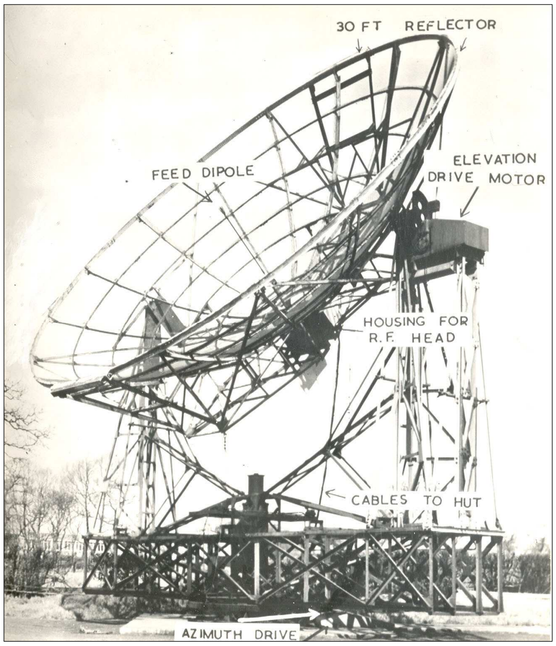

Figure 3: The 30-ft telescope at Jodrell Bank used for the first HI observations in 1954. This antenna was originally sited on the south coast of England during WWII where it was used for anti-aircraft surveillance (after Davies, Ph.D. thesis, University of Manchester, 1956).

Following the first detection at Potts Hill, Chris and Jim made a broad survey of the H-line in the southern sky using the 18 × 16-ft radio telescope (sometimes referred to as the 25 m^2 telescope). Its elevation range was increased to allow the H-line survey to cover the declination range -50^o to $+50^o$. Between June and September 1951 the survey was completed by taking spectra along lines of declination separated by 5^o; the beam width was 2.3^o. This work is described in Christiansen and Hindman (1952). A typical spectrum in the Galactic Anticentre region, where the line is narrow and bright, is seen in Figure 2 as recorded in the frequency-differencing mode. All the spectra were recorded on paper charts and were analyzed by hand. The next phase of the Radiophysics H-line research was with a dedicated 36-ft transit radio telescope that would be constructed at Potts Hill under the leadership of Frank Kerr upon his return from Harvard in 1952.

I was not to know at the time that within a little more than two years I too would also be building a hydrogen line system, but this time at Jodrell Bank. It is interesting to note the similarities between these two first detection projects. My fellow Ph.D. student, D.R.W. (David) Williams, and I used a 30-ft paraboloid (Figure 3) which Bernard Lovell had acquired from the Services upon his return to Manchester. It had been used on the South Coast of England to detect hostile aircraft as they crossed the Channel. Our workshops built an altazimuth drive for it so that it could be used for radio astronomy. David and I built a control system which allowed us to track positions on the sky. My experience at Radiophysics stood me in good stead in building a front-end receiver system and the narrow-band spectrometer, again with its output going to a chart recorder. Figure 4 shows a typical spectrum from those days, obtained in the Cygnus region. Our first observations led to the detection of H-line absorption in front of the brightest radio sources, thereby allowing a determination of their distances (see Williams and Davies 1954). Following this work I used the 30-ft telescope to made an H-line survey of the northern sky, as seen from Jodrell Bank, which clarified the existence of the local Gould Belt system in hydrogen (Davies, 1960). The beam width was 1.55^o. Line observations with the 250-ft Lovell Telescope began in 1958.

3 THE 32-ELEMENT GRATING INTERFEROMETER

After Chris' H-line diversion he returned to solar work, and the construction of the first of two solar grating arrays at Potts Hill (see Wendt, Orchiston and Slee, 2008a). This was a 32-element E-W interferometer (Figure 5), and from early 1951 I worked with the team on the construction of the interferometer elements. This included digging the post holes for the mounts that supported each of the 6-ft dishes, and we soon became qualified posthole diggers (Ph.D.s), although I had actually obtained my first degree in this field on our family farm in South Australia! By the second half of 1952, Chris, Joe Warburton and I were making regular observations of the Sun with the completed array. As soon as this interferometer was fully operational, I also began making regular observations with a spectrohelioscope in order to obtain H-alpha images of the solar disk. The spectrohelioscope was on loan from the Commonwealth Observatory in Canberra, and was supervised by R.G. (Ron) Giovanelli from the National Physical Laboratory (which was also based in the grounds of the University of Sydney). It would appear that the move of the spectrohelioscope to Potts Hill occurred in late 1952. My recollections are that it was set up in a hut next to the 16 × 18-ft parabola used for the H-line observations. Our paper

(Christiansen, Warburton and Davies, 1957) states that the first scans with the E-W grating array were obtained on 20 June 1952.

During my daily observations of the Sun with the spectroheliosccope the active areas were plotted on a Stonyhurst Disk. This enabled the solar coordinates to be determined and compared with the positions of the 21cm radio plages. Active regions seen with the spectrohelioscope included sunspots and H-alpha plages; the latter were brightenings around sunspots, but sometimes they also were seen before sunspots appeared in a region and/or after they had disappeared. The discovery that radio emission was closely linked to the chromospheric plages rather than photospheric sunpots was my great excitement at Potts Hill. It was during these daily observations that I observed the ascending prominence of 26 February 1953 which is reported in Davies (1953). I still remember the reprimand that Joe Pawsey gave me for not staying on at Potts Hill that day so that I could follow the prominence until sunset, or at least until it moved behind the trees on the horizon. Instead I took the bus back to the Radiophysics Laboratory rather than staying at my post and then hitch-hiking back to Sydney!

I made these daily observations until I left the Radiophysics Division in August 1953, when I was appointed to a lectureship at Manchester University and began my researches at Jodrell Bank. After I left, Chris and Joe continued observing with the E-W grating array until December 1953. When analysis of our observations were undertaken in 1955-1956 for the Christiansen, Warburton and Davies (1957) paper, we used the more extensive optical data available in the *Quarterly Bulletin of Solar Activity*, which contained good quantitative information on chromospheric plages supplied by M. and Mme. D'Azambuja.[6] As far as I know, no further systematic observations with the spectrohelioscope were made at Potts Hill after I left; by then, this instrument had served its purpose in allowing us to correlate the radio 'hotspots' on the Sun with the chromospheric plages. However, it was used later in connection with Paul Wild's solar burst work at Dapto (e.g., see Giovanelli and Roberts, 1958).

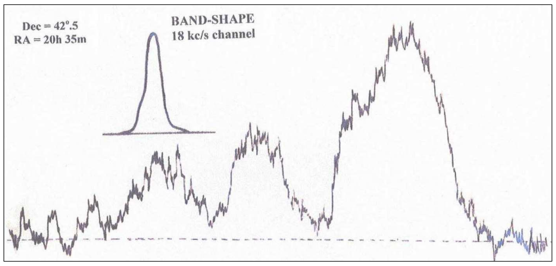

Figure 4: An HI spectrum taken with the 30-ft telescope on the Galactic plane in the Cygnus region showing the 3 spiral arms in this direction. The radio source Cygnus A was found to have HI absorption in all three arms, and was therefore concluded to be extragalactic (after Williams and Davies; 1954, and Davies, Ph.D. thesis, University of Manchester, 1956).

4 SOLAR BURST OBSERVATIONS AT POTTS HILL

When I arrived at Potts Hill in 1951 two monitoring programmes were in progress. Ruby Payne-Scott and A.G. (Alec) Little were recording radio emission from solar bursts with a 97 MHz three-element interferometer located on the edge of the reservoir (Figure 6). They were also measuring the linear polarization of the burst emission. Ruby soon resigned from Radiophysics in order to start a family, and Alec then worked with Bernie Mills on the prototype Mills Cross which they built at Potts Hill over the next year or so (see Mills and Little, 1953).

Figure 5: The 32-element solar grating interferometer at Potts Hill photographed on completion in late 1952. The first serious solar observations began in February 1953 (photograph by the author).

Figure 6: View showing two of the three 97 MHz crossed Yagis comprising Ruby Payne-Scott and Alec Little’s solar interferometer. The second Yagi can be discerned behind the colourful garden display maintained by the Water Board (photograph by the author in 1951).

Chris and his technical assistants, Jack Harragon, George Fairweather and Charlie Fryar, used the 16 × 18-ft radio telescope to monitor burst activity on the Sun at 600 and 1200 MHz. A double feed system was placed at the telescope focus. Daily flux density measurements were made at the two frequencies. In earlier years, small paraboloids were used to measure solar activity at higher frequencies (for details see Wendt, 2008).

Chris’ last paper on solar burst observations was a radio study of large solar disturbances on 17, 21 and 22 February 1950 (Christiansen, Hindman, Little, Payne-Scott, Yabsley and Allen, 1951) covering the frequency range 60 to 9000 MHz. This material included data from the 3-element polarization interferometer operated by Ruby Payne-Scott and Alec Little illustrated in Figure 6. The 600 and 1200 MHz data were from the 16 × 18-ft radio telescope, while the 3000 MHz data were from a small paraboloid located nearby.

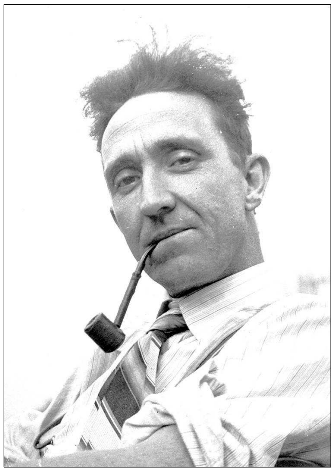

Figure 7: George Fairweather, a valued member of Chris Christiansen’s technical staff (photograph by the author).

5 CHRIS THE COLLEAGUE

Chris was very much an ‘ideas man’. He clearly enjoyed the research freedom allowed under Joe Pawsey’s regime at Radiophysics. He came to Radiophysics from the commercial atmosphere of Amalgamated Wireless (Australasia) Ltd. where he was an aerials specialist, and upon joining Radiophysics he developed and used aerial systems for a wide range of solar observations. By 1951, when I joined his group, he had designed the 32-element solar grating array and was in the throes of building it. At the same time, along with other Radiophysics staff, he was looking at innovative ways of building a really large radio telescope and his idea was to float a huge spherical antenna in a hydraulic spherical bearing. The more conventional altazimuth-mounted paraboloid was to be the ultimate choice. Chris left CSIRO in 1960 for the University of Sydney to develop the Chris Cross at Fleurs into the Fleurs Synthesis Telescope (see Orchiston and Mathewson, 2009).

Chris’ research enthusiasm was infectious. He encouraged me in my investigation of the Radiophysics solar burst records, even though this was not directly under his supervision. Looking back, I see that a substantial amount of the data was from the daily observations which he had made. He also welcomed me back into the fold after I had spent some time working with Jack Piddington on the physics of the solar corona, a project that was based on Radiophysics data collected over the years (see Piddington and Davies 1953a; 1953b). Chris and Jack were poles apart in their politics and their outlook on life.

Chris encouraged a strong team spirit at Potts Hill. The technical staff were dedicated to Chris’s projects and would give them all their efforts. These activities were sometimes rather gruelling at critical times during the commissioning phases, especially for the 21cm confirmation and the solar grating interferometer. I particularly remember Charlie Fryar, and George Fairweather with his quaint pipe (Figure 7). We always had a break for lunch. A cricket bat was an essential piece of equipment at Potts Hill, and Chris was an accomplished batsman (Figure 8).

Upon reflection, cricket played no small part in the ethos of the Radiophysics establishment, and I enjoyed playing with the Radiophysics team in a (mostly!) friendly league in the Sydney suburbs. During my time the captain was either John Bolton or Paul Wild, depending upon their outside commitments. Interestingly, as soon as I arrived at Jodrell Bank, Bernard Lovell, who was captain of the local cricket team, had me playing on Cheshire turf. It was rumoured that Bernard only appointed people to his staff if they played cricket or the piano; I believe there may have been some truth in this!

Chris had a strong social concern which showed itself in a number of ways, including helping developing nations with their scientific growth (e.g. see Wang Shouguan, 2009). This led to the Potts Hill E-W solar grating array being sent to India in 1960, where it was used to stimulate their radio astronomy. Govind Swarup and R. Parthasarathy (1955) had previously converted it to 600 MHz at Potts Hill, so Govind was well placed to recommission it in India (for details see Swarup, 2006; 2008).

6 CONCLUDING REMARKS

Looking back on my time with Chris in the Radiophysics Division of CSIRO, I now realize even more strongly than I could have done at the time that he had assembled a remarkable team and that I was extremely fortunate to start my scientific career in such an environment and under the influence of outstanding colleagues. Chris was internationally-recognized by being elected President of the International Union of Radio Science (URSI) from 1978 to 1981; he was also elected an Honorary Life President. His was one of the early elections to the Fellowship of the Australian Academy of Sciences (FAAS).

The radio astronomy group in CSIRO was one of the most highly-awarded in the subject: of those on the staff when I was there, eight were elected to the FAAS (Bowen, Christiansen, Mills, Minnett, Pawsey, Piddington, Robinson and Wild) and five were elected Fellows of the Royal Society (Bolton, Bowen, Mills, Pawsey and Wild). I also find it amazing that three of the young appointees on the staff during my time in the Radio Astronomy group were subsequently elected FRSs (Govind Swarup, Ashesh Mitra and myself); we owed much to the inspiration of Chris and other CSIRO colleagues.

7 NOTES

1 The Council for Scientific and Industrial Research in 1949 became the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

2 Observations of solar radio emission with a Royal Australian Air Force radar unit at Collaroy in suburban Sydney commenced in October 1945, and are discussed in Orchiston, Slee and Burman, 2006.

3. In the early 1950s, apart from Dover Heights and Potts Hill, the Division of Radiophysics also maintained field stations at Badgerys Creek, Dapto, Hornsby Valley and Fleurs. For an overview of these, earlier and later field stations, and associated remote sites, see Orchiston and Slee (2005), while detailed studies of Dapto and Potts Hill have been presented by Stewart (2009) and Wendt (2008) respectively.

4 Frank Kerr was in the USA at that time in order to study for a Masters degree in astronomy at Harvard. Since many of the early RP staff had radio engineering or radar backgrounds, but no formal knowledge of or training in astronomy, it was Radiophysics policy to send selected staff members to England or the USA for post-graduate training in astronomy (see Sullivan, 2005).

5 This 16 × 18-ft section of a parabola began life as a WWII experimental radar antenna at Georges Heights, overlooking the entrance to Sydney Harbour. It was then used briefly by Lehany and Yabsley for solar research when RP gained access to Georges Heights at the end of the War (see Orchiston, 2004). In 1948 the antenna was relocated to RP's Potts Hill field station and installed on an equatorial mounting in time to be used for observations of the 1 November partial solar eclipse (Christiansen, Yabsley and Mills, 1949a; 1949b). Thereafter it was used extensively at Potts Hill for solar, galactic and extragalactic research. A detailed review of the role that this pioneering radio telescope played in the development of radio astronomy is presented in Orchiston and Wendt (n.d.).

6 Dr and Mrs D'Azambuja referred to chromospheric plages as 'plages faculaires'.

8 ACKNOWLEDGEMENTS

I thank Wayne Orchiston for giving me the opportunity to write this appreciation of Chris Christiansen. It has enabled me to recall fond memories of my time at Potts Hill with Chris and colleagues. Thanks are also due to Wayne for help in preparing this paper.

Figure 8: Lunch-time activity at Potts Hill on an improvised cricket pitch. Chris kept his eye on the ball in more ways than one. Jim Hindman, who was probably bowling, was no mean bowler. Charlie Fryar is keeping wicket (photograph by the author).

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Rodney Davies FRS, CBE, is a former Director of the Jodrell Bank Observatory and Professor of Radioastronomy in the University of Manchester. His research interests are in the field of radioastronomical techniques, in studies of our Galaxy and nearby galaxies in the hydrogen line. Most recently he has been observing the Cosmic Microwave Background and is currently involved in the ESA Planck mission to observe the CMB. He has published more than 200 papers and 3 books.

2009JAHH...12..110

Journal of Astronomical History and Heritage, 12(1), 11-32 (2009).

CHRIS CHRISTIANSEN AND THE CHRIS CROSS

Wayne Orchiston
Centre for Astronomy, James Cook University, Townsville,
Queensland 4811, Australia.
E-mail: Wayne.Orchiston@jcu.edu.au

and

Don Mathewson
20 Beston Place, Queanbeyan, NSW 2620, Australia.
E-mail: Felix8@bigpond.com

Abstract: The Chris Cross was the world's first crossed-grating interferometer, and was the brainchild of one of Australia's foremost radio astronomers, W.N. (Chris) Christiansen, from the CSIRO's Division of Radiophysics in Sydney. Inspired by the innovative and highly-successful E-W and N-S solar grating arrays that he constructed at Potts Hill (Sydney) in the early 1950s, Christiansen sited the Chris Cross at the Division's Fleurs field station near Sydney, and from 1957 to 1988 it provided two-dimensional maps of solar radio emission at 1423 MHz.

In 1960 an 18m parabolic antenna was installed adjacent to the Chris Cross array, and when used with the Chris Cross formed the Southern Hemisphere's first high-resolution compound interferometer. A survey of discrete radio sources was carried out with this radio telescope.

The Division of Radiophysics handed the Fleurs field station over to the School of Engineering at the University of Sydney in 1963, and Christiansen and his colleagues from the Department of Electrical Engineering proceeded to develop the Chris Cross into the Fleurs Synthesis Telescope (FST) by adding six stand-alone 13.7m parabolic antennas. The FST was used for detailed studies of large radio galaxies, supernova remnants and emission nebulae.

The FST was closed down in 1988, and antennas in the original Chris Cross array quickly began to deteriorate. A number of individual antennas in the central part of the array received a new lease of life in 1991 when they were refurbished by staff and students from the Department of Electrical Engineering at the University of Western Sydney, but this only proved to be a temporary reprieve as even these aerials were bulldozed by the landowner in 2004, bringing to an untimely end one of the world's most remarkable radio telescopes.

Keywords: W.N. Christiansen, Chris Cross, cross-grating interferometer, Fleurs field station, 1420 MHz radio plages, Fleurs Compound Interferometer, Fleurs Synthesis Telescope.

1 INTRODUCTION

Wilbur Norman ('Chris') Christiansen (Figure 1) is one of the pioneers of Australian radio astronomy. After joining the CSIRO's Division of Radiophysics (RP) in 1948, he carried out observations of partial solar eclipses in 1948 (Christiansen, Yabsley and Mills, 1949a; 1949b) and 1949 (Wendt, Orchiston and Slee, 2008a), then briefly investigated the newly-discovered 21cm hydrogen line (Wendt, Orchiston and Slee, 2008c), before returning to solar radio astronomy and developing his E-W and N-S grating arrays at Potts Hill field station in 1952 and 1953 respectively (Christiansen and Warburton, 1953). These innovative radio telescopes provided valuable information on the one-dimensional and two-dimensional distribution of radio emission across the solar disk at 1420 MHz (for details see Wendt, Orchiston and Slee, 2008b).

As a result of contacts made during the 1952 URSI General Assembly in Sydney, Christiansen spent part of 1954 and 1955 in France, and during his 'sabbatical' he decided to build a new radio telescope in Sydney that would yield daily two-dimensional maps of the Sun at 1420 MHz. The inspiration for this came from his successful Potts Hill grating arrays (Christiansen, 1953) and Bernard Mills' development of the 'Mills Cross' (Mills and Little, 1953). Christiansen (1984: 122) was later to comment:

> While visiting Potts Hill one morning in 1953, Mills asked me why we did not couple the two arrays to produce high resolving power in two dimensions. During the ensuing discussion it was agreed that for this to be effective the centres of the two arrays must not be separated (as they were in the Potts Hill antenna), and also that some means had to be devised to multiply the outputs of the array. By the next morning Mills had devised the Cross Antenna consisting of a pair of thin orthogonal antennas with their outputs multiplied to give a single narrow response.

Figure 1: W.N. Christiansen (far left) with Sir Edward Appleton (far right) and other URSI General Assembly delegates at Potts Hill in 1952 (courtesy ATNF Historic Photographic Archive: B2842-66).

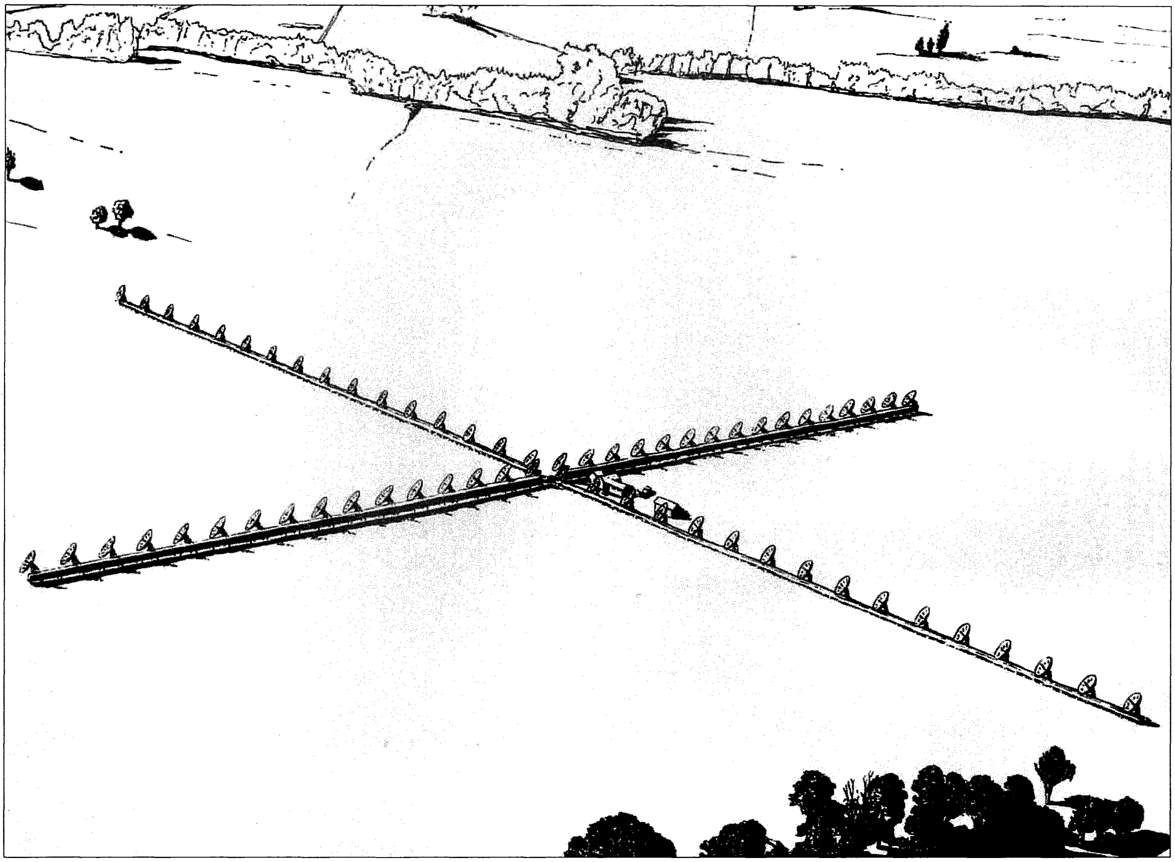

Figure 2: Schematic aerial view of the Chris Cross, looking north-east (after Christiansen et al., 1961: 49).

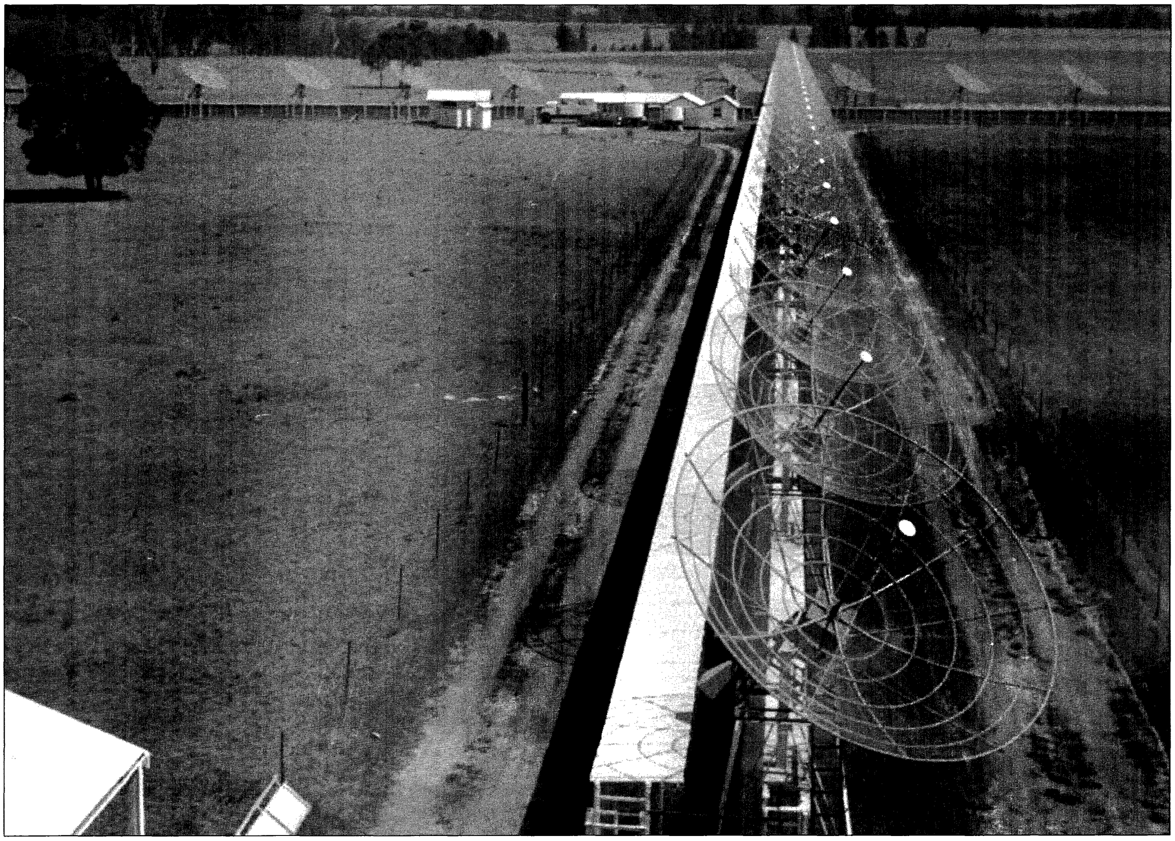

Figure 3: View from the eastern end of the E-W arm of the Chris Cross looking west towards the N-S arm and the receiver hut (courtesy ATNF Historic Photographic Archive).

The new radio telescope, affectionately known as the 'Chris Cross', was the world's first crossed-grating interferometer, and was constructed at the Fleurs field station in 1957 (Orchiston, 2004). Christiansen et al. (1961: 48) described the Chris Cross as

> …a novel solution to the problem of attaining high angular resolution at reasonable cost. Operating at a wavelength of 21 cm, it provides, for the first time sufficient discrimination in two dimensions to permit the production of 'radio pictures' of the sun, i.e. detailed maps of the radio-brightness distribution over the solar disk …

In a short paper submitted to *Nature* announcing the completion of this new radio telescope, Christiansen, Don Mathewson and Joe Pawsey (1957) drew on optical analogues in calling the Chris Cross a "radioheliograph".

In this paper we discuss its design, construction, observational programs and research outcomes, before briefly examining its subsequent development into the Fleurs Synthesis Telescope and the preservation and ultimate demise of this historic radio telescope.[1]

2 THE CHRIS CROSS

2.1 The Concept

The Chris Cross consisted of 378 m long N-S and E-W arms, each containing 32 equatorially-mounted parabolic antennas 5.8m in diameter and spaced at 12.3m intervals (Figures 2 and 3). Antennas in the N-S arm produced a series of E-W fan beams, and antennas in the E-W arm a series of N-S fan beams. Combining the signals from the two arrays in phase and out of phase produced a network of pencil beams at the junction points of the fan beams. Each pencil beam was ~3 arc minutes in diameter, and was separated from its neighbours by 1°. Since the Sun has an angular diameter of 30 arc-minutes, it was only possible for one pencil beam to fall on the Sun at any one time (see Figure 4).

In an informative paper titled "The crossed grating interferometer: a new high-resolution radio telescope", Christiansen et al. (1961: 51-52) assign almost a page to the "Choice of Equipment Parameters". They explain that the array operated at 1423 MHz because radio plages are prominent at this frequency. The ability to resolve these radio plages dictated the size of the pencil beams, but an unfortunate feature of the crossed-array design is that the side lobes associated with individual pencil beams are up to 20% of the main response (see Figure 5a). In order to reduce this to acceptable levels (i.e. <3%), it is necessary to taper the currents in the N-S and E-W arrays from the centre of the Cross out to the end antennas in each arm (see Figure 5b). Meanwhile, the length of each of the arms of the Cross is dictated by the diameter of the pencil beams. However, this is an over-simplification:

> For a beam width of 3′, an aperture of 1 800λ, or 380 m (about 1 200 ft) is required. In directions away from the zenith, the beam width is increased by the foreshortening of the arrays. This deterioration can be almost eliminated in the case of the east-west array by restricting the observations each day to a period within about two hours of transit; some broadening of the north-south array beams must, however, be accepted in the winter months. In the latitude of Sydney, the zenith distance of the sun at transit is 56° at the winter solstice. The effective aperture of the north-south array in that direction is 1 030λ, and the width of the pencil beam in the north-south plane is then 5.4′. If the receiver bandwidth is excessive, a further loss of directivity occurs at large zenith distances … a compromise … value of 300 kc/s was adopted … [and] this spreads the aerial beam by a further 1.1′ at zenith distance 56°, so that, for mid-winter solstice observations, the pencil beam is 5.4′ wide in the north-south plane. At mid-summer the corresponding beam width is 3.1′. (Christiansen et al., 1961: 51).

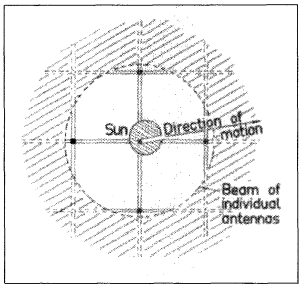

Figure 4: The network of pencil beams (after Christiansen et al., 1957: 945).

The 1° separation of the pencil beams, θ_1, in Figure 4 determined the distance, d, between the individual antennas in the orthogonal arrays, according to the formula

$$\theta_1 = \frac{\lambda}{d \cos\theta} \qquad (1)$$

where λ is the wavelength and θ is the angle between the normal to the system and the direction of the ray. Given the angular diameter of the Sun, the minimum value of θ_1 was set at 1°, which provided a spacing of $d = 58\lambda$, or 12.3m (i.e. 40ft).

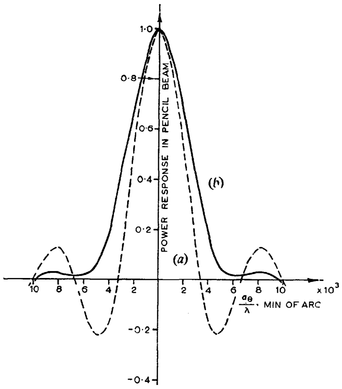

Figure 5: Polar diagrams showing the pencil beam responses at the zenith for (a) uniform arrays, and (b) arrays with tapered current distribution (after Christiansen et al., 1961: 51).

The ideal diameter of the parabolic aerials in the two orthogonal arrays was primarily determined by sensitivity considerations, on the basis that

> … the overall sensitivity of the system should be such that the pencil-beam signal due to quiet sun radiation alone would give a receiver output equal to 15 times the r.m.s. noise fluctuations … If the efficiency of [a dipole-fed parabolic reflector] … is taken as 0.5 (a fairly low estimate), the required reflector diameter for the elements of the interferometer array is 5.8 m (19 ft). (Christiansen et al., 1961: 52).

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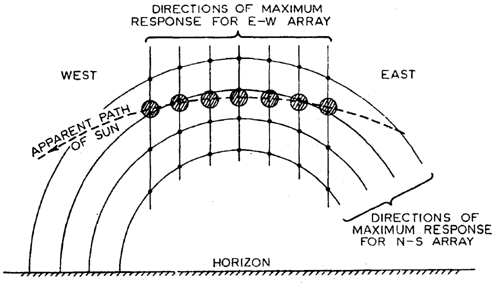

Figure 6: Movement of the Sun through the Chris Cross pencil beams (after Christiansen et al., 1961: 51).

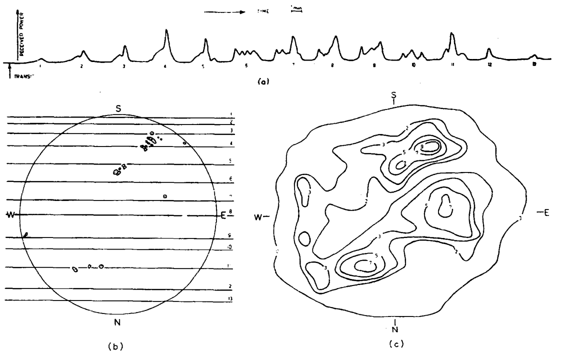

Figure 7: Diagram showing (a) a succession of 13 E-W scans, (b) their corresponding positions on the solar disk, and (c) the resulting isophote map (adapted from Christiansen and Mullaly, 1963: 170).

In principle, the basic operation of the Chris Cross was simple: as the Earth rotated, the network of pencil beams shown in Figure 6 moved together across the sky and different pencil beams scanned successive strips of the Sun, producing a series of E-W profiles (Figure 7). In reality, the scanning process was accelerated by shifting the pencil beams in declination, "... so as to maintain a space about equal to the beam width between adjacent scans." (Christiansen et al., 1961: 51). This was accomplished by using a phase-shifting mechanism on the N-S arm of the Cross so that it only took about half an hour for the whole Sun to be scanned. In this way, "The distribution of radio emissivity over the solar disk is thus determined in a direct, rapid and unambiguous fashion." (Christiansen et al., 1961: 49).

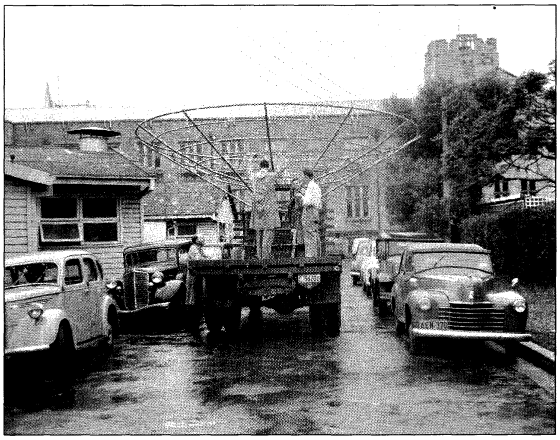

Figure 8: Loading the Chris Cross test antenna onto a truck at the RP Workshop, ready for its transfer to Potts Hill field station (courtesy ATNF Historic Photographic Archive: B3858-3).

2.2 The Prototype Antenna at Potts Hill

Apart from providing the inspiration for the Chris Cross, the Potts Hill field station had one other important link with this new radio telescope: it provided a suitable site where a prototype of the aerial could be erected and thoroughly tested. A 5.8m antenna was constructed in the Workshop at the Radiophysics headquarters in the grounds of the University of Sydney and on 25 November 1956 it was loaded onto a truck (Figure 8) and transported by road the 16km to Potts Hill where it was subsequently erected alongside the original N-S grating array (see Figure 9).

2.3 Construction of the Chris Cross

By 1956 the Potts Hill field station was starting to experience significant interference at 1420 MHz, and there was insufficient land there anyway, so another site had to be found for the new solar crossed-grating interferometer. Fleurs field station (Orchiston and Slee, 2002) was the obvious choice. It was a relatively radio-quiet location, accessible by car from Sydney, a suitable flat site, and already boasted two cross-type radio telescopes: the 85 MHz Mills Cross, constructed in 1954, and the much larger 19.7 MHz Shain Cross, which was erected in 1956 (Figure 10). The Chris Cross would be in good company!

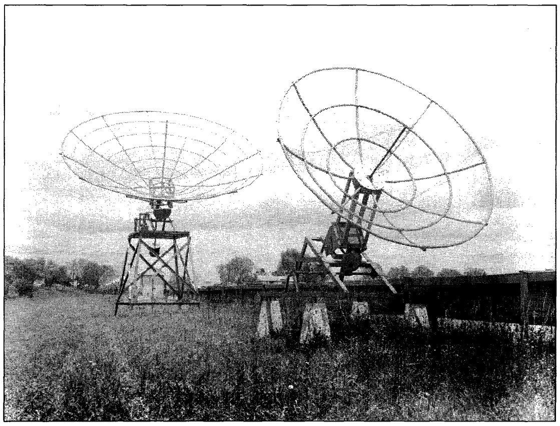

Figure 9: The Chris Cross test antenna at Potts Hill (second from right), shown between elements in the N-S grating array (courtesy ATNF Historic Photographic Archive: B3881-2).

From the time of his return to Sydney in early 1955, Christiansen lobbied relentlessly for his new cross telescope, and although formal approval was granted, progress was painfully slow when it came to the actual construction. As one of the authors (DM) reminisces, Christiansen liked to get results and his eventual response was typical:

> Late 1955 I joined Chris at RP helping him to build his Chris Cross at Fleurs. We worked at Potts Hill on the prototype, testing the various designs. But in 1956 although RP had funded the Cross, no construction work had started.
>
> One day Chris said to me, "We're going to Fleurs to build the Cross." Joined by a secretary from the Office, we put a theodolite and sledgehammer in the back of a battered old RP truck, picked up from a nearby factory hundreds of starposts, and bumped and rattled our way out to Fleurs. Joined by Charlie Higgins, we spent the next four days hammering in the starposts to build the fence surrounding the Chris Cross.

At the end of the week, exhausted and covered in blisters, we sat in the back of the truck surveying our handiwork. Chris was dressed in khaki shorts and shirt with a battered old sunhat perched on the back of his head. As he rolled a cigarette, he drily remarked, "That's the straightest fence that's ever been built. On Monday I'll send Taffy[2] our wages bill for the week and how much it would cost if we continued to build the whole Cross." Next week six workman had been assigned to the task and construction of the Chris Cross started!

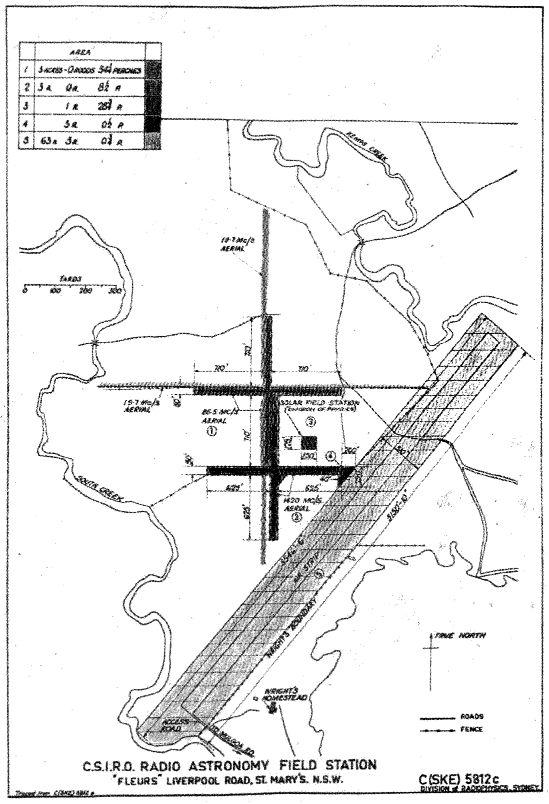

Figure 10: The Fleurs field station showing the disused WWII air strip (pink) extending from Kemps Creek in the east to South Creek in the west, and the positions of the Mills Cross (dark brown), Shain Cross (pale brown) and Chris Cross (blue) (courtesy ATNF Historic Photographic Archive).

Christiansen et al (1961: 52) emphasized that

> In designing the aerials and the feeders, which together account for most of the cost of the instrument, it was important to aim at the cheapest possible construction consistent with the required performance and durability.

Just as he had done previously with the Potts Hill grating arrays and the Fleurs Mills Cross, RP's resident Engineer, Keith McAlister, responded brilliantly to this design challenge. Each 5.8m diameter aerial had a focal length of 1.9m (6ft 3in) and was composed of 12.7mm (half-inch) galvanised wire mesh on a tubular aluminium framework. The dipole and its reflector plate were at the end of a metal tube which was attached to the centre of the antenna. A twin-wire transmission line ran from the dipole down the inside of this metal tube. As Figures 11 and 12 reveal, each aerial was attached to an equatorial mounting which contained declination and hour angle scales to permit careful pointing of the aerial. The equatorial mounting was attached to the top of a tubular steel frame-work which has four feet bolted to concrete blocks that were set in the ground.

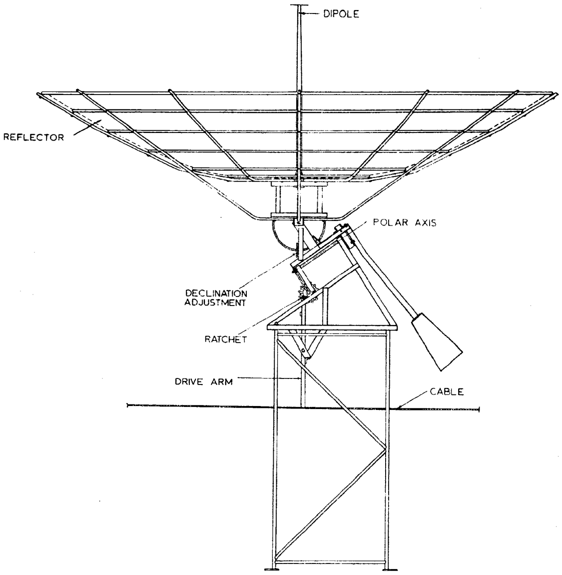

Figure 11: Engineering drawing of a Chris Cross antenna, equatorial mounting and supporting tower (after Christiansen et al., 1961: 53).

Construction of the Chris Cross took place on-site, with the parabolas fabricated on the ground (Figure 13) while at the same time their supporting towers and equatorial mountings were assembled and installed within "... the straightest fence that's ever been built". Each antenna was then moved to its designated mounting (Figure 14), and subsequently they were all hoisted into position.

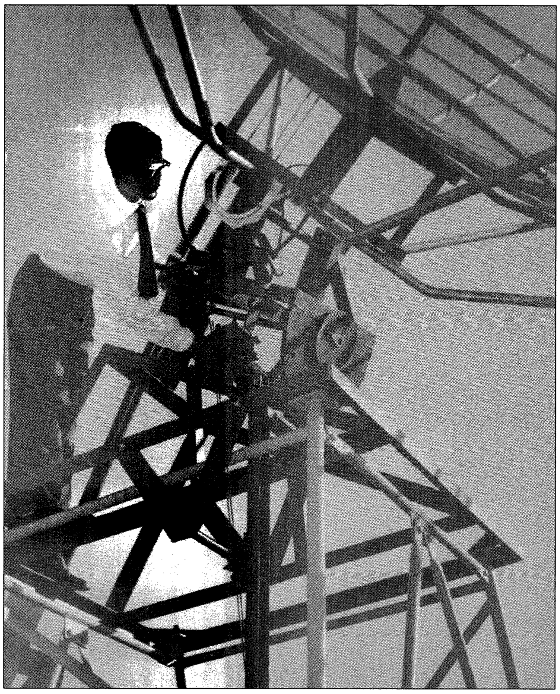

Figure 12: Close-up of the equatorial mounting, showing the hour angle circle, the white declination sector and the ratchet wheel used to drive the aerial when observing the Sun (courtesy ATNF Historic Photographic Archive: B5804-4).

Figure 13: Aerial view showing huts, cylindrical frames and the antenna assembly area of the new Chris Cross, located very close to the central point of the Cross (courtesy ATNF Historic Photographic Archive: B5042-2).

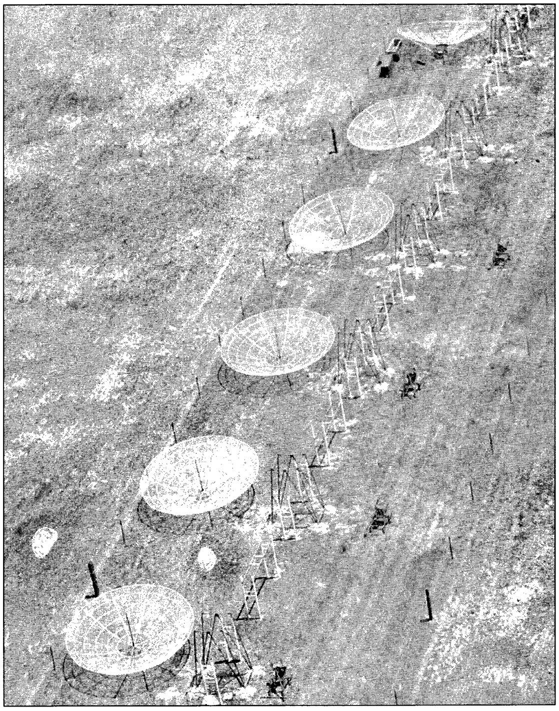

Figure 14: The assembled Chris Cross antennas alongside their partially-completed mounts (courtesy ATNF Historic Photographic Archive: B5042-4).

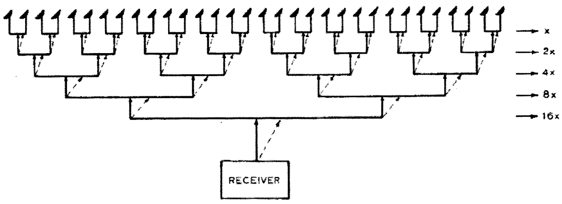

Figure 15: The branched feeder system of the N-S arm of the Chris Crosss. The dashed arrows show the movements required in the T-junctions at each level in order to change the relative feeder lengths for adjacent aerials by an amount of 2*x* (after Christiansen et al., 1961: 53).

The transmission lines from the different aerials were connected to tensioned copper wire feeders supported by polythene insulators spaced at 5.5m (18ft) intervals. Christiansen et al. (1961: 53) noted that

> Because of the great electrical length of the feeder lines (the outermost aerials in each array are over 900 wavelengths from the receiver), care must be taken to prevent phase shifts between the signals from the various elements due either to thermal expansion of the lines or to changes in atmospheric humidity. These effects are minimized by using a branching system of transmission lines with equal lengths of line between all the aerials and the receiver. Any change in the electrical length thus affects all the aerials equally.

Five twin feeder lines mounted one above the other were run the length of each array. The aerials were connected in pairs to sections of the top twin line, and each of these sections was then connected via a T-junction at its mid-point to the twin line below, and so on. A schematic view of this branched feeder system is shown in Figure 15.

The total length of twin-feeder line from each aerial to the central receiver was about 183m (i.e. 600ft), and included five different T-junctions. The design of these T-junctions is illustrated in Figure 16. Apart from allowing connections between the different sets of twin feeder lines, these T-junctions had two other functions:

> They determined the current division between the various branches, to give the prescribed distribution along the array; and, in the north-south array, they are movable so that the position of the interference pattern can be adjusted by phase-changing. (Christiansen et al., 1961: 54).

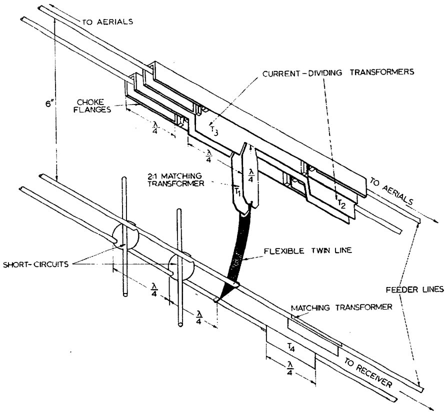

Figure 16: Design of the twin feeder line T-junction (after Christiansen et al., 1961: 54).

The phase-changing mechanism in the N-S arm used to adjust the interference pattern is shown in Figure 17. A progressive variable phase shift

> … may be introduced between the aerials of the array … by moving all the feeder junctions simultaneously … [In Figure 15] if the movements are, from top to bottom line, *x*, 2*x*, 4*x*, 8*x* and 16*x*, respectively, towards the north the length of feeder between a given aerial and the receiver is increased by 2*x* in relation to that for the next aerial to the north. A change of one wavelength between adjacent aerials shifts the interference pattern by an amount equal to the interval between successive maxima, i.e. about 1°. (Christiansen et al., 1961: 54).

Finally, the twin-wire feeder lines were linked via a balance-to-unbalance transformer and a coaxial-line phase switch to a superheterodyne receiver (in the centrally-located Receiver Hut). The receiver consisted of

> … a crystal mixer, to which a 1.393 Gc/s heterodyne oscillator is also coupled. The intermediate-frequency amplifier is tuned to 30 Mc/s, with 300 kc/s bandwidth. The second detector has a square-law characteristic (this is necessary in order to make the 25 c/s output independent of the total 30 Mc/s input to the amplifier, which varies with the power received by the fan-beam systems as a whole).
>
> The output is applied to a low-frequency amplifier and then to a phase-sensitive detector … The signal is [then] applied to a pen recorder. (Christiansen, et al., 1961: 55).

Figure 18 shows the receiver and other equipment in the Receiver Hut.

Adjacent to the Receiver Hut was a smaller building which housed an hydraulic ram that was attached to a 9mm (⅜in) steel cable that extended the full length of each array and was used to drive all of the aerials in hour angle as they observed the Sun. At each aerial, this cable

> … is clamped to a pivoted drive arm which advances a ratchet wheel by one tooth for each to-and-fro movement of the cable. This drives the aerial about its polar axis. Each stroke changes the hour angle by ⅛°, which corresponds to the earth's rotation in 30 sec of time. (Christiansen, et al., 1961: 52).

This ratchet wheel is visible in Figures 11 and 12.

Construction of the Chris Cross was completed early in 1957 (Figure 19) and after mandatory 'debugging', regular solar observations began on 28 June (see Aerials at "Fleurs" …, 1964). Subsequently, superstructure was installed along each arm of the Cross to protect the twin feeder lines from the elements (see Figure 20).

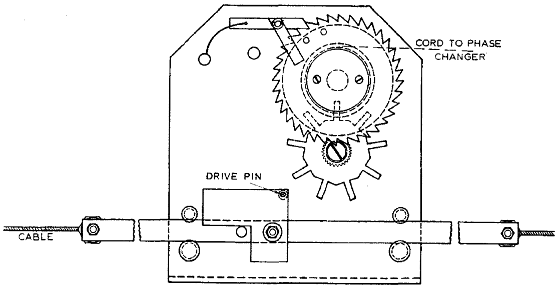

Figure 17: The phase-changing mechanism (after Christiansen et al., 1961: 55).

2.4 The Daily Solar Maps

As Figure 7 illustrates, by analysing strip scans taken on any day and measuring the relative amplitudes of different peaks, one could generate a radio map of the 1423 MHz solar emission, with isophotes indicating the relative flux levels of the different active regions. From July 1957 the Chris Cross was used to generate daily solar maps, and these were distributed to interested observatories worldwide and were published in the IAU's *Quarterly Bulletin on Solar Activity*.

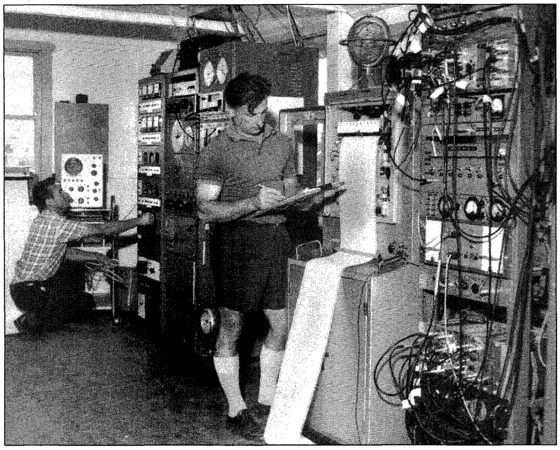

Figure 18: View showing part of the interior of the Receiver Hut (courtesy ATNF Historic Photographic Archive).

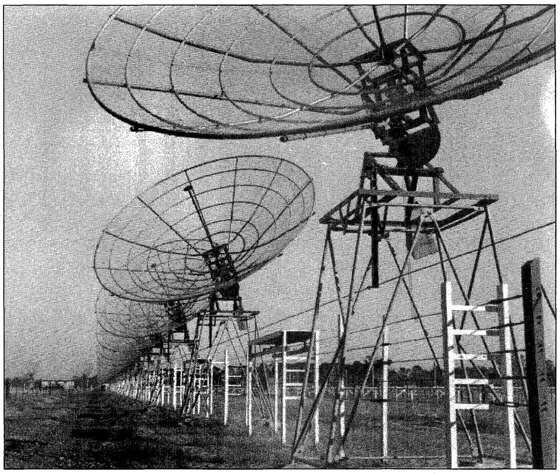

Figure 19: View of the newly-completed Chris Cross, looking south along the N-S arm. Note the five vertically-stacked twin feeder lines, and the steel cable used to drive the array (courtesy ATNF Historic Photographic Archive: B5192-5).

A prominent feature of the daily isophote maps (see Figure 21) are the localised regions of enhanced emission, termed 'radio plages', which were located in the lower corona but—in most instances—were found to correlate with photospheric sunspots and chromospheric Hα and calcium H and K plages visible on spectroheliograms (Christiansen and Mathewson, 1959).

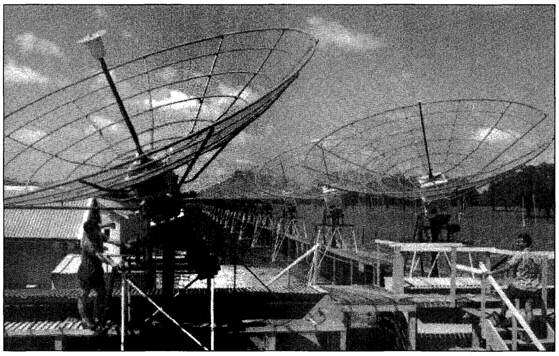

Figure 20: View looking south along the N-S arm, near the centre of the Cross. Note the superstructure erected to protect the feeder lines from the elements (courtesy ATNF Historic Photographic Archive: B9097-12).

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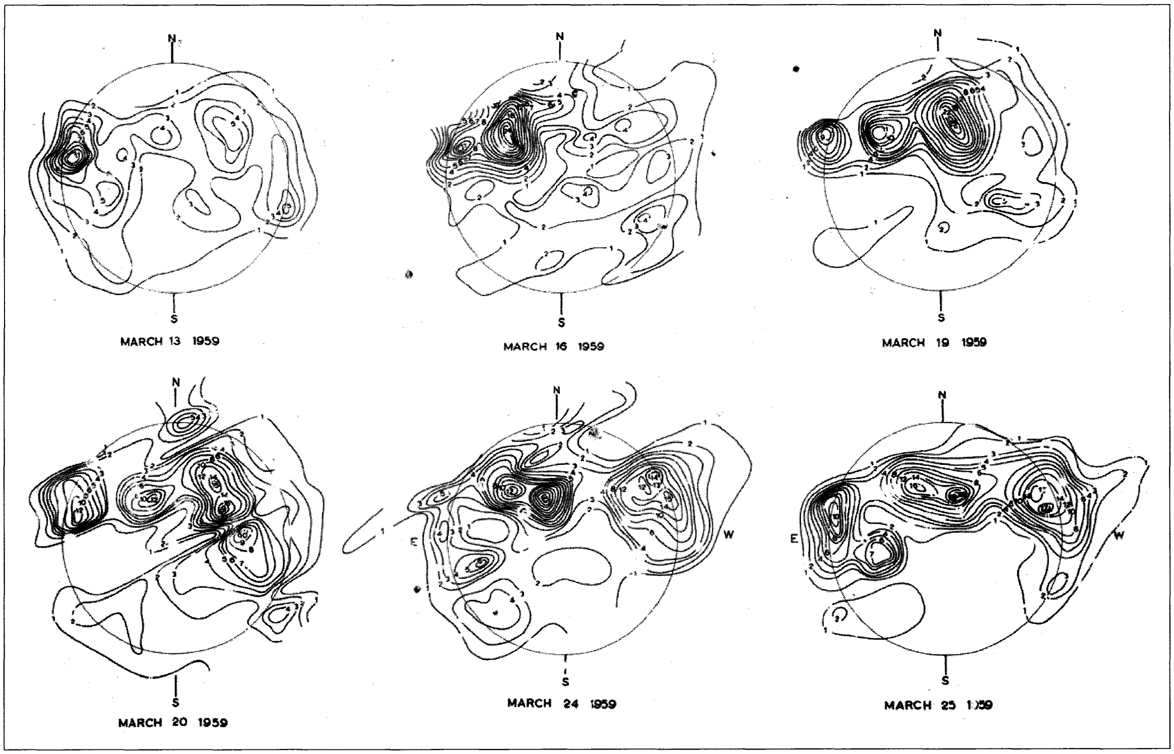


Figure 21: Six Chris Cross solar isophote maps for the period 13-25 March 1959. A notable feature is the prevalence of radio plages (courtesy ATNF Historic Photographic Archive: B6215-4).

When the Chris Cross became operational, Christiansen and Mathewson (1958: 131) were hopeful that the daily isophote maps would

> ... allow a study to be made of the development and decay of individual radio sources [= radio plages] on the sun and the general changes that these sources undergo during the solar cycle.

By the end of 1962 a large amount of data existed on the positions, sizes, temperatures and lifetimes of radio plages. Typically, they were found to be disk-like regions parallel to the photosphere with lateral dimensions of ~25 x 10^4 km and brightness temperatures of ~6 x 10^5 K (Christiansen and Mathewson, 1959: 110, 112). Meanwhile, the height of a radio plage was revealed by its rate of rotation across the solar disk. When this is plotted, as in Figure 22, the gradient of the line of best fit gives the height of the radio plage in the solar atmosphere. Such plots showed that radio plages are located between 2 x 10^4 and 10^5 km (with an error of ±10^4 km) above the photosphere, i.e. in the lower corona.

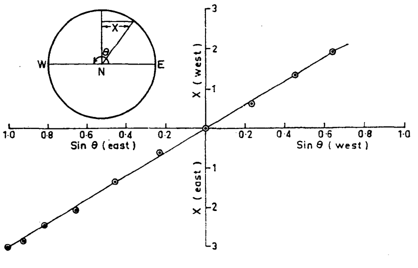


Figure 22: Plot of the displacement of a radio plage from the central meridian of the Sun against the sine of the angle of rotation of the Sun. The slope of the line gives the height of the radio plage in the solar atmosphere (after Christiansen and Mathewson, 1959: 110).

There was abundant evidence that radio plages were associated with chromospheric Hα plages and with sunspots in the photosphere, and their magnetic fields. Typical radio plages have lifetimes of about three months, so it is not uncommon for an individual plage to be seen on three (or even more) successive solar rotations (Christiansen and Mathewson, 1959).

Christiansen and Richard F. Mullaly (1963: 171) describe the physical nature of radio plages:

> It is believed ... [that they] consist of large clouds of gas (principally hydrogen) in the lower corona, much denser than the surrounding atmosphere. These clouds are prevented from dissipating presumably by magnetic fields ... The clouds are sufficiently dense to be opaque (optically thick) to decimetre radio waves; the gas of the surrounding corona at these heights is not. It is believed that the radio-frequency emission is thermal in origin, arising from collisions (without capture) between an electron and a proton ("free-free transitions").

At 1420 MHz, three basic types of solar radiation were recognised:

1) emission from the quiet Sun which remained constant for long periods, but may change in the course of the solar cycle;
2) a 'slowly-varying component' which varied from day to day; and
3) occasional intense bursts of emission.

Radio plages were responsible for the 'slowly-varying component'.

2.5 Associated Research Projects

In addition to monitoring the behaviour and duration of individual radio plages, the Chris Cross was used to investigate emission from the quiet Sun (1 above), solar bursts (3), and other short-term phenomena.

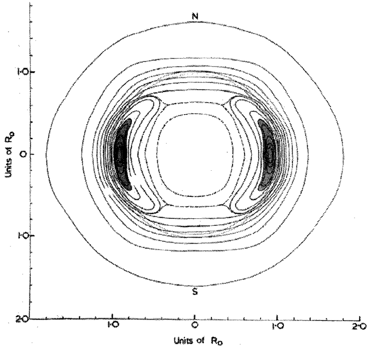


Figure 23: The two-dimensional distribution of radio brightness across the solar disk at 1420 MHz in 1952-1954 (after Christiansen and Warburton, 1955b).

As Christiansen and Mullaly (1963: 169) note,

> Radio measurements of the quiet Sun are of importance, since they can provide information on temperatures and electron densities in layers of the solar atmosphere which are difficult to observe optically.

Observations carried out at Potts Hill with the two grating arrays showed that at 1420 MHz the Sun was non-symmetrical and exhibited distinct equatorial limb-brightening (see Figure 23), and that the central brightness temperature was 4.7 × 10^4 K (Christiansen and Warburton, 1955a: 482). However, this research was carried out near sunspot minimum, and any attempt to replicate it using the Chris Cross was fraught with difficulty given that the plethora of radio plages present near sunspot maximum tended to mask the quiet Sun radiation.

This, then, was Norman Labrum's challenge, and he responded admirably to it: first he used the Chris Cross between May and November 1958 to identify specific regions near the centre of the solar disk devoid of radio plages, and then he went on to determine the central brightness temperature of these (but only after making allowances for the effects of side lobes). The results are plotted in Figure 24, where a value of $10^5 \pm 10^4$ K accommodates all of the individual observations. This equates to an apparent disk temperature of between 13 × 10^4 and 16 × 10^4 K.

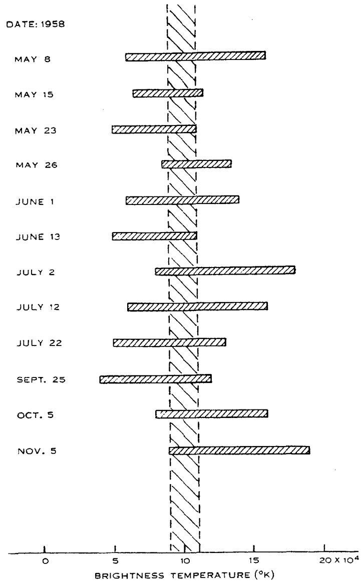


Figure 24: Twelve estimates of the central disk temperature of the quiet Sun in 1958, with the horizontal strips showing the limits of error of the individual records; the vertical band accommodates all of the individual observations (after Labrum, 1960: 703).

Labrum also tried another approach, one modelled on the procedure adopted previously by Christiansen and Warburton at Potts Hill. He took a set of twenty daily strip scans obtained with the N-S arm of the Chris Cross between September and November 1958, and tried to identify the lower (i.e. non-radio plage) envelope for each of these. All twenty scans are superimposed in Figure 25, where the confusion caused by radio plages is very apparent. After graphically estimating the mean value of the centre of the solar disk, Labrum derived the quiet Sun profile shown here in Figure 26, which produced a disk temperature of between 13 × 10^4 and 15 × 10^4 K. This agrees with the values obtained from the full Cross observations.

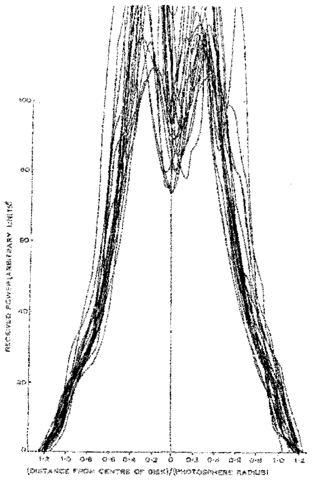


Figure 25: Twenty superimposed strip scans of the Sun obtained between September and November 1958 with the N-S arm of the Chris Cross (after Labrum, 1960: 707).

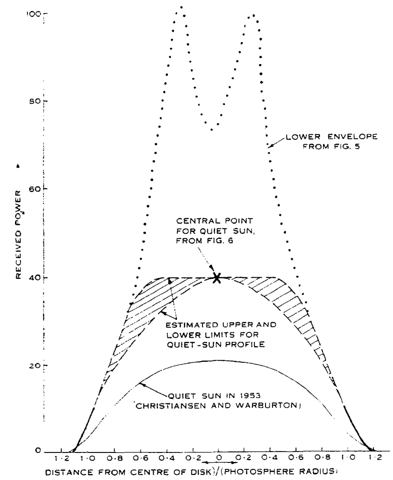


Figure 26: Profile of the quiet Sun derived from the scans in Figure 25. Christiansen and Warburton's 1955 profile is drawn on the same scale (after Labrum, 1960: 709).

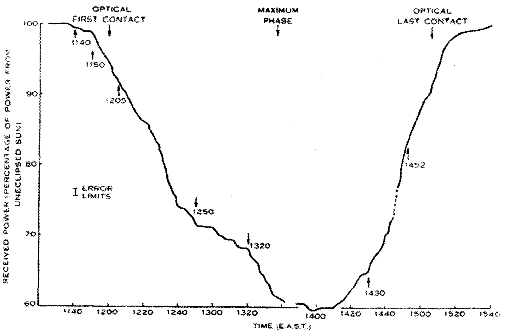


Figure 27: Eclipse curve obtained with the Potts Hill radiometer. The dashed region shows when calibrations were made (after Krishnan and Labrum, 1961: 408).

Back in 1953 Christiansen and Warburton (1955a) obtained an apparent disk temperature for the centre of the solar disk of 7 x 10^4 K, whereas a value ~14 x 10^4 K applied in 1958, indicating that the temperature of the quiet Sun increased by a factor of two between sunspot minimum and sunspot maximum.

Because of the prevalence of radio plages in 1958 Labrum could not construct an isophote map like the one in Figure 23 but on the basis of the 1953 and 1958 profiles shown in Figure 26 he was able to conclude:

> The two profiles are similar in shape; the ratio of corresponding ordinates in both equatorial and polar sections is approximately 2 : 1. It therefore seems likely that the brightness distribution is much the same at sunspot maximum and minimum. In particular, the pronounced limb darkening at the poles, which was detected from the earlier observations, was also present in 1958. (Labrum, 1960: 710).

On 8 April 1959 there was a partial solar eclipse that was visible from Sydney, and Labrum teamed with the visiting Indian radio astronomer, T. Krishnan, to observe this and carry out a further investigation of the distribution of radio brightness across the solar disk. The eclipse was observed with the Chris Cross and with the 16 x 18ft ex-WWII experimental radar antenna at Potts Hill. The latter radio telescope functioned as a total power radiometer, producing the eclipse curve shown above in Figure 27. The Chris Cross isophote plot showed six different radio plages on the Sun at the time, and these went some of the way towards explaining the nature of the eclipse curve. However, they did not tell the whole story.

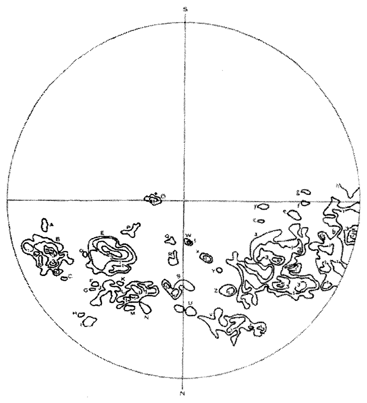


Figure 28: Photometric scan of calcium K line chromospheric plages visible on the northern half of the Sun (which alone was masked by the Moon) at the time of the eclipse; here south is at the top (after Krishnan and Labrum, 1961: 412).

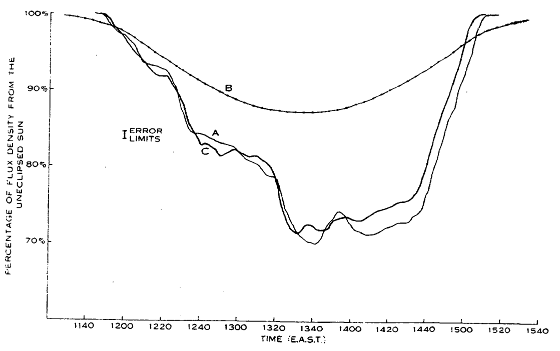


Figure 29: A is the eclipse curve for the optical plages; B is the curve obtained by using quiet Sun model number (4) discussed below; and C was obtained by subtracting curve B from the actual eclipse curve shown in Figure 27 (after Krishnan and Labrum, 1961: 415).

Given the association between optical plages and radio plages, Krishnan and Labrum proceeded to photometrically scan a photograph of calcium K line plages visible at the time of the eclipse (Figure 28), artificially eclipse this, adjust it so as to allow it to lie radially 7 × 10^4 km above the photosphere, and then compare this curve with the actual eclipse curve using four different models of the quiet Sun. The plot that gave the closest fit is reproduced here as Figure 29, and involved a Christiansen-Warburton type two-dimensional radio brightness distribution (as in Figure 23), but with the temperature gradient in the 'ear component' (alone) scaled up by a factor of 2 to allow for the solar maximum. The 'ear component' refers to the conspicuous equatorial limb-brightening shown in Figure 23. The four different models that Krishnan and Labrum investigated are shown in Figure 30, and the one labelled '(4)' was used in deriving Figure 29.

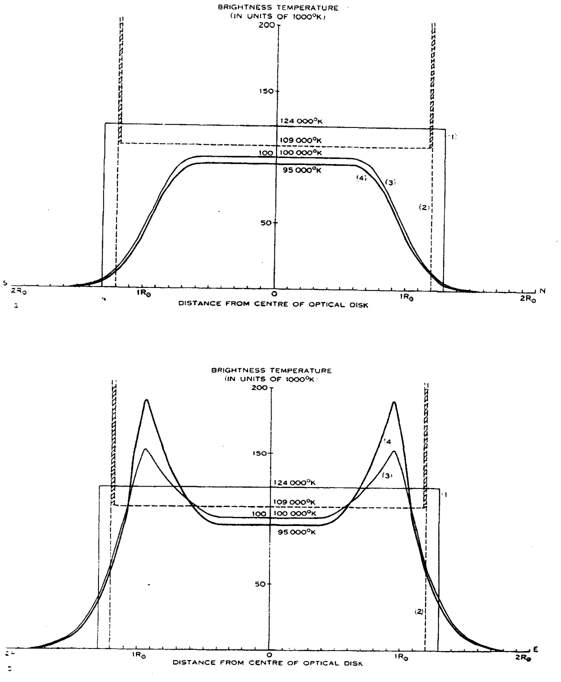


Figure 30: The four different quiet Sun models, (1)-(4), used in the analysis. Top: a plot of the distribution along the solar axis. Bottom: a plot along a line perpendicular to the solar axis and passing through the centre of the disk (after Krishnan and Labrum, 1961: 417).

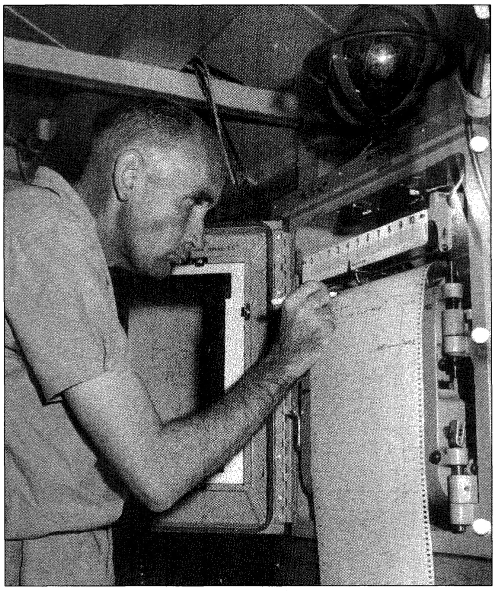


Figure 31: Dr Richard F. (Dick) Mullaly marking up a Chris Cross scan as it appears on the chart recorder (courtesy ATNF Historic Photographic Archive: B9097-4).

Krishnan and Labrum (1961: 418) conclude:

> The quiet-Sun model that we have derived agrees with other observations in this laboratory (Labrum 1960) taken at sunspot maximum. While the method of analysis does not allow a very sensitive interpretation of the distribution of the quiet-Sun component, our result does seem to indicate limb brightening at the equator and the absence of limb brightening at the poles. The fact that the model with the gradient of the ear component stepped-up, fits best, indicates a limb-brightened model closer to those predicted theoretically than the Christiansen and Warburton (1955) model for sunspot minimum and brings out the advantages of higher resolution obtained at eclipse observations. It is interesting in this connexion to note that Tanaka and Kakinuma (1959) in the interpretation of their eclipse observations of April 1958 (near sunspot maximum) have also been led to suggest an ear component.

Although solar bursts were much more common at lower frequencies (see Stewart, 2009), they were occasionally recorded by the Chris Cross at 1423 MHz, and are the subject of three papers by Krishnan and Richard F. Mullaly. Figure 31 features Mullaly.

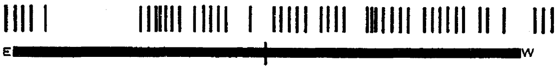


Figure 32: The longitude distribution of the 46 bursts observed with the Chris Cross (after Mullaly and Krishnan, 1963: 12).

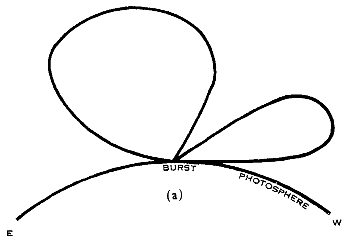


Figure 33: A possible double lobe burst polar diagram which accounts for the longitude distribution in Figure 32 (after Mullaly and Krishnan, 1963: 13).

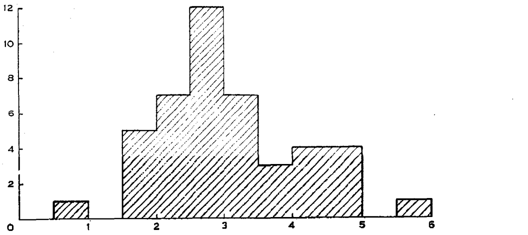


Figure 34: Plot of number of bursts versus angular size (in minutes of arc) (after Mullaly and Krishnan, 1963: 14).

In a paper titled "Solar decimetre radio bursts", Mullaly and Krishnan (1963) discuss 46 bursts observed between 1958 and 1961 (inclusive). Their aim was primarily "... to determine typical physical characteristics of the decimetre burst sources: their sizes, positions, brightness temperatures, and movements." (Mullaly and Krishnan, 1963: 9). Most observations were carried out with the E-W arm of the Chris Cross, which allowed successive scans of the Sun to be obtained every 4 minutes. All but one of the bursts were associated with individual radio plages, and when a burst occurred it was manifest by a sudden increase in the height of the radio plage. Sometimes when there were sudden intense bursts the chart recorder pen went off-scale, and the receiver gain had to be turned down.

When the heliocentric longitudes of the bursts were plotted they were found to be non-randomly distributed, with fewer bursts near the limbs than near the central meridian. There was also a suggestion of east-west asymmetry in the distribution, and there was a 30° region towards the eastern limb with no bursts whatsoever (see Figure 32). All this suggested to Mullaly and Krishnan (1963: 13) that these bursts "... typically have a polar diagram, with two lobes, asymmetrically disposed ..." as illustrated here in Figure 33.

The angular sizes of the burst sources were investigated, using the formula

$$S = (W^2 - b^2)^{1/2} \qquad (2)$$

where S is the size in minutes of arc, W the half-power width of the burst and b the beamwidth of the fan beam. Values of S ranged between $<1'$ and $6'$ (Figure 34), with a mean of $3'$. When the angular sizes were plotted against the heliocentric longitudes of the bursts no significant differences were noted between the sizes of bursts near the central meridian and those near the limbs of the Sun (see Figure 35).

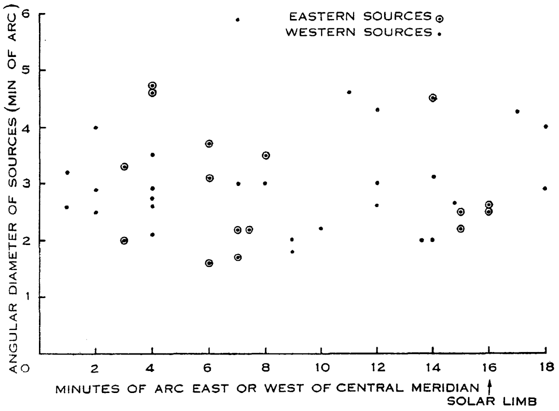


Figure 35: Plot of angular size of burst sources vs heliocentric longitude of the bursts (after Mullaly and Krishnan, 1963: 15).

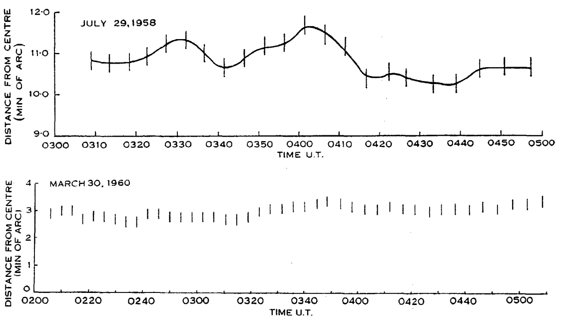


Figure 36: Two bursts showing apparent movement of the centroid of the emission sources through time. The vertical bars are running means for three successive scans (after Mullaly and Krishnan, 1963: 17).

In general, the angular sizes of the sources of Chris Cross bursts showed little or no change during the lifetimes of the bursts. The most notable exception occurred on 29 April 1960. In this case, the source systematically increased from ~1.5′ to ~3.5′ over the course of more than two hours, but during part of this interval (from 0300 to 0350 hrs UT) the source was inactive. On one or two occasions bursts were recorded which decreased in source size with the passage of time:

> Thus a very intense burst on July 14, 1959 had an initial stage of very strong emission with an angular size of about 4′ or 4′.5 of arc, followed by a period of weaker emission during which the size appeared to be about 3′. (Mullaly and Krishnan, 1963: 16).

While no large-scale changes in the positions of the sources were ever observed, sometimes bursts did exhibit small fluctuations in position of up to ±1′ over the course of tens of minutes to hours. Two of the most notable examples are shown here in Figure 36. Mullaly and Krishnan (1963: 17) suggested that such movements were perhaps due to "… the brightening or darkening of one part of the burst source relative to another, rather than a bodily movement in the source region as a whole."

The peak brightness temperature (T_b) of each burst was investigated, using the formula

$$T_b = F/1.88 \times 10^{-27}(S/32\lambda)^2 \qquad (3)$$

where F is the flux density in $\mathrm{Wm^{-2}(c/s)^{-1}}$, S is the size of the source in minutes of arc, and λ is the wavelength in metres. All of the bursts had peak brightness temperatures between 10^6 K and 2×10^9 K, with 84% between 10^6 and 10^8 K (Figure 37). Noting that there were no bursts with $T_b < 10^6$ K, Mullaly and Krishan (1963: 18-19) concluded:

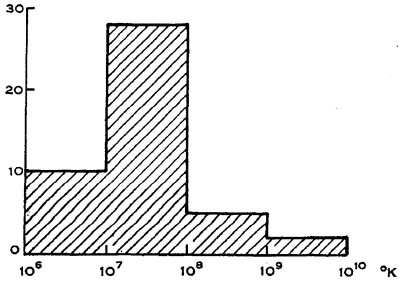


Figure 37: Histogram of the peak brightness temperatures of all bursts (after Mullaly and Krishnan, 1963: 19).

> It seems then that there may be a cut-off and that bursts with peak brightness temperatures much below 10^6 °K do not occur or occur infrequently. On the other hand, such bursts may escape observation by being of very short duration or unusually small angular size. The question of a cut-off is of interest for the discussion of possible mechanisms of production of burst radiation.

Towards the end of their paper Mullaly and Krishnan (1963: 22) address this last-mentioned issue, pointing out that "It is difficult to account for temperatures of the order of 10^8 °K on the basis of thermal emission alone." They note that Takakura (1960) has suggested synchrotron radiation as a possible mechanism, while Hachenberg and Wallis (1961) advocate quasi-thermal emission, with bands of weak synchrotron radiation superimposed, but the Chris Cross data did not allow them to distinguish between the two mechanisms.

Mullaly and Krishnan also investigated the sizes of burst sources relative to their associated radio plages and found no direct correlation. Many sources were comparable in size to their parent plages, but some were smaller; "The striking feature, however, is that *none of the burst sources substantially exceed* [sic.] *their associated plages in size.*" (Mullaly and Krishnan, 1963: 20; their italics).

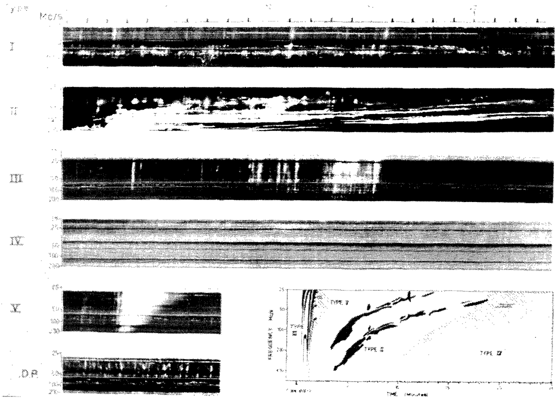


Figure 38: The different spectral types of solar bursts; time is in minutes. Type IV continuum emission (fourth strip from top) can last for days (courtesy ATNF Historic Photographic Archive: B6317).

The heights in the solar atmosphere of ten burst sources near the limb were examined and their displacement from the positions of their parent plages was measured. Six coincided in position; one was closer to the central meridian by 0.5 ± 0.3′, and three were further away from the central meridian by ~0.7 ± 0.3′, indicating that most burst sources were situated within $\pm 2 \times 10^4$ km of their parent radio plages (Mullaly and Krishnan, 1963: 19-20).

Before writing their 1963 paper, Krishnan and Mullaly investigated Chris Cross bursts that were known to be associated with metre-wave continuum emission of spectral Type IV (see Figure 38). Eight different bursts were recorded between July 1958 and November 1960 (inclusive).

The heights of these burst sources in the solar atmosphere were calculated using the following formula (and on the assumption that they lay radially above the associated flares):

$$H = R_\odot Y/X \qquad (4)$$

where H is the height radially above the Hα flare in km, $R_{\odot}$ is the radius of the Sun, and X and $X + Y$ respectively denote the perpendiculars from the centroid of the flare position (see Krishnan and Mullaly, 1962: 91, Figure 4). Values of H for the eight bursts were all $<3.5 \times 10^4$ km, except on one day when the source was close to the central meridian and this method was not applicable. Krishnan and Mullaly (1962: 91) conclude that "… the regions of origin of 1420 Mc/s bursts are situated in the lower solar atmosphere and not in the upper corona."

Angular sizes of the sources of the eight bursts were calculated using Equation (2) above and ranged from <2.0′ to 4.6′ (see Krishnan and Mullaly, 1962: 90). No significant changes in source sizes were detected during the lifetimes of the bursts. Peak brightness temperatures of the bursts were also calculated, from Equation (3) above, with values ranging from 2×10^7 K up to 2×10^9 K (ibid.).

One of the features of metre wave Type IV events is that some of the sources of the continuum radiation show rapid movement away from the Sun, while other source regions remain stationary (see Stewart, 2009). Krishnan and Mullaly were keen to see if the sources observed with the Chris Cross followed a similar pattern, but only three of their bursts were accompanied by Dapto interferometer records at 45-60 MHz. These three events are shown in Figure 39, where two of the three Type IV burst sources exhibit large-scale outward motion from the Sun, while the third burst (on 15 November 1960) shows significant oscillations in its position in the corona. In contrast, there were no changes in the positions of any of the Chris Cross sources. Krishnan and Mullaly (1962: 95) conclude that the Chris Cross emission and Type IV metre wave emission were generated simultaneously, but at widely different levels in the solar atmosphere, and "It is clear that the decimetre [i.e. Chris Cross] radiation, which is known to be broad-banded, cannot be described simply as an extension of the metre wavelength type IV continuum." We should note that one year earlier, Krishnan and Mullaly (1961) had summarized their principal findings in a short paper which was published in *Nature*.

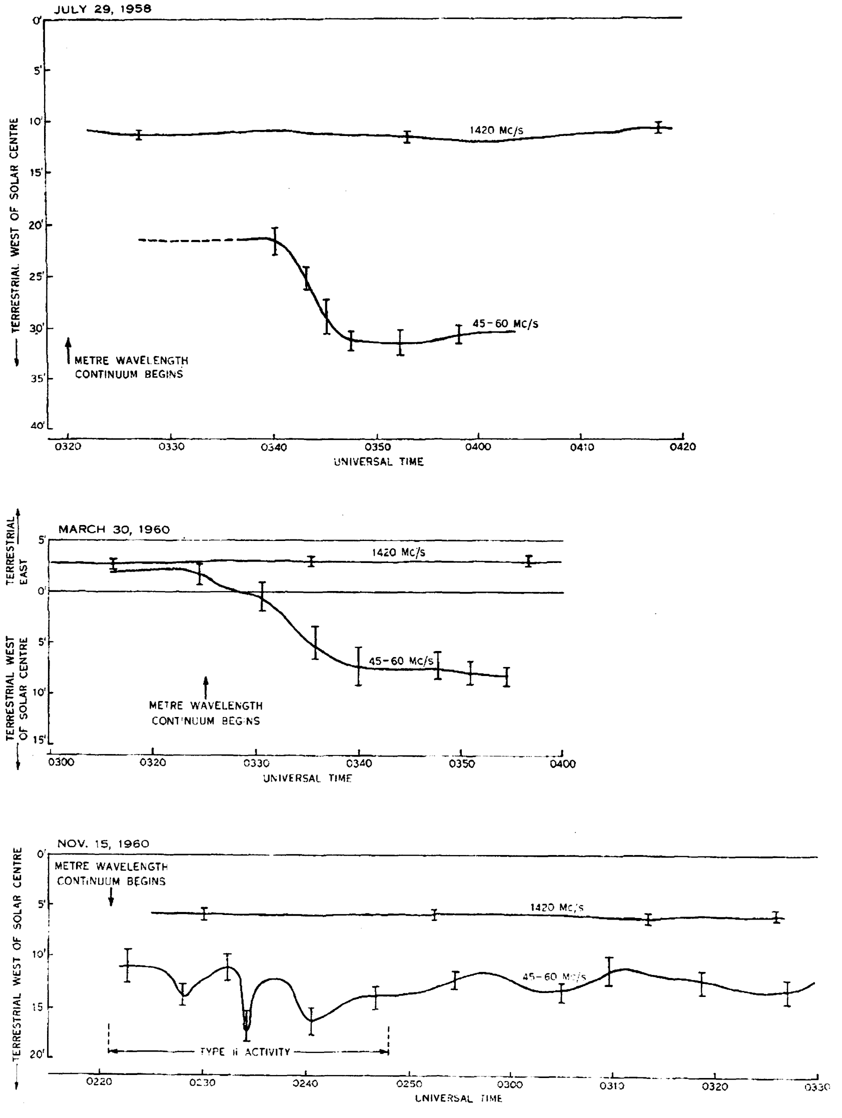


Figure 39: The E-W positions of three Chris Cross bursts at 1423 MHz and their corresponding Type IV bursts at 45-60 MHz. The bars at 45-60 MHz indicate that variations in position that occurred between 45 and 60 MHz (after Krishnan and Mullaly, 1962: 94).

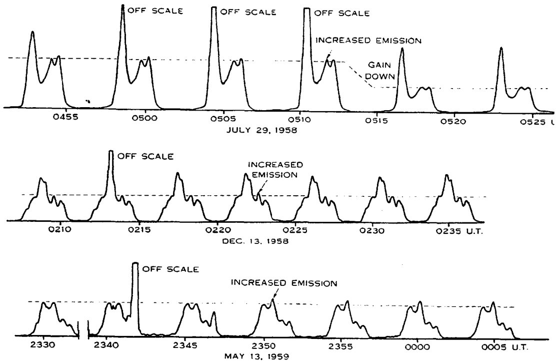


Figure 40: Three sets of Chris Cross E-W strip scans of the Sun showing in each case a burst followed about 10 minutes later by a small enhancement in the level of a quite different radio plage (after Mullaly, 1961: 541).

In 1961 Mullaly also published a short paper in which he reported three cases where a small 1423 MHz burst was followed within 8-9 minutes by a small-scale localised brightening of a distant radio plage (see Figure 40). Mullaly (1961: 541) explains these enhancements:

> The immediate deduction from the observations is that the secondary increases are stimulated by something (e.g. a plasma cloud or a shock wave) propagated from the region of the main burst. The velocity of propagation appears in all cases to lie between 1000 and 2000 km/s ...

Two of the three events were possibly associated with optical surges and Mullaly (1961: 542) noted that Athay and Moreton (1961) recently reported optical observations of what they interpreted as plasma clouds travelling out from the regions of solar flares at velocities between 10^3 and 2.5 x 10^3 km/s. They also mentioned that on some such occasions sudden optical changes were observed in filaments located as far away as 7 x 10^5 km from the original flare site.

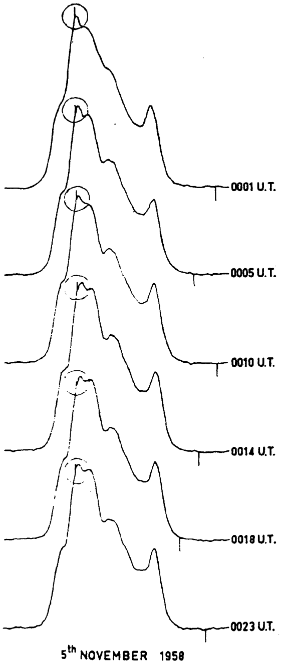


Figure 41: Examples of 'pips' (circled) recorded on successive E-W. Chris Cross scans on 5 November 1958 (after Christiansen and Mullaly, 1963: 173.

The final type of anomalous solar phenomenon discovered with the Chris Cross involved a project that was carried out jointly by Mullaly and the first author of this paper, up until the former suddenly left the CSIRO's Division of Radiophysics in 1962 and joined Christiansen at the University of Sydney. Our planned paper on "Solar Microwave Transients", or 'Pips' as we colloquially called them, never materialised, but they were discussed briefly by Christiansen and Mullaly in their 1963 review paper on the Chris Cross.

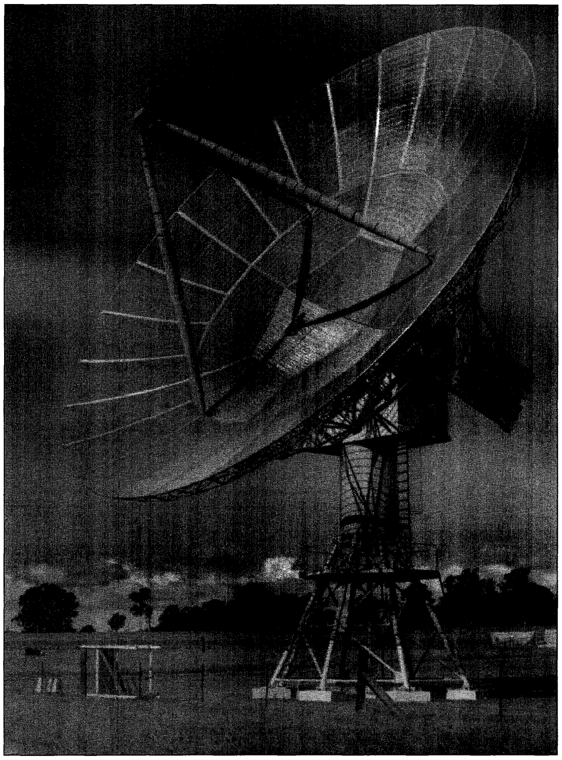


Figure 42: The 18m Kennedy Dish (courtesy ATNF Historic Photographic Archive: B6499-7).

They describe these pips:

> On certain days when continued East-West strip scanning was being carried out it was found that the recorder pen repeatedly exhibited momentary deflections ("pips") when a particular radio plage region was in the aerial beam, but at no other time. (Christiansen and Mullaly, 1963: 172).

Figure 41 shows six successive E-W array scans, and a pip is present on every scan, near the peak of the most intense radio plage. Pips tended to occur in 'pip storms', when 60-100% of all scans showed pips, and always associated with the same radio plage. Some radio plages seemed prone to pips, which occurred repeatedly over a number of successive days.

Pips were always <1 second in duration (the resolving time of the receiver), and in intensity were typically 5-10% of that of the associated radio plage. As for the origin of pips, and the emitting sources:

> Nothing is known of the dimensions of the sources of the transient emission, except that they are not larger than a typical radio plage region. Assuming an angular diameter of 2′ of arc and a duration of 1 second, a typical pip must represent a momentary flash with a brightness temperature of at least 10^5 °K [sic.]. If the diameter is less (as *a priori* seems likely), or the dura-

> tion shorter, the brightness temperature attained could well be much greater than this. (ibid.)

Christiansen and Mullaly (ibid.) note that pips were a feature of the solar maximum. Early in 1960 activity began to decline, and towards the end of that year pips had all but disappeared.

2.6 Non-Solar Astronomy

In 1958 three non-solar staff members from the Division of Radiophysics realised that a high-resolution instrument like the Chris Cross had the potential to contribute to galactic and extragalactic research, and they used the E-W arm of the Cross at 1427 MHz to investigate a number of discrete sources (see Twiss, Carter and Little, 1960; 1962).

Their one-dimensional brightness distribution for Centaurus-A confirmed earlier studies which showed a complex source with "… two bright regions, each of about 2½′ arc between half-intensity points and separated by 5′ arc." (Twiss et al., 1960: 156).

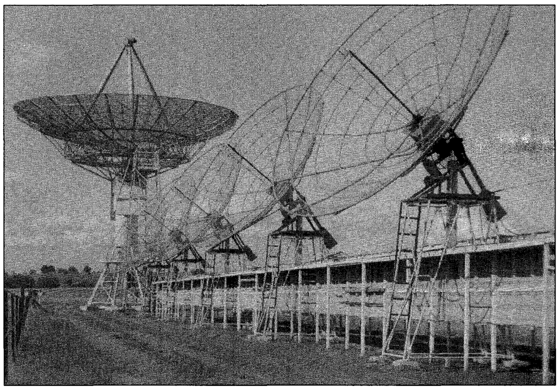


Figure 43: View looking east showing the Kennedy Dish and part of the E-W arm of the Chris Cross (courtesy ATNF Historic Photographic Archive: B6499).

Taurus-A proved to be a single source, with the brightness distribution indicating that nearly all the radiation at 1427 MHz derived from a region about 8′ across. However, observations with the N-S arm of the Cross and also with NE-SW baselines revealed the source to be elliptical, with the major axis at position angle 135° (Twiss et al., 1960: 157). No polarisation was detected Twiss et al., 1962: 386).

A single source was also found to be associated with the Great Orion Nebula:

> The radio source has a simple, approximately Gaussian, shape with a width of 3′ between the points of half intensity. Nearly all the radiation appears to come from a region less than 12′ across. There is some asymmetry and the edge of the source is brighter on the eastern than on the western side. (Twiss et al., 1960: 159).

Cygnus-A was the other discrete source observed with the Chris Cross, but its far northern declination created problems. In general, the results obtained tended to confirm the earlier findings of other researchers.

3 THE FLEURS COMPOUND INTERFEROMETER

In November 1960 the 'Kennedy Dish' (Figure 42), an 18.2m (60ft) American prefabricated steerable parabolic reflector on an altazimuth mounting, was installed at Fleurs 24.4m (80ft, or double the spacing of individual elements of the Chris Cross) beyond the eastern end of the E-W arm of the Chris Cross (Figure 43).[3] When used as a multiplying element with the E-W arm of the Cross it formed the Fleurs Compound Interferometer (FCI) (Figure 44), having a fan beam with a half-power beam width of 1.53′ (see Labrum et al., 1963; 1964). As indicated in Figure 45, the uncorrected polar diagram showed unacceptably high side lobes, but by convolving the observed response with a correcting function these were reduced to <4% of the main response (i.e. curve (b) in Figure 45).

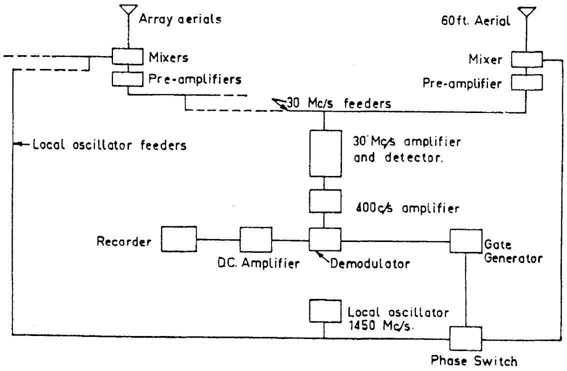


Figure 44: Block diagram of the Fleurs Compound Interferometer receiving system (after Labrum et al., 1963: 151).

From August 1961 until October 1962 (Aerials at "Fleurs" …, 1964) the FCI was used to determine the right ascensions and angular sizes of eight well-known discrete sources.[4] The observational procedure was outlined by Labrum et al. (1963: 151):

> An improvement of √20 times in sensitivity was obtained by recording the passage of each source through 5 successive lobes of the interference pattern, and repeating the whole sequence on 4 nights, thus giving 20 observations which were subsequently integrated. On this basis, the intensity of the minimum detectable point source should be roughly 10×10^{-26}wm^{-2}(c/s)$^{-1}$.

The observations, in each case, were carried out over a period of about one week. The results are summarised in Table 1, and Figure 46 shows the observed E-W profiles of the various sources.

Table 1: Positions and corrected sizes of selected discrete sources observed with the Fleurs Compound Interferometer (adapted from Labrum et al., 1964: 326)

Source	Position (epoch 1960)				Size	
	Right Ascension			P.E.	E-W	P.E.
	h	m	s	(s)	(′)	(′)
Sagittarius-A	17	42	28.8	±0.8	4.1	±0.05
Taurus-A	05	31	27.3	±0.7	3.6	±0.05
Centaurus-A	13	22	16.4	±0.9	2.1	±0.10
	13	22	44.2	±0.9	2.7	±0.10
Omega Neb.	18	17	32.9	±0.7	4.1	±0.05
	18	17	51.3	±1.5	2.5	±0.15
Orion Nebula	05	32	48.9	±0.7	3.4	±0.10
Hydra-A	09	15	41.5	±0.7	0.5	±0.20
Virgo-A	12	28	17.0	±0.7	1.25	±0.15
Cygnus-A	19	57	44.4	±1.0	---	---

Sagittarius-A was of considerable interest in that Drake (1959) had suggested that the position adopted for it by Gum and Pawsey (1960) when recalibrating the new galactic coordinate system was several seconds of arc too far to the east, and that "… the intense main source is associated with a complex of weaker but more extended components." (Labrum et al., 1964: 327 -328). The FCI observations (Figure 46a) confirmed these findings.

High-resolution studies of Centaurus-A by a number of researchers had shown this source to consist of two emitting regions, extending over several degrees in declination, with a bright central core which itself was a double source. The Fleurs observations (Figure 46c) confirmed this, showing the core sources were 5.1′ apart and had E-W widths of 2.1′ and 2.7′.

The E-W profile for the Omega Nebula (Figure 46d) exhibits conspicuous asymmetry which Labrum et al. (1964: 331) attribute to the presence of a weak secondary source about 18 seconds east of the main source. This is listed separately in Table 1.

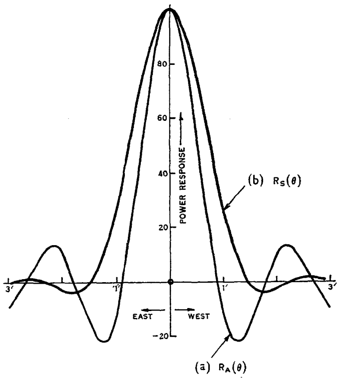
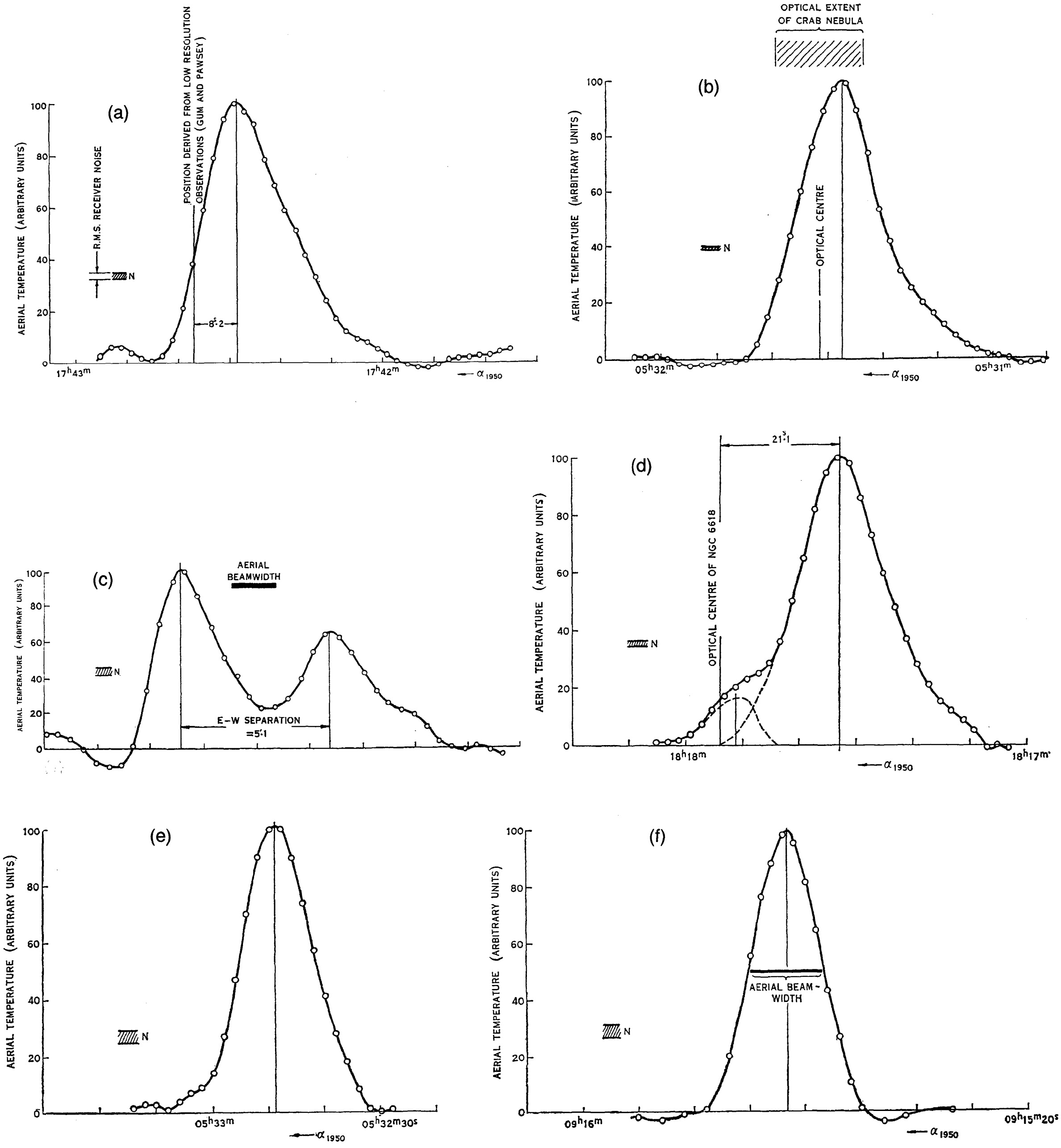


Figure 45: Polar diagrams of the Fleurs Compound Interferometer, showing the uncorrected (a) and corrected (b) curves (after Labrum et al., 1964: 325).



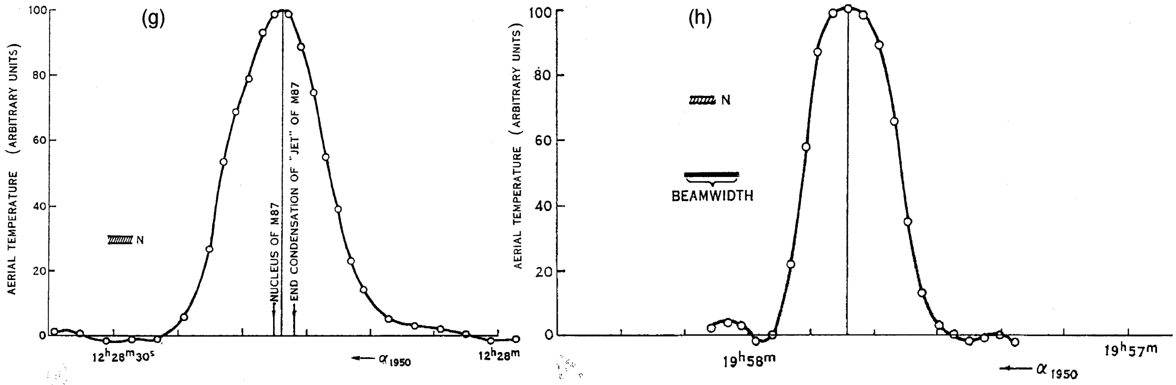


Figure 46: Fleurs Compound Interferometer E-W profiles for the following sources: (a) Sagittarius-A; (b) Taurus-A; (c) Centaurus-A; (d) Omega Nebula; (e) the Great Orion Nebula; (f) Hydra-A; (g) Virgo-A; and (h) Cygnus-A (after Labrum et al., 1964: 328-334).

Earlier reports suggested that the radio source associated with the Great Orion Nebula coincided with the position of θ^1 Orionis, and the FCI observations (Figure 46e) confirmed this.

Virgo-A was another source of particular interest to the FCI team in that

> Shklovskii (1955) suggested that the radio emission from this source originates as synchrotron radiation from the "jet", a structure which extends some 20″ westwards from the optical centre of M87. (Labrum et al., 1964: 332).

The Fleurs observations placed the centre of the radio source between the centre of the galaxy and the end of the jet (Figure 46g), and on the basis of this finding and results reported earlier by other radio astronomers Labrum et al. (1964: 333) supported Shklovskii's conclusion.

The enigmatic source Cygnus-A was also observed with the FCI, but under unfavourable conditions given its far northern declination. It only had an elevation of 15.5° at meridian transit. Consequently

> Tropospheric refraction had an appreciable effect upon the apparent declination of the source, and so on the relative phases of the signals from the array and from the single-aerial element. It was in fact found that the phase changed slightly from night to night, and that it was necessary on each occasion to estimate the phase error from the appearance of a preliminary scan across the source. An empirical phase correction was then made before the beginning of the main part of the record. (Labrum et al., 1964: 333).

Reports by other observers showed the source to be double, with the space between the two components bridged by a broad weak source. The resolution of the FCI was not quite sufficient to show these structural details (see Figure 46h), but by using the *uncorrected* polar diagram and three different models of the source (see Figure 47), useful conclusions were reached:

> … the source has two main components which are both too narrow in the east-west plane to be resolved by the interferometer … [but] where an extended component is included in the model … the east-west spacing of the doublet is found to be 99″. This agrees very well with the work of Swarup … (Labrum et al., 1964: 335).

The Kennedy Dish was relocated to Parkes in 1963 in order to be used in conjunction with the 64m Parkes Radio Telescope, so the Fleurs Compound Interferometer only had a short life. However, it had allowed the Chris Cross to be used of an evening for further non-solar work, and it gave three members of the RP Solar Group (Labrum, Krishnan and Payten) a brief opportunity to dabble in non-solar radio astronomy. Although Christiansen was not personally involved in this work (having already transferred to the School of Electrical Engineering at the University of Sydney), he is acknowledged in both of the Labrum et al. papers (1963 and 1964) for his helpful advice, constant interest and encouragement. In their 1963 paper the authors also make the interesting point that it was Christiansen who initiated the Fleurs Compound Interferometer Project.[5]

4 THE FLEURS SYNTHESIS TELESCOPE

In 1963, after making important contributions to solar, galactic and extragalactic astronomy for twenty years (see Mills, 1984; Orchiston, 2004; Orchiston and Slee, 2002), the Fleurs field station became surplus to RP requirements and was closed down. This followed the relocation of the Kennedy Dish to Parkes and the consolidation of the Division's galactic and extragalactic research at Parkes.

The initial plan was to demolish the Mills Cross, Shain Cross and Chris Cross, but after representations from the University of Sydney a decision was made to simply transfer the site lease to the University. This officially occurred on 1 July 1963, when all of the equipment remaining at the site was also formally handed over to the University.

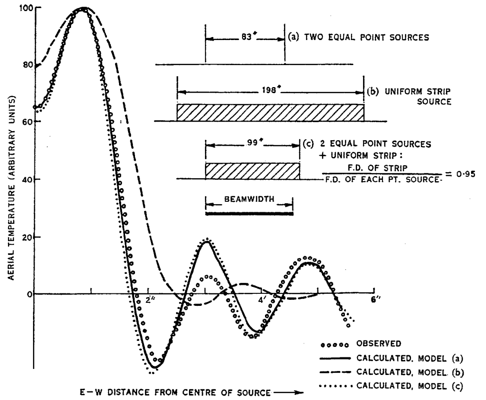


Figure 47: Fleurs Compound Interferometer observations of Cygnus-A (small circles) compared with three different source models (a), (b) and (c) (after Labrum et al., 1964: 335).

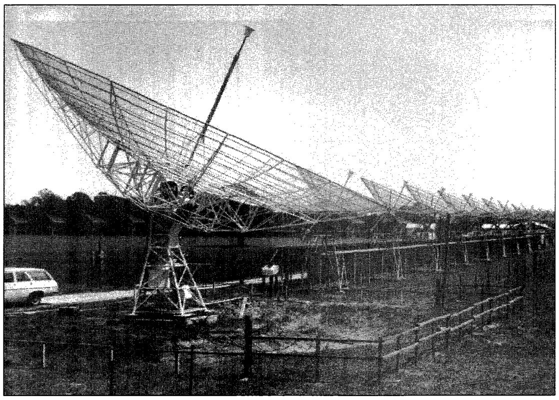


Figure 48: One of the Fleurs Synthesis Telescope's 13.7m antennas, located at the eastern end of the Chris Cross (courtesy ATNF Historic Photographic Archive: 9097-11).

This initiated a new era in the site's history, and although regular Chris Cross solar observations were continued (Christiansen, 1967)—but on a somewhat curtailed scale—Christiansen's main effort went into converting the Chris Cross into the Fleurs Synthesis Telescope (FST). This ambitious project would occupy staff from the School of Electrical Engineering and their graduate students for the next two decades and result in a radio telescope comprising the original Chris Cross and six stand-alone 13.7m parabolic antennas (Figure 48) with a 20 arc second beam (see *The Fleurs Synthesis Radio Telescope*, 1973). During the 1970s and 1980s the FST was used to study large radio galaxies, supernova remnants and emission nebulae.

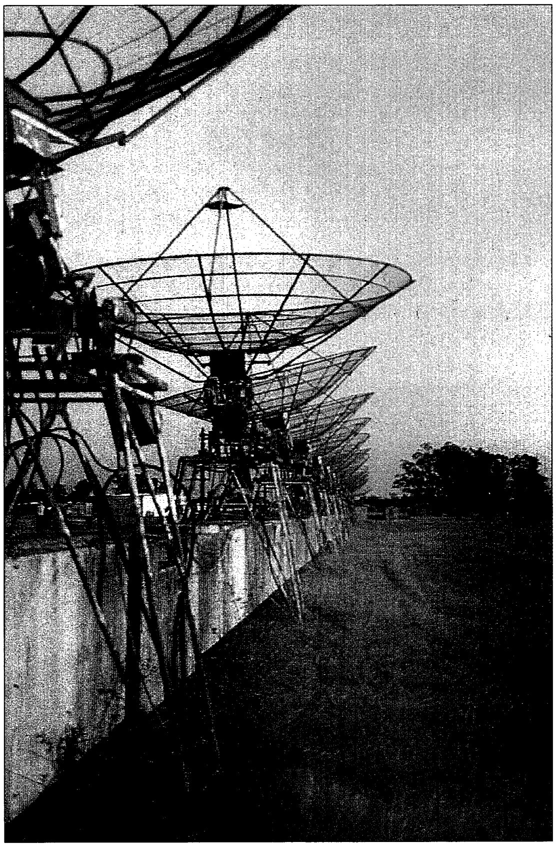


Figure 49: A view looking south along the N-S arm of the decommissioned Chris Cross showing rusting antennas (courtesy John Leahy).

A detailed account of the FST and Christiansen's pivotal role in its planning, development and use will be presented by Miller Goss in a later issue of this journal.

5 THE DEMISE OF FLEURS

The Fleurs Synthesis Telescope was closed down in 1988, bringing to an end 34 years of research into solar, galactic and extra-galactic radio astronomy at Fleurs, and the site was transferred to the Engineering Faculty at the University of Western Sydney to serve as a teaching facility for undergraduate students. In the mean time, the Mills Cross and the Shain Cross rapidly deteriorated, and the Chris Cross dishes and larger antennas of the Fleurs Synthesis Telescope continued to rust (Figure 49).

In 1990 the University of Western Sydney recognised the historical importance of the Fleurs field station, and a decision was made to restore one of the 13.7m Fleurs Synthesis Telescope antennas and the twelve centrally-located Chris Cross antennas, but to remove all of the other Chris Cross antennas and superstructure from the site. It was also decided that a section of the Mills Cross should be reconstructed.

Staff and undergraduate students worked diligently on this project, and by 22 November 1991 all was ready for a ceremony to mark the refurbishment of these historic radio telescopes (Figure 50). It was only appropriate that one of the speakers on this occasion was Professor W.N. Christiansen (see Figure 51).

In 1998, the Fleurs field station again became surplus to requirements and was closed down by the University of Western Sydney. This brought into sharp focus the long-term future of the remaining elements of the Fleurs Synthesis Telescope, including the twelve refurbished Chris Cross antennas.

6 DISCUSSION

6.1 The Chris Cross in International Context

By mid-1957, when the Chris Cross became operational, a number of others nations were actively engaged in solar radio astronomy, but with instrumentation that was relatively less sophisticated than that used by the Division of Radiophysics in Australia.

Britain and Australia were the leading radio astronomy nations in the decade following World War II, and although some solar work was carried out in Britain using 2-element interferometers (see Smith, 2007), the main focus of research at Jodrell Bank and Cambridge was meteors, and galactic and extragalactic sources.

In contrast, Canada was one nation that specialised in solar radio astronomy, beginning in 1946. The following year the Goth Hill Radio Observatory was founded, which featured a small steerable dish and a slotted waveguide array. By January 1956 this array and an adjacent array had been developed as a compound interferometer with a 2.4′ fan beam (see Covington, 1984).

Another nation to focus on solar radio astronomy was Japan. The earliest observations were carried out in 1949 with a steerable horn at Osaka University and a small broadside array at the Tokyo Astronomical Observatory at Mitaka. A 10-m dish was erected at Mitaka in 1953, and in this same year a 5-element grating array developed by Nagoya University was operational at Toyokawa. In 1954 this was extended to an 8-element array. However, Tanaka (1984: 340) stresses that the first grating array "…was planned and built quite independently of the one developed by Christiansen …"

Solar radio astronomy was initially also the focus of the French radio astronomy teams at the École Normale Supérieure and the Institut d'Astrophysique in Paris. In 1954 the former team transferred to the Paris Observatory. Early observations were made mainly with small steerable dishes and recycled WWII Würzburg antennas (see Orchiston and Steinberg, 2007; Orchiston, et al., 2007; Orchiston, et al., 2009), but by 1957 two multi-element E-W grating arrays—inspired by Christiansen's efforts at Potts Hill—were operational at Nançay (see Denisse, 1984).

In post-war Netherlands, the main interest of the fledgling radio astronomy group was galactic and extragalactic research, especially that associated with the 21cm hydrogen line (Van Woerden and Strom, 2006), but the Government's Post, Telephone and Telegraph department ran a multi-wavelength solar monitoring program using two ex-WWII Würzburg antennas, a 10-m dish, a corner reflector and a simple 2-element interferometer (see Strom, 2005).

One other nation to intensively research solar radio astronomy in the decade following WWII was the Soviet Union, commencing with solar eclipse observations in 1947. The following year radio astronomy began at the P.N. Lebedev Physical Institute, and by the mid-1950s a number of solar radio telescopes were operational. These comprised stand-alone dishes—including a Würzburg antenna (Dagkesamanskii, 2007)—and interferometers, some of novel design. One of these was the Big Pulkovo Radio Telescope, which began operations in 1956 under the auspices of the newly-formed Department of Radio Astronomy at the Main Astronomical Observatory in Pulkovo (Parijskij, 2007). Other institutes which ran solar radio astronomy research programs in the mid-1950s were the Byurakan Astrophysical Observatory in Armenia; the Crimean Astrophysical Observatory; the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation in Moscow; and the Radiophysical Research Institute in Gorky (see Salomonovich, 1984).

This brief review reveals that by 1957 a number of nations had grating interferometers analogous to the Potts Hill arrays, but the first institution to develop a crossed-grating interferometer like the Chris Cross was Stanford University in the USA. This became operational in 1960, and is discussed in Bracewell and Swarup (1961) and Bracewell (2005).

6.2 Heritage Considerations

Between 1945 and 1965, at one time or another the CSIRO's Division of Radiophysics maintained radio astronomy field stations at Badgerys Creek, Bankstown Airport, Dover Heights, Fleurs, Georges Heights, Murraybank, Penrith, and Potts Hill in or near Sydney, and at Dapto near Wollongong, and a number of associated remote sites near Sydney and up and down the New South Wales coast (see Orchiston and Slee, 2005; Stewart, 2009; Wendt, 2008). In 2004, one of us (WO) wrote:

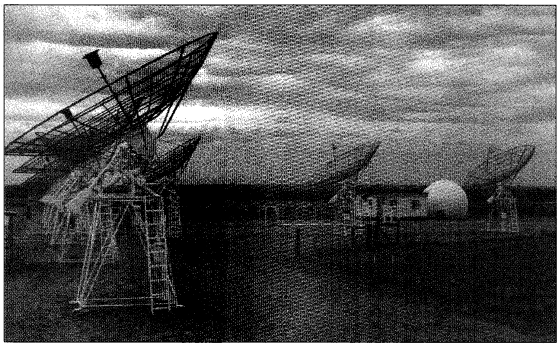


Figure 50: A view looking west showing nine of the twelve refurbished Chris Cross antennas (courtesy John Leahy).

> Important radio telescopes, many of novel design, were sited at these field stations, and pioneering studies were undertaken in solar, galactic and extra-galactic radio astronomy. It is a sobering fact that of all of these radio telescopes, the only ones that have managed to survive through to the present day are the twelve central elements from the Chris Cross at Fleurs. (Orchiston, 2004: 161).

It is frightening to realise that later that very year the twelve restored Chris Cross antennas were bulldozed (Figure 52), highlighting the extreme vulnerability of our radio astronomical heritage. Most optical telescopes that have made important contributions to science are cherished and preserved for posterity, but the same sentiment rarely applies to radio telescopes. All too often, they are viewed merely as tools used to address specific research problems, and their importance as heritage instruments *per se* is ignored. If we are to make any progress in preserving our radio astronomical heritage we must urgently address and reverse this prevailing mind-set.

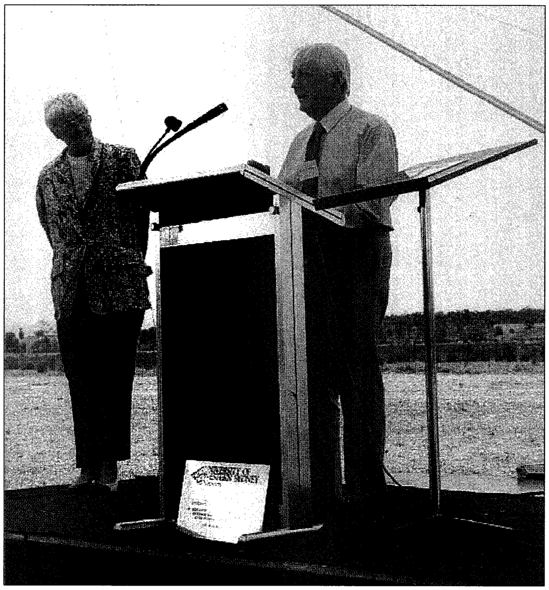


Figure 51: Professor Christiansen speaking at the 22 Novemsber 1991 ceremony at Fleurs (courtesy John Leahy).

The Chris Cross may have disappeared entirely from the Fleurs landscape, but by a strange twist of fate at least two of the aerials have survived in close to their original condition (see Figure 53). They were acquired from the University of Western Sydney by amateur astronomer and SETI enthusiast, Leon Darcy, and are now located at Bungonia in the Southern Highlands of New South Wales where they are used for interferometry (D. Whiteman, pers. comm., 2004). In addition, the Astronomical Society of New South Wales has been restoring a Chris Cross antenna which is located at their Wiruna Dark Sky Site a 3hr drive west of Sydney (see www.asnsw.com/wiruna/rt.asp).

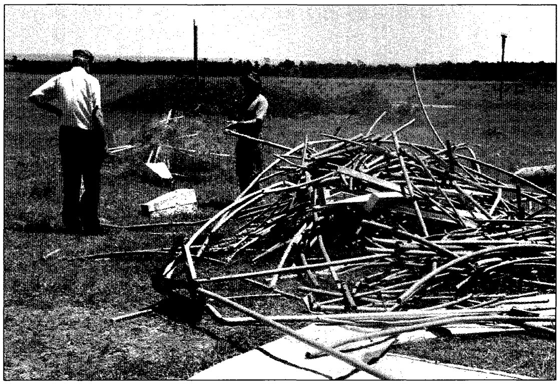


Figure 52: The bulldozed remains of some of the preserved Chris Cross aerials (courtesy John Leahy).

7 CONCLUDING REMARKS

The Chris Cross is a remarkable radio telescope with a memorable history. When constructed in 1957 it was the world's first cross-grating interferometer, and the first radio telescope to provide daily two-dimensional radio maps of the Sun. Its obvious research potential and innovative design subsequently inspired the construction of similar radio telescopes in other countries.

Despite this, with the benefit of hind-sight, Christiansen (1984: 124) had a rather modest perception of the significance of the solar investigations carried out with the Chris Cross:

> They led to a better understanding of the Sun's outer atmosphere, but to no spectacular discoveries. Their real excitement was in the development of new instruments superior in resolving power to any in existence.

We think he was a tad too modest!

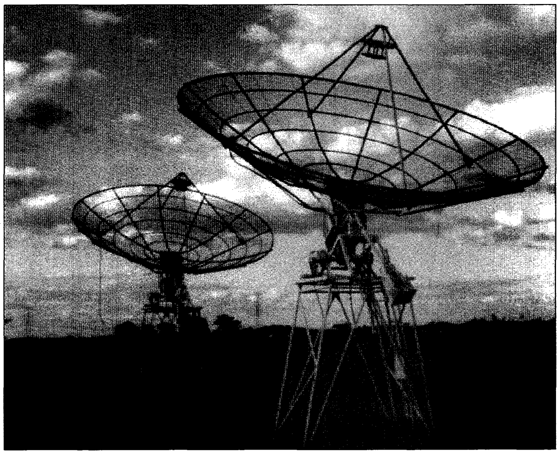


Figure 53: Leon Darcy's 2-element interferometer at Bungonia, which utilises two ex-Chris Cross antennas and mountings (courtesy Don Whiteman).

As a significant component of the Fleurs Compound Interferometer and, later, the Fleurs Synthesis Telescope, the Chris Cross also played a key role in international non-solar radio astronomy, providing new perspectives on discrete radio sources, but particularly large radio galaxies, supernova remnants and emission nebulae.

With the advent of The Australia Telescope in 1988 the FST was closed down as a research instrument, but it did serve for a time as a teaching instrument. However, the various antennas continued to rust, and in 1991 a decision was made by the then custodians of the array to restore and preserve the twelve antennas at the centre of the Chris Cross along with one of the six 13.7m FST antennas. Yet this only served as a temporary reprieve: the Fleurs field station was finally closed in 1998 and less than a decade later the landowner made a unilateral decision to bulldoze the restored Chris Cross antennas and their mountings, thereby bringing to a sudden and tragic end one of the world's most remarkable solar radio telescopes. Subsequent to this inglorious event, two of the 13.7m FST antennas were relocated to the Australia Telescope National Facility headquarters at Marsfield, Sydney (as part of SKA experimentation), and all that now remains at Fleurs to remind visitors of the invaluable contributions that the Chris Cross, Mills Cross and Shain Cross made to international radio astronomy (see Orchiston and Slee, 2002) are the four remaining rusting large dishes associated with the FST.

8 NOTES

1. In the past, both authors had close associations with the Chris Cross. Don Mathewson was involved in the construction and early operation of the Cross, while Wayne Orchiston used the Cross and produced the daily solar maps during the final year that this radio telescope was maintained by the CSIRO's Division of Radiophysics, before it was handed over to the University of Sydney.
2. "Taffy" was Dr E.G. (Taffy) Bowen, Chief of the Division of Radiophysics.
3. The original plan was to install the Kennedy Dish at the Murraybank field station, and use it for H-line research (see Wendt, 2008).
4. By the time routine Fleurs Compound Interferometer observations began, Christiansen had already left the Division of Radiophysics and accepted a Chair in the School of Electrical Engineering at the University of Sydney. For the background to this transfer see Sullivan (2005).
5. This is discussed in the letter reproduced here in the Appendix.

9 ACKNOWLEDGEMENTS

We are grateful to the Australia Telescope National Facility, Dr John Leahy (CSIRO Telecommunications and Industrial Physics) and Don Whiteman (Astronomical Society of New South Wales) for kindly supplying Figures 1, 3, 8-10, 12-14, 18-21, 31, 38, 42-43 and 48-56. We also wish to thank Professor Bruce Slee (Australia Telescope National Facility, and Centre for Astronomy, James Cook University), Ron Stewart (Centre for Astronomy, James Cook University), Professor Richard Strom (ASTRON, the Netherlands, and Centre for Astronomy, James Cook University) and Dr Harry Wendt (Centre for Astronomy, James Cook University) for reading and commenting on the manuscript.

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11 APPENDIX

The following letter, dated 15 September 1960, from Professor W.N. Christiansen to Dr E.G. Bowen, discusses the development of the Fleurs Compound Interferometer, and is reproduced here in full.

> Dear Dr Bowen,
>
> At your suggestion, and before I leave for Holland, I am setting down the arrangements which were made in connection with the new multi-aerial interferometer at Fleurs, on which I was working before I left the Division of Radiophysics. These arrangements were made at a meeting in May at which you and Dr. Pawsey and I discussed the possibility of co-operation in research between your Division and the School of Electrical Engineering at the University of Sydney. At this meeting we decided that I should have no responsibility for the solar work being conducted at Fleurs but should be available for advice if required.
>
> We decided, also, that the new project, which involves a combination of a grating interferometer with a 60′ paraboloid and the extensive use of preamplifiers to improve the sensitivity of the equipment, should be carried out jointly, under the direction of Dr. Pawsey, by your Division and the School of Electrical Engineering. The purpose of this work is to produce a system which has a single fan-beam of angular dimensions ′ × 1° and adequate sensitivity (roughly equal to that of the two-aerial interferometer of the California Institute of Technology) for a detailed study of the shapes of radio sources.
>
> The time-table which was suggested involved about one year's observations after the completion of the instrument. It was thought probable that, at the end of this time, the 60′ paraboloid would be removed to Parkes.
>
> I consulted the Vice-Chancellor of the University on this co-operative venture and obtained his approval. Subsequently I arranged for two people on the lecturing staff of the School, Murray and Docherty, to work on this project. So far they have spent what time was available to them on the aspects of the work which involve the measurement and adjustment of the relative phases of the different aerials of the system. In addition I have obtained the approval of the Vice-Chancellor to engage an electrical technician for a period of one year; the technician will spend all of his time on this project.
>
> It appears that good progress has been made on the project, and I am confident that it will be successful. I hope that it will provide a pattern for future co-operative ventures of the Division of Radiophysics and the School of Electrical Engineering.
>
> Yours sincerely

Dr Wayne Orchiston is a Reader in the Centre for Astronomy at James Cook University, and is particularly interested in the history of radio astronomy in Australia, France and New Zealand. He is editor of the book *The New Astronomy: Opening the Electromagnetic Window and Expanding our View of Planet Earth* (Springer, 2005) which contains various papers on the history of radio astronomy, and chairs the IAU Working Group on Historic Radio Astronomy.

Don Mathewson joined Chris Christiansen at Fleurs in 1955, and helped him build the Chris Cross. Don lived at Fleurs with the Division of Radiophysics construction team, comprising Charlie Chenhall, Sid Hucker, Bill and George Coulter and Charlie Turrell. One of the proudest moments in Don's life was when he was invited into St. Marys to join them for their after-work beers and later to share their evening meals in a gypsy-style caravan parked on site at Fleurs. Life was not exactly 'a bed of roses': ten-hour days were the norm; the tents were draughty; there was only rainwater on site; an overhead bucket with a tap served as a shower, although everybody mostly used a large wash basin on the tank stand; a chocolate wheel was our toilet; all meals were cooked on 'Elsie' an old woodstove sheltered from the elements by corrugated iron; and any differences were settled by fisticuffs, generally after dinner—all very gentlemanly (and all very Australian)!

Don left Fleurs in August 1958 and presented some of the Chris Cross results at the Paris Symposium on Radio Astronomy. Then he spent several years at Jodrell Bank using the newly-commissioned 250ft Dish. During this time he visited Bologna University three times as a consultant for the Italian Northern Cross antenna which was inspired by the Chris Cross.

Returning to Australia, Don went back to Fleurs with two physics students, John Healey and John Rome, and used the 60ft (Kennedy) Dish at the eastern end of the Chris Cross to survey the Milky Way at 20cm. Later this map was regularly used as a finding chart for the Parkes Dish.

After three years at Parkes, Don worked in the US and Holland and then joined Mount Stromlo and Siding Spring Observatories, which he directed from 1977 to 1986. In 1995 he was farewelled at the Heron Island Workshop on Large Scale Motions in the Local Universe, although he remained active in astronomy as a Vice President of the IAU.

Journal of Astronomical History and Heritage, 12(1), 33-38 (2009).

PERSONAL RECOLLECTIONS OF W.N. CHRISTIANSEN AND THE EARLY DAYS OF CHINESE RADIO ASTRONOMY

Wang Shouguan
National Astronomical Observatory, Chinese Academy of Sciences,
A20 Datun Road, Chaoyang District, Beijing 100012, China.
Email: shouguanwang@yahoo.com.cn

Abstract: Between 1963 and 1998, Professor W.N. Christiansen visited China more than a dozen times, bringing valuable scientific information, expert guidance and all possible help to the young Chinese radio astronomy team. Here, the writer presents his memories of two typical, deeply-shared experiences, 'The Shahe Experiment' and 'The Making of the Miyun Meter Wave Aperture Synthesis Telescope', as expressions of the kind thoughts of a whole generation of Chinese researchers in astronomy.

Keywords: W.N. Christiansen, Prof. Ke, Chinese radio astronomy, the Shahe Experiment, the Miyun Aperture Synthesis Telescope

1 FOREWORD

Childhood memory is precious. The 'childhood'—or early days—of Chinese radio astronomy went through unusual trials and tribulations. The first team of Chinese researchers in radio astronomy, so very young at the time, and so deeply engulfed in stormy weather during their first steps, will hold dear in their memory the arrival of a senior colleague from the West. During this period, W.N. Christiansen (affectionately known by us as 'Prof. Ke', 'Ke' being the first of the five Chinese characters that transcribe his surname) made the long journey to us more than a dozen times (see Figure 1), and brought to us valuable scientific information, specialist guidance and assistance.

The memories of our discipline's infancy are still fresh with us, and our feelings cannot be expressed by ordinary words. Here, we recall a couple of the most typical events, as emissaries carrying the thoughts of an entire era.

2 RECOLLECTIONS OF THE SHAHE EXPERIMENT

Prof. Ke visited China for the first time in 1963. At that time, the Chinese Academy of Sciences' Beijing Observatory had a site in a Beijing suburb, Shahe, and the Radio Astronomy Section had installed there two cm-wave solar radiometers, copies of ones then in Soviet Russia.

In the early 1960s, our contact with Russia had fallen to a low ebb, and our contact with the West was nil. Members of our team at that time, with one or two exceptions, were all young people in their early 20s. In line with the whole of China, we subscribed to the slogans, 'Self-Renewal Through Self-Effort' and 'March Into Science'. However, electronics in China was just being born, and if we were to pull ourselves up by our own boot straps the only option that was technically feasible at all was working at meter wavelengths.

Figure 1: Beijing 1987. Professor and Mrs Christiansen with the then young Chinese team of radio astronomers.

Figure 2: View of the central part of the Chris Cross, looking west at sunset. This array comprised E-W and N-S arms each with 32 steerable parabolic antennas of 5.8m diameter. This was the world's first crossed-grating interferometer and it was used to produce daily isophote maps of solar emission at 1423 MHz (photography courtesy John Leahy).

After going over the problem again and again, we opted to start with solar observations at meter wavelengths, and we considered constructing a copy of the Chris Cross (Figure 2) which Professor W.N. ('Chris') Christiansen had erected at Fleurs near Sydney (Australia) in 1957 (see Christiansen et al., 1961; Orchiston and Mathewson, 2009).[1] In 1963, we were working on the 32 antennas specified in the project, having basically decided on the site for the antenna array, but we had not solved the key technical problem of the transmission lines. At that time, China still could not produce co-axial cables, and they were hard to import from Russia or from Eastern Europe. And, in particular, none of us had any idea on the overall technology of the antenna array. So, when we were told that Professor Christiansen, the inventor of the Chris Cross, was coming to visit us, it was like a happiness that had fallen from heaven.

Our joy was redoubled by a fact known to all: the Chinese scientific community at the time had been cut off from the West for more than a decade, as though we were sealed inside an hermetic wall. And this was the first time that a small door would open in this wall, and who should come through that door but the very man we most wanted to meet, Professor W.N. Christiansen!

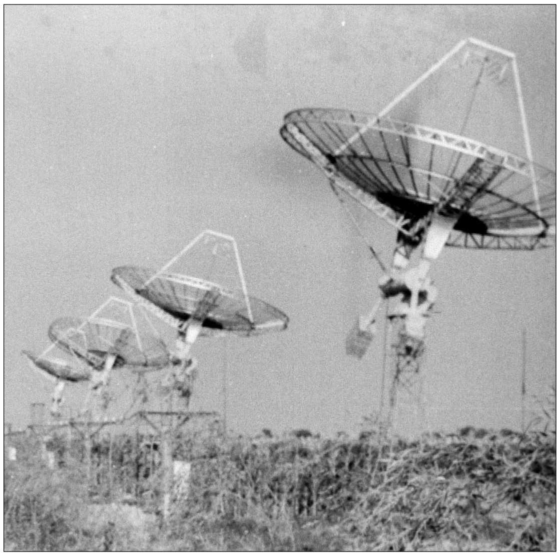

Figure 3: The four-antenna Shahe test array.

After a brief meeting, the Professor invited the author to visit Australia, and in 1964 Dr Wu Huai-wei and I took up this invitation and went to Sydney. At that time there were no diplomatic relations between China and Australia, so we stayed in Professor Christiansen's home and at the Hall of Residence at the University of Sydney.

During this trip, we made a point of visiting all of the radio astronomy establishments in Australia (but especially Fleurs), and we got an inkling of the scientific developments of the time and established many useful contacts. We discussed in detail with Prof. Ke ways of developing radio astronomy at the Beijing Observatory, and we arranged for Prof. Ke to visit us again in 1965 in order to help us with some of the technical challenges of the antenna array.

In 1965 we installed four 6-metre antennas at Shahe (Figure 3), so that we could carry out 'interim tests'. As soon as Prof. Ke arrived, he guided us to start building the twin wire transmission line system that he himself had specially designed, using a material which we could easily obtain at that time, copper wire. Two parallel copper wires of 4mm diameter made up the transmission lines, and the copper tubes that encased the wires were used to make an 'adder' that added up two radio frequency signals, and a connector that served as a 'matching transformer' between the cable and the copper tube. And there was the detector Prof. Ke himself designed for testing stationary waves. By left-right sliding movements of the adder the relative phase of the two signals was adjusted, thereby completing the 'two-two addition'.

When the Shahe Experiment was entering its final stage, China began sliding into a 10-year period of chaos, and all work was derailed, and even stopped completely at one stage. Nevertheless, by 1967 a meter wave 'Christiansen array' of 16 east-west elements was installed at the new Miyun Observing Station, and test observations produced the first one-dimensional maps of the Sun. Originally the aim was to erect a 32-element crossed-grating interferometer (similar to the Fleurs one), but we had to revise this plan and ended up with the 16-element array instead.

The realisation of the twin-wire transmission line system marked not only the completion of the new radio telescope, but equally important, it taught us (complete 'new hands' at the game) a profound lesson: by making the best of the situation, one can successfully carry out scientific research under difficult conditions. And this is precisely what we understood by the term 'Christiansen Style'.

3 THE MAKING OF THE MIYUN METER WAVE APERTURE SYNTHESIS TELESCOPE

After 1966, work at observatories throughout China stopped for a time, but the situation relaxed somewhat during the 1970s and from time to time we were able to carry out some work at the Miyun Observing Station. During this period, Prof. Ke came to China many times to bring us news of developments in radio astronomy abroad. And whatever little work we could do at the time always got support from him (on occasions he even brought us small electronics components that we needed). When in 1973 we heard the news that the Fleurs array was being converted into an aperture synthesis instrument,[2] we felt that once work resumed at Miyun this would also be the best goal for our endeavour. During one of Prof. Ke's visits we discussed this idea in detail, and the Professor then made a move that was most extraordinary at the time: he proposed that China send two radio astronomers to Australia on a cultural exchange. As a result, in 1975 two members of the Miyun team, Drs Chen Hong-shen and Ren Fang-bin, spent eight months based in the School of Electrical Engineering at the University of Sydney where they learnt about the hardware associated with the analogue receiver system of the Fleurs Aperture Synthesis. This provided, ahead of time, useful preparation for our later work.

The year 1976 saw the end of chaos in China and order was gradually restored at Miyun. Our first task was to convert the Miyun array into an Earth-rotation aperture synthesis instrument. Originally 32 antennas had been constructed when we began making the Miyun array, but many of these found their way to various locations in China during the years of unrest. Fortunately, we managed to track down most of these surplus antennas and bring them back to the Miyun Observing Station, ending up with a 28-element east-west array (Figure 4), where the diameter of each aerial was increased from 6 metres to 9 metres.

The making of the Miyun Aperture Synthesis Telescope was a gradual process. We started at a very low point, when the material conditions were difficult and the technological base was weak. But we had made preparations beforehand, and our target was clearly defined (as during the earlier Shahe period), so by making the best of a very difficult situation and bringing out our hidden potential we were able to keep forging ahead. The main problem at this time was the introduction of digital techniques and solving the complicated problem of data processing. Here, again, we had Prof. Ke's whole-hearted support. In 1979, he sent his research student, Dr C.K. Kwong, to Beijing to help set up a digital receiver, and in 1980 he again invited two Miyun colleagues, Drs Chen Hong-shen and Zheng Yi-jia to Sydney to familiarize themselves with the software and hardware of the Fleurs Synthesis Telescope.

At this point the blueprint of the Miyun Meter Wave Aperture Synthesis System was finalized, but it then took another four years to complete the experimentation, installation and testing.

The Miyun Aperture Synthesis Telescope consists of 28 antennas each of 9m diameter, divided into Array A (16 antennas) and Array B (12 antennas) arranged as shown in Figure 5), making up 192 interferometer pairs, with baselines 3do, 4do, ... 194do (where do = 6 m). The system works at two frequencies, 232MHz and 408MHz. At 232MHz, each cycle of 12 hours' observation gives an overall resolution of 3.8 × 3.8 arc min. csc δ, and a 'thermal noise limited' sensitivity of 0.05Jy (SNR= 6) covering a field of 8 × 8 square degrees.

Now, when we recall this series of efforts, we recognize it to be precisely what enabled the Miyun team to pass the starting line of technological modernization, and throughout this eventful journey, which lasted ten years, we benefited from the guidance and concern of our good teacher and friend, Prof. Ke.

The Miyun Meter Wave Aperture Synthesis Telescope was formally commissioned in 1984 (see Wang, 1986), and Prof. Ke made a special journey to take part in the appraisal of the Facility. He and other Appraisal Committee members are shown in Figure 6.

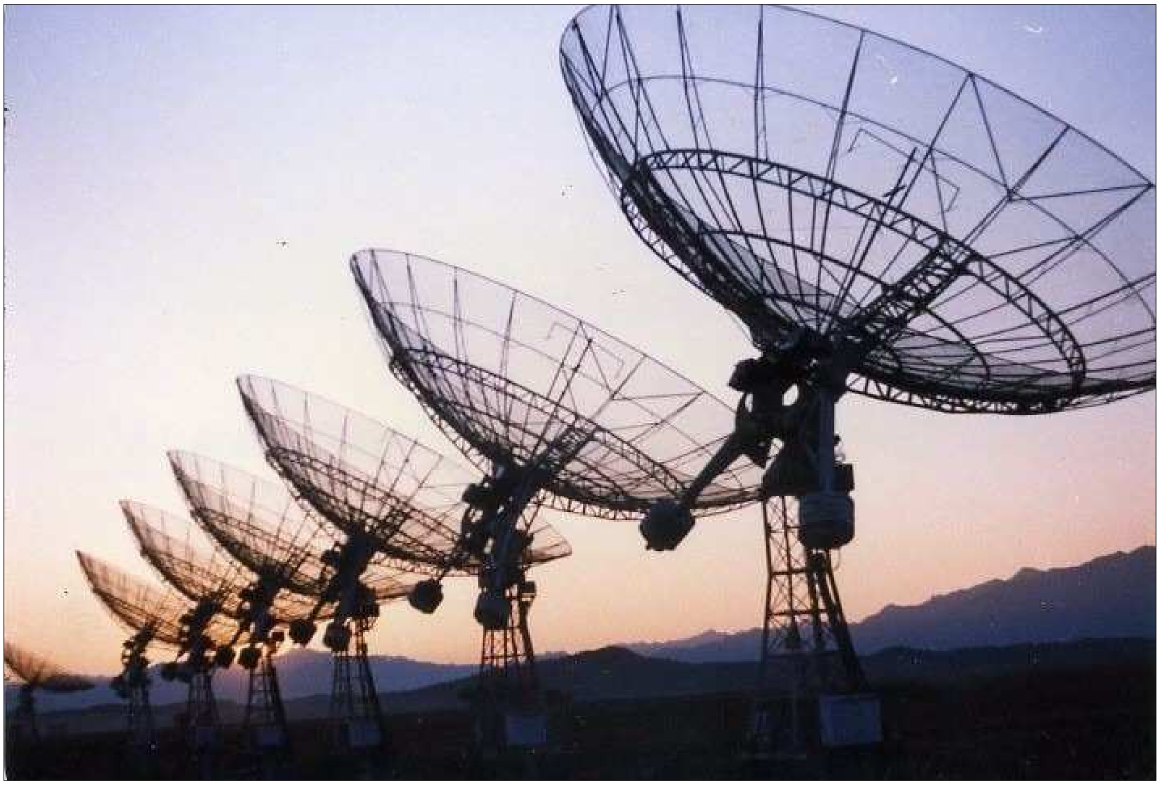

Figure 4: The Miyun 28-antenna Meter Wave Aperture Synthesis Array.

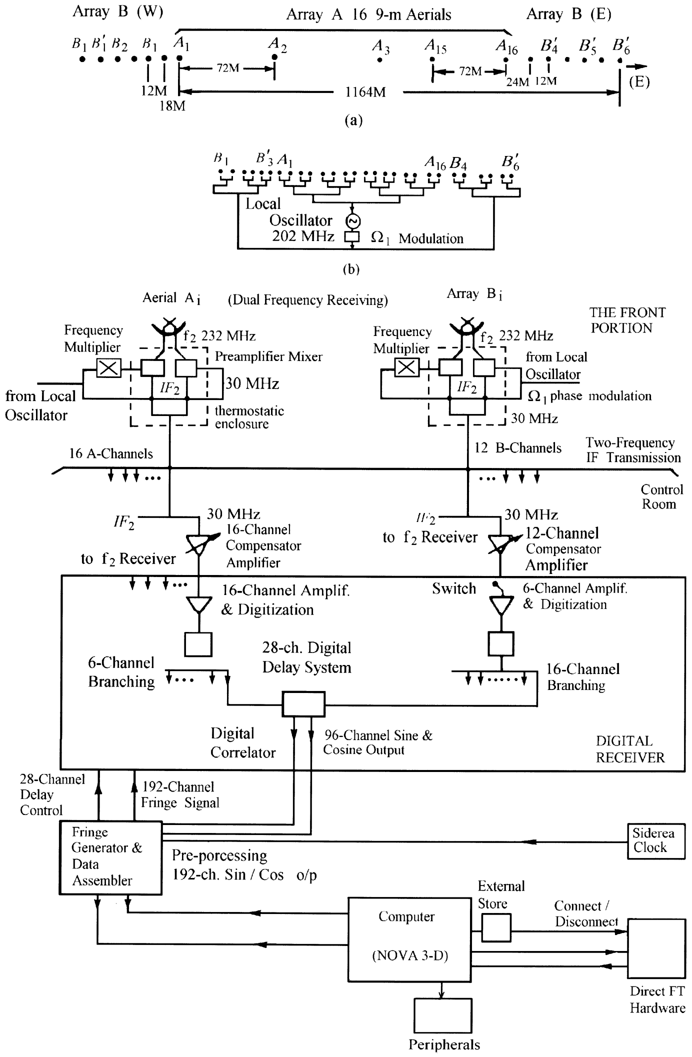

Figure 5: A structural overview of the Miyun Aperture Synthesis Telescope system.

4 PROF KE AND THE CHINESE ACADEMY OF SCIENCES (CAS)

Although just two examples may not do full justice to the history of ‘Prof. Ke and China’, which spanned more than a third of a century, these two examples are typical, and are so deeply and indelibly impressed in our memories that they serve to illustrate the impact of his strong personality on our hearts and his contribution to the establishment and growth of radio astronomy in China. Over thirty-plus years, he became familiar with all of China’s astronomical institutions and their radio astronomy divisions. Besides Beijing Observatory, the Purple Mountain Observatory, Shanghai Observatory, Yunnan Observatory and the Urumqi Astronomical Station all kept records of the many lectures and visits by Prof. Ke, and of the numerous astronomers (and not just radio astronomers) from various places in China who visited Australia over the years and enjoyed kind hospitality and concrete help from Prof. and Mrs Ke. Furthermore, Prof. Ke encouraged other Western radio astronomers to come to China, and many of them—including Rob Frater, Miller Goss, George Miley, Bruce Slee and Richard Wielebinski—have established deep friendships with us. Like Prof. Ke, many of them made personal efforts to help China move out of isolation and rejoin the international astronomical community. Prof. Ke also, through his personal influence in international academic circles, did much to help return China to such international organizations as the IAU, URSI and the ICSU.

Prof. Ke’s deep friendship towards China was not confined to the Miyun radio astronomy team, or even to the Chinese astronomical community. His academic distinction and his sincerity elicited widespread respect and admiration in the wider scientific community. Apart from his aforementioned dealings with astronomers, especially the younger ones, many scientists from our older generations, including Go Moruo, Y.H. Woo and Chou Peiyuan, became close personal friends of his. Figure 7 is an historically-significant photograph. It was taken in the 1960s and although rather ‘formal’, it records some of these ‘older scientists’—who were not very old then—in company with Prof. and Mrs Ke.

In recognition of his long and important contribution to Chinese astronomy, in 1996 Professor Christiansen was elected a Foreign Member of the Chinese Academy of Sciences.

Figure 6: The Appraisal Committee of the Miyun Meter Wave Aperture Synthesis Telescope.

Figure 7: Professor and Mrs Christiansen with Go Moruo, the first President of the Chinese Academy of Sciences (sixth from left), Y.H. Woo, physicist and Vice-President of the Chinese Academy of Sciences (fourth from left), Chou Peiyuan, physicist and President of Peking University (third from left) and the astronomer Tcheng Mao-lin (second from left).

5 CONCLUDING REMARKS

I would like to conclude this short article with two photographs taken during the Ninth Assembly of Members of the CAS in 1998 (Figures 8 and 9 on page 38), for this was to be the last of the many occasions when Prof. Ke was with us (since 1963).

Let these solemn records convey from all of us—friends in a country that he loved—our deepest feelings for him as we look on the passing of history.

6 NOTES

1. Christiansen was on the staff of the CSIRO's Division of Radiophysics in Sydney when the Chris Cross was built, but in 1960 he moved to a Chair in Electrical Engineering at the University of Sydney.
2. For details of the Fleurs Synthesis Telescope see the various papers in the September 1973 special issue of the *Proceedings of the Institution of Radio and Electronics Engineers Australia* (Vol. 34, No. 8).

Figure 8: Professor Christiansen (front row, second from left) at the Ninth Assembly of Members of the Chinese Academy of Sciences in 1998, during his last visit to China.

Figure 9: Professor Christiansen speaking at the Ninth Assembly of Members of the Chinese Academy of Sciences.

7 ACKNOWLEDGEMENTS

I am grateful to Dr John Leahy (through Dr Wayne Orchiston) for kindly supplying Figure 2, and to Dr T. Kiang for translating this paper from Chinese into English.

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Wang Shouguan is a member of the Chinese Academy of Sciences and a Research Professor at the National Observatories. He was formerly Director of the Beijing Astronomical Observatory and leader of the first team of Chinese researchers involved in radio astronomy.

Journal of Astronomical History and Heritage, 12(1), 39-59 (2009).

THE DUNHUANG CHINESE SKY: A COMPREHENSIVE STUDY OF THE OLDEST KNOWN STAR ATLAS

Jean-Marc Bonnet-Bidaud
Commissariat à l'Energie Atomique, Centre de Saclay, F-91191 Gif-sur-Yvette, France.
E-mail: jean-marc.bonnet-bidaud@cea.fr

Françoise Praderie
Observatoire de Paris, 61 Avenue de l'Observatoire, F-75014 Paris, France.

and

Susan Whitfield
The British Library, 96 Euston Road, London NW1 2DB, UK.
E-mail: susan.whitfield@bl.uk

Abstract: This paper presents an analysis of the star atlas included in the medieval Chinese manuscript Or.8210/S.3326 discovered in 1907 by the archaeologist Aurel Stein at the Silk Road town of Dunhuang and now housed in the British Library. Although partially studied by a few Chinese scholars, it has never been fully displayed and discussed in the Western world. This set of sky maps (12 hour-angle maps in quasi-cylindrical projection and a circumpolar map in azimuthal projection), displaying the full sky visible from the Northern Hemisphere, is up to now the oldest complete preserved star atlas known from any civilisation. It is also the earliest known pictorial representation of the quasi-totality of Chinese constellations.

This paper describes the history of the physical object—a roll of thin paper drawn with ink. We analyse the stellar content of each map (1,339 stars, 257 asterisms) and the texts associated with the maps. We establish the precision with which the maps were drawn (1.5-4° for the brightest stars) and examine the type of projections used. We conclude that precise mathematical methods were used to produce the Atlas. We also discuss the dating of the manuscript and its possible author, and we confirm the date +649-684 (early Tang Dynasty) as most probable based on the available evidence. This is at variance with a prior estimate of around +940. Finally, we present a brief comparison with later sky maps, both from China and Europe.

Keywords: Chinese astronomy, Dunhuang Star Atlas, star catalogues, Silk Road.

1 INTRODUCTION

The Dunhuang Star Atlas is one of the most spectacular documents in the history of astronomy. It is a complete representation of the Chinese sky, including numerous stars and asterisms, depicted in a succession of maps covering the whole sky (Figure 1). Apart from its aesthetic appeal, this document found on the Silk Road is remarkable, as it is the oldest star atlas known today from any civilization.

This Atlas is unique in the information it gives, which is discussed in more detail below: a) more than 1,300 individual stars are represented, as could be observed by eye from the Chinese Imperial Observatory; b) the sky is displayed as in the most modern charts with twelve hour-angle maps, plus a North polar map; c) the Chinese constellations are indicated with their names; d) the atlas is drawn in two colours on the finest paper and accompanied by complementtary text; e) the document is shown to date from the early Tang period (+618-907), while the next-oldest Chinese star atlases date from the eleventh century.

The manuscript is very often quoted in encyclopaedic and popular publications as an illustration of Chinese astronomical knowledge. However, despite its crucial historical and scientific importance, no extensive description and analysis of the Atlas exists in Western literature. In 1959, Needham (1959: 264) reproduced part of the manuscript and gave only a very short description. Since then it has received only brief mentions in other studies (see Deng Wenkuan and Liu Lexian, 2003: 76; Sun Xiaochun and Kistemaker, 1997: 29).

We decided to undertake a detailed study of the Star Atlas after the exhibition on the Silk Road organised in 2004 by the British Library, where the document was shown and a preliminary analysis was given (Bonnet-Bidaud and Praderie, 2004). In the present paper, we shall first give a full review of the Chinese sources (Section 2), then give a general description of the Star Atlas (Section 3), examine the accuracy and the type of planar projection used and also present a method to give a date from astronomical arguments (Section 4). We then discuss the date of the Star Atlas, compare the Dunhuang Star Atlas with other Chinese atlases, and comment further on the status of these documents (Section 5). In the Appendices, we also include in-depth descriptions of two representative sections of the Atlas. This study was made possible by the use of high-resolution digital copies of the Star Atlas made available to us by the International Dunhuang Project.[1] This is the first publication in a Western language, and is aimed at making available basic information on this important document.

1.1 The 'Discovery' of the Star Atlas

Inscribed on a roll of Chinese paper, the manuscript star atlas is surprisingly well preserved. The conditions in which the document was found are well known and leave no doubt about its antiquity. It was discovered by the British-nationalised but Hungarian-born archaeologist Aurel Stein in 1907 among a pile of at least 40,000 manuscripts (Hamilton, 1986) enclosed in the so-called 'Library Cave' (Cave 17) in the Mogao ensemble, also known as the 'Caves of the Thousand Buddhas', near Dunhuang (Gansu). The Mogao caves are a set of several hundred Buddhist temples cut into a cliff and heavily decorated with statues and murals. The site was active from about +360[2] up to the end of the Mongol period. In about +1000, one cave was apparently sealed (Rong Xinjiang, 1999) to preserve a collection of precious manuscripts and some printed material, including the world's earliest dated complete printed book (Whitfield and Sims-Williams, 2004). The sealed cave was rediscovered by accident and re-opened only a few years before the arrival of Stein in 1907. He was therefore the first European visitor to see the hidden library.

These circumstances, together with the dry desert climate of Dunhuang, contributed to excellent conservation of the cave's contents. Most of the Dunhuang manuscripts are religious texts on Buddhism but there are some socio-economic documents and a few concern medicine, divination and astronomy (Kalinowski, 2003). The astronomical texts are all calendars or almanacs, with the exception of two star charts. One of them contains the representation of the whole sky as it could be observed from a latitude of ~34° N. This is now known as the Dunhuang Star Atlas. The other (which is probably only a fragment) represents part of the polar region, but not the rest of the sky.

After Stein's visit and subsequent visits by other foreigners such as Paul Pelliot, Otani Kozui and Sergei Oldenburg, the cave was cleared by the Chinese Government and the manuscripts were dispersed to England, France, Russia, China and Japan.[3] Stein's collections were transferred to the British Museum, where the Dunhuang Star Atlas received the registration number Or.8210/S.3326 (S. for Stein; hereafter this document is simply referred to as S.3326).[4] The other star chart (DB 76) is preserved in the Dunhuang City Museum in China.

S.3326 did not receive much attention at the time of its discovery. This manuscript, which is in two sections, was catalogued by Lionel Giles (1957). He listed it under the classification 'divination' (cat. no. 6974) for the first section and described the second section as "… 13 star-maps with explanatory text." He did not estimate a date. His catalogue was published in 1957 but it had been ready for publication since 1947.[5] Around this earlier date, Joseph Needham and Chen Shixiang studied the Stein collection of astronomy-related manuscripts when researching their volume on Chinese astronomy (Needham, 1959). In a footnote in the volume, Needham (1959: 264) claims to have been the one to recognize the worth of the star atlas: "I discovered this extremely interesting map in conjunction with my friend Prof. Chhen Shih-Hsiang." Needham is also probably responsible for the initial dating of this manuscript, quoted in most studies thereafter, as he continues (ibid.): "Its probable date makes it about contemporary with the maps in the 'Book of the Fixed Stars' ... (+903 to +986 …) …" and he puts the date at "ca. +940" in his text and captions to the reproduced images (his Figures 99 and 100).

Unfortunately, the Needham archives do not yield any further information about Needham's visit to the British Museum to view the manuscripts, nor his research notes (John Moffett, pers. comm., 9 January 2007). The astronomy volume was published in 1959 but most of the work was carried out between 1949 and 1956, when the manuscript for this volume was completed. It is probable, therefore, that the 'discovery' was in the early 1950s. By this time, Giles had completed work on his catalogue, although it was still unpublished, and could have directed Needham to the astronomy-related manuscripts.

2 THE CHINESE CONTEXT

2.1 Chinese Astronomical Background

Although we know that the sky was carefully observed for at least four millennia in China, India and Mesopotamia, what remains in written or graphical form of these observations is very patchy. China is noticeable, though, since astronomical chapters can be found in every one of the official dynastic historical records, starting in the second century BCE with the *Historical Records* (*Shiji* 史记)[6] of Sima Qian (司马迁) (Chavannes, 1895), generally considered to be the first history of China. The astronomical chapters of the *Shiji* include stellar catalogues, which are copies of older, lost ones composed during the Warring States period (–476 to –221). They are known to result from different schools led by three astronomers of ancient times, Shi Shen (石申), Gan De (甘德) and Wu Xian (巫咸), who composed reference books describing the stars and the different astrological predictions associated with them (Chavannes, 1895; Maspero, 1929). Although Sima Qian himself does not differentiate information from the three schools of astronomers, the three distinct catalogues were maintained through the Han period (–206 to +220) and later combined by the astronomer Chen Zhuo (陈卓) (+220-280). The tradition of attributing each asterism (or Chinese constellation) to a different school survived because of the demands of astrological prediction.

The most complete and detailed description of the Chinese sky, including positions given by coordinates in Chinese degrees, is later found in the *Astrological Treatise of the Kaiyuan Period* (*Kaiyuan Zhanjing* 开元占经), a compilation attributed to the astronomer Qutan Xida (瞿坛悉达) in +729. Part of this information is also present in the astronomical chapters of the *History of the Jin* (*Jinshu* 晋书) and *History of the Sui* (*Suishu* 隋书), both probably written by the astronomer Li Chunfeng 李淳风 (+602–670) (Ho, 1966; Needham, 1959: 197, 201).

Chinese astronomy differs from the ecliptic-based Chaldeo-Greek tradition by its equatorial character, due to the central role of the Pole Star (Biot, 1862; de Saussure, 1930). The celestial region close to the Equator is divided into 28 asterisms (group of stars), called *xiu* (宿), and often translated as 'mansions' or 'lunar lodges' (hereafter referred to as 'mansions'), which can be considered as an equatorial Chinese zodiac.[7] A mansion is defined by an hourly interval corresponding to the meridian passage of two successive leading stars. The grouping of the stars in China is also totally different from the Greek tradition. Besides the equatorial region, the rest of the sky is divided into very numerous small asterisms (nearly three hundred), most associated with practical objects or persons of the Chinese Empire, leading to astrological predictions. Lists of the Chinese constellations were maintained all through Chinese history and did not change much over time. They form the basis of the Chinese astronomical tradition (Ho, 1966; Sun and Kistemaker, 1997).

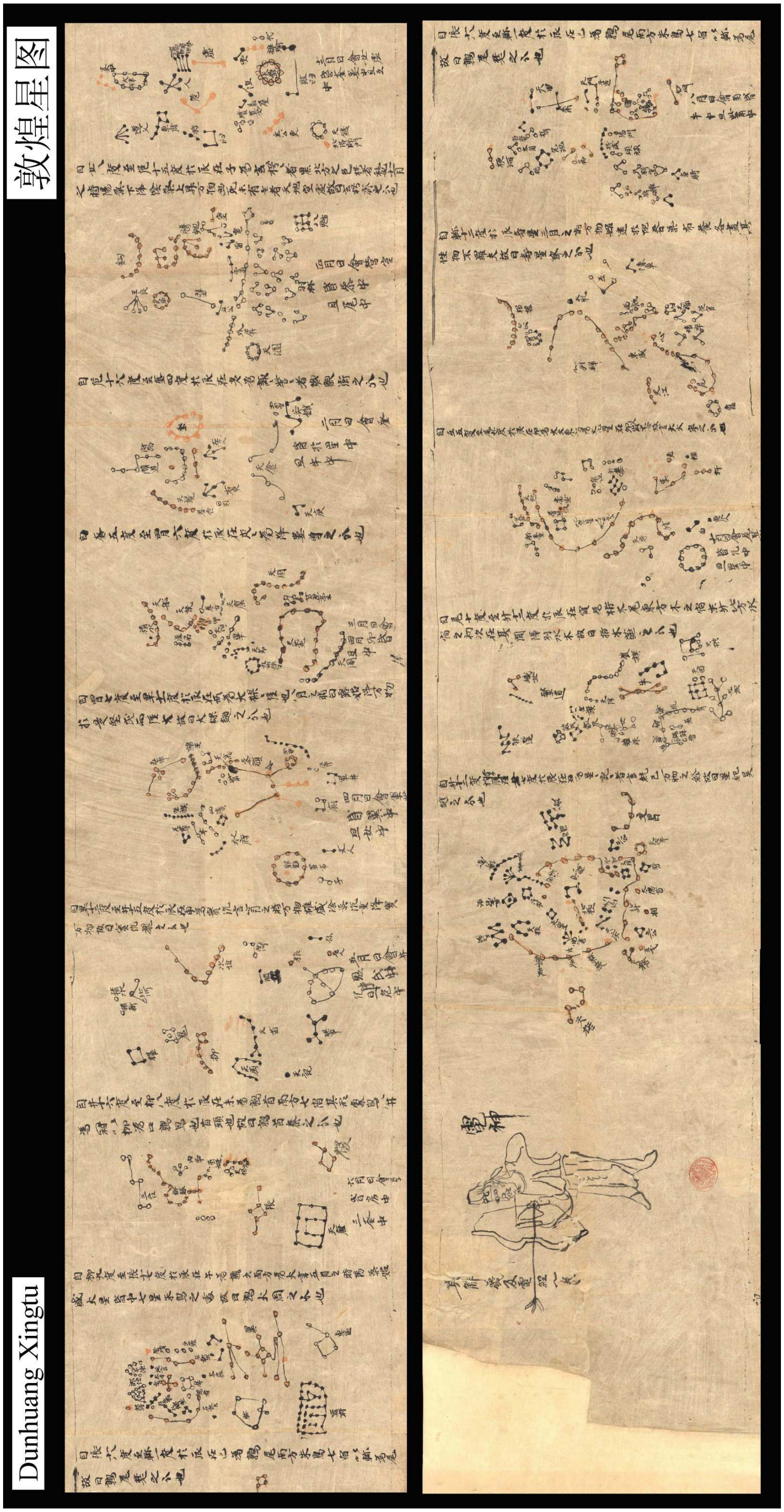


Figure 1: The complete Dunhuang Star Atlas, the last section of the Or.8210/S.3326 British Library manuscript, showing the twelve star maps (as seen above, from top to bottom and left to right), followed by the circumpolar map and ending with the drawing of a bowman in traditional clothes. The total dimensions are 2100 mm in length and 244 mm in width.

2.2 Review of the Chinese Sources on S.3326

Based on different photographic reproductions, Chinese scholars, both historians and astronomers, have produced several papers in Chinese about S.3326 since the 1960s.

Xi Zezong (1966) first published an article with complete images. He probably used facsimile images of S.3326 taken from the microfilm. He emphasizes the progress represented for the first time by the representation of the sky charts not on a circular plan but in a way similar to the Mercator projection, several hundred years before Mercator. He notes that the column texts accompanying each hour-angle map are similar to the ones found in Chapter 64 in the *Kaiyuan Zhanjing* and provides more complete versions based on this text. He then describes the hour-angle maps and the circumpolar map, giving the number of stars by asterism, with asterisms being ordered according to the mansions. He counts 1,359 stars in total and compares it to the Chen Zhuo list giving 1,464 stars following a compilation of the catalogues of Shi Shen, Gan De and Wu Xian (Needham, 1959: 265).

Ma Shichang (1983) paid particular attention to the dating of S.3326. While Needham (1959) mentions, without any justification, a date of ca. +940, Ma Shichang analyzes three elements in the document: a) the style of writing, b) the clothing of the bowman whose drawing ends the manuscript, and c) the taboo characters in the text.[8] He cites the taboo form of the character 民 (*min*) to infer that the manuscript was copied after the reign of Li Shimin (李世民), the personal name of the Taizong emperor (r. +626-649). He argues further that since the character 旦 (*dan*) occurs several times, the manuscript was written before the reign of the Ruizong emperor (i.e. before +710), who had this character as his personal name, Li Dan (李旦). Starting with his reign, the character 旦 should have been replaced. Ma Shichang narrows the time gap further by using the types of clothes worn by the bowman (see also Section. 5.1), saying that this type was in use only since the time of Empress Wu Zetian (r. +690-705). Since the manuscript has no Empress Wu taboo characters, it had to be written after her reign, i.e. after +705. From this evidence he concludes that S.3326 was written in about +705-710. His argument, however, contains inconsistencies (see also Section 5.1).

Pan Nai (1989: 148) also produced a description of S.3326, with a valuable discussion on its date. He is careful to point out the distinction between the original star atlas and copies and he notes that in the section of S.3326 devoted to divination, there is a possible reference to Li Chunfeng. He refutes the claim (made in Li Guohao, 1982) that S.3326 was inspired by *Songs of Pacing the Heavens (Bu Tian Ge* 步天歌) (Iannaccone, 2002; Zhou, 2004), a book dating to +590-600 with verses including some sky illustrations. Pan Nai supports the idea that there was an original star atlas prepared by Li Chunfeng from which S.3326 was copied. Considering the style of writing of the accompanying text, he proposes without any further argument that the copy may date from the tenth century, thus concurring with Needham (see also Section 5.1).

Deng Wenkuan (1996: 58ff), in the context of a study of astronomical texts and calendars found in Dunhuang, reproduces the S.3326 Star Atlas with explanatory notes and punctuated versions of the text. In a more recent book, Deng (2002: 25-37) dedicates a chapter to S.3326 and finds similarity with several other texts such as the astronomical chapters of the *Jinshu*, another text by Li Chunfeng (*Yisi Zhan* 乙巳占), and the *Kaiyuan Zhanjing*.

In a book on ancient Chinese star atlases, Feng Shi (2001: 330) also gives a brief survey of S.3326.

3 GENERAL DESCRIPTION OF S.3326

3.1 Physical Characteristics of the Manuscript

S.3326, now held at the British Library, is a paper scroll of total length 3,940mm and width 244mm. It is in reasonable condition. The thickness of the original paper is about 0.04mm (0.16mm with the modern lining). The manuscript is currently wrapped in a silk wrapper and supported by a wooden roller, both being later additions. The Chinese paper is very fine and a recent analysis revealed that it is made of pure mulberry fibres.[9] The scroll is fully lined with a brown Kraft paper.[10] The lining on the object is a treatment performed in the 1950s, its style and materials being consistent with the type of interventions performed during that period and the following decade at the British Museum. The microfilm provides further evidence. This was shot in 1953 and shows the manuscript already lined. It is possible that the Kraft paper lining was only added to the manuscript after Needham's discovery of it. It is clear that those items in the Stein Collection that received the most attention from scholars were those that received conservation treatment. The remainder were largely left in their original condition.

The scroll is inscribed on one side only. The beginning of the scroll is however missing so that there is no title or names of the authors. The bottom section is also missing at the beginning of the document. In some parts there are traces of replication marks by contact due to the long conservation in a rolled state. The document is divided into two different parts. From right to left, the first section is an uranomancy/meteoromancy text containing 80 extant columns of text below 26 drawings of clouds of different shapes. In this part there is an interesting citation under column 43 which can be translated as "… according to your servant Chunfeng ..." (Deng and Liu, 2003; Pan, 1989), a possible direct reference to the astronomer Li Chunfeng. Lü Buwei (吕不韋) (ca. –291-235), advisor to the First Emperor of China, Qin Shihuangdi, is also mentioned (Figure 2; see also Section 5.1 below).

The star atlas follows this first section without a break. The atlas is 2,100mm in length and consists of 12 vertical maps, each with accompanying texts in columns on the left, followed by one map of the circumpolar region with no text, and one column at the end, making 50 columns and 13 maps in total. The full star atlas is presented in Figure 1. The very last part of Figure 1 is a drawing of a bowman in traditional clothes shooting an arrow and, judging by the caption to his right, this depicts the god of lightning. He is followed by what appears to be a title (to his left). It is common in Chinese manuscripts to note the title at the beginning and end of the document so it is most probable, therefore, that this title refers to the previous parts. However, the meaning of this title remains a mystery and it has not yet been possible to make sense of it;[11] moreover, a survey of Chinese historical and bibliographical sources failed to reveal a similar title.

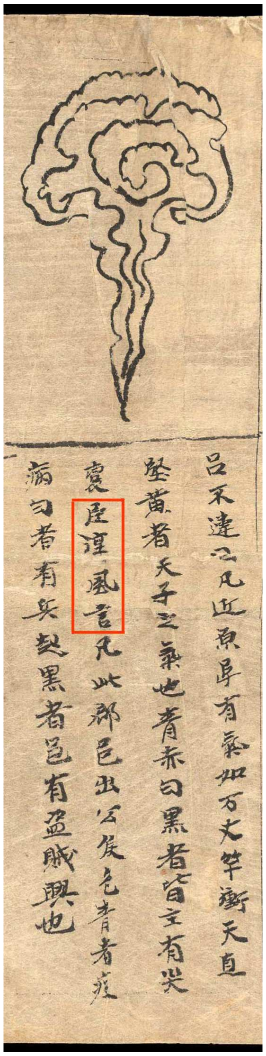
3.2 The Astronomical Content

3.2.1 The Star Maps

The twelve star maps are arranged in separate hour-angle sections, beginning with the mansions of *Xu* (虛) and *Wei* (危) and covering the entire sky, namely the 28 mansions and their North and South prolongations, by slots of about 30° in the East-West direction. In each map, the Chinese asterisms with their names are drawn from declination about −40° to about +40°. The stars are shown as coloured dots, the majority of which are encircled in black. All dots are of similar size. Black lines joining the dots indicate the constellations or asterisms. The orientation is such that North is up and West is to the right so that the star right ascensions (or celestial longitudes) increase from right to left in the direction of the document. The Celestial Equator and the Ecliptic are not represented and the Milky Way is not apparent. There is no co-ordinate grid either. The thirteenth and last map is the North circumpolar region, represented as a planisphere of radius about ~40° (i.e. covering the declination zone from 90° to 50°). Obviously, the 12 maps are limited towards the South by the visibility above the horizon of the night sky from the Imperial Observatory, which might have been in Chang'an (present-day Xi'an) or Luoyang, both of which have a latitude of ~34° N.

Noticeably, S.3326 records however the presence of several very southern objects, hardly observable from Chang'an or Luoyang. On the map corresponding to the fifth lunar month (Map 6), the star *Laoren* 老人 (α Carinae, or Canopus) is displayed, though misplaced towards the north and closer to the Equator than it is in reality. Despite its southern position, the star is also included in Sima Qian's astronomical chapter. He indicates it symmetrically about *Tian Lang* 天狼 (α Canis Majoris, or Sirius) as "… a big star called 'the old man of the south pole' (*Nanji Laoren* 南极老人)." Also shown, are the very southern stars, *Beiluo shimen* 北落柿门 (Map 1 - α Piscis Austrini) and *Nanmen* 南门 (Map 9 - two stars of Centaurus), also reported by Sima Qian. This shows that Chinese astronomers explored the Southern sky and had done so long before the southern expedition of +724-725. This was led by Yi Xing 一行 (+683-727), a Tang astronomer who re-measured the positions of many stars in the Chen Zhuo list and established at least eleven observing stations, down to latitude 17.4° near Hué in present-day Vietnam (Beer et al, 1961).

The individual stars appear to have been taken from a composite catalogue, established by the astronomer Chen Zhuo, by merging the observations of the 'Three Schools' astronomical tradition (see Section 2.1). Although the Chen Zhuo catalogue, which is also said to have contained a star atlas (Ho, 1966: 67), is lost, *Kaiyuan Zhanjing* has preserved the list of constellations of the Three Schools, with 1,464 stars grouped in 283 asterisms. S.3326 contains similar information and is the first known document which shows stars as different coloured dots to differentiate between the astronomers of the Three Schools: Shi Shen (red), Gan De (black) and Wu Xian (white and/or yellow). Here the colour conventions are *grosso modo* followed. There are many changes however, which suggests that this tradition was less rigidly followed at the time S.3326 was drawn. We have counted 1,339 stars grouped in 257 asterisms, although some overlapping and some non-encircled dots prevent an accurate census. For the same chart, Xi Zezong (1966) gives 1,359 stars. We were able to identify all but fifteen asterisms, as their Chinese names are given on the map.



呂不達之凡近京阜有氣如万丈竿衝天直

堅黃者天子之氣也青赤白黑者皆主有災

褒臣淳風言凡此郡邑出公侯色青者疾

病白者有兵赤黑者邑有盜賊興也

Figure 2: Part of the S.3326 first section (cloud divination texts). Columns 41 to 44 are shown, 41 to the right. The text (fully translated in Section 5.1 in the present paper) includes a reference to the possible author of S.3326, the astronomer Li Chunfeng (text in red frame).

Out of the 28 mansions, 27 are shown on S.3326, as a belt roughly following the Celestial Equator, and all show up with their leading star. The only missing one is *Wei* (胃) or belly which may be present in the eastern part of Map 3 but with a character including a mistake. As in the description by Li Chunfeng given in the astronomical chapters of the *Jinshu* (Ho, 1966), the Chinese sky exhibited by S.3326 displays the three *yuan* (垣 enclosures or wall systems), namely *Ziwei* (紫微), *Taiwei* (太微) and *Tianshi* (天市), which encircle different groups of stars. These are regions of the present Pole Star, α Ursae Minoris, and stars in

Draco and Cassiopeia for *Ziwei*; β Virginis and stars in Virgo for *Taiwei*; and ζ Ophiuchi and stars in Ophiuchus for *Tianshi*. All the bright stars visible from latitude 34° N are found on the map. As to the faintest ones, they correspond to naked eye observations of astronomers with very sharp eyesight. It is puzzling, as has been noted for a long time, that Chinese astronomers did not pay attention to visual magnitudes when drawing star atlases. This is the case with S.3326, where we estimate that stars as faint as visual magnitude 6.5 are present.

Figure 3: The Orion star map (Map 5, lunar month 4th). The map shows the recognizable Western constellation, Orion, and includes additional calendar texts (on the left) and culmination texts (at the bottom).

The document, drawn by hand and most possibly a copy, shows the positions of the stars with, in general, good precision (see Section 4.1). In Chinese astronomy, the large number of asterisms (257 as compared to the 88 modern constellations) allows one to specify fairly well the 'co-ordinates' of non-stationary heavenly bodies such as the Sun, Moon and five planets, and unexpected events such as 'guest stars' (comets or novae). None of the latter appears on S.3326.

We have noted some misplacements of stars or asterisms, which are either errors or show lack of attention on the part of the copyist. For instance, on Map 6 the asterism *Liu* 柳 (part of Hydra) should be at the same declination as *Nanhe* 南 河 (containing α Canis Minoris) while on the map *Liu* is too far to the North. We also note that the same name appears for different groups of stars, but this is in accordance with Chinese tradition. For instance, *Tiantian* 天田 denotes an asterism south of the mansion *Niu* 牛 (Map 12) as well as an asterism of three stars north of the mansion *Jiao* 角 (Map 9). On Map 13, there are also two groups of three stars with the same name, *Sangong* 三公 (Three excellencies), one to the south of the handle of *Beidou* 北斗 , the other near the star α Ursae Majoris also in *Beidou*, but this appears here to be a faulty duplication. Finally, there is some confusion between left (*zuo* 左) and right (*you* 右) when denoting east and west relative to a given star or asterism. An example is found on Map 3, with *You-geng* 右更 being east and *Zuogeng* 左更 west of *Lou* and on Map 8 with *Youzhifa* east and *Zuozhifa* west of *Taiwei* 太微 (β Virginis). This seems in both cases an error of the author of the S.3326 map, an error which is not repeated on Map 12 where *Youqi* 右旗 is west and *Zuoqi* 左旗 is east.

Two representative maps, the Orion region (Map 5) and the circumpolar region (Map 13) are shown respectively in Figures 3 and 4 and are fully described in the Appendices.

3.2.2 The Calendar Texts (Jupiter Stations)

Each of the twelve hour-angle maps comes with an explanatory text in one or two columns located to the left. The north polar map has no such text.

The texts are a description of the twelve divisions of the Chinese year with their associated astrological predictions. In each map, the equatorial zone (including classically 2 or 3 mansions) is defined precisely by its extension in Chinese degrees,[12] and related to the corresponding station of Jupiter (the so-called 'year star'). The sidereal period of Jupiter being 11.86 tropical years, it was approximated to 12 years in Chinese tradition. The sky was therefore divided in twelve sectors, successively occupied by Jupiter in 12 years, and named Jupiter stations (*ci* 次). Moreover, each column text gives two more indications: the name of each terrestrial branch (one element in the enumeration of days in the Chinese calendar) associated with the Jupiter station, and the name of the state within the Chinese Empire supposedly influenced by that region of the sky (see Table 1).

As an example, the first map refers to the Jupiter station *Xuan Xiao*. The text reads:

> From the 8th degree of *Nü* to the 15th degree of *Wei*, associated with [the terrestrial branch] *zi*, is [the Jupiter station] *Xuan Xiao*. The colour of the North direction is black. When *Xu* [appears], [it will be] a bad harvest. At the 11th month, the spirit *yang* contracts, the spirit *yin* expands, the ten thousand beings [all creation] disappear into the darkness, there is no life, sky and Earth are without substance, the Sun [goes] into *Xuan Xiao*. This division corresponds to [the state of] *Qi*.

These texts are mainly of astrological use but the scientific notation in degrees reveals that they are based on astronomical observations and have been produced with the attempt to be as precise as possible for this period. Interestingly, a reduced version of similar texts is found in the astronomical chapters of the *Jinshu* with a later redaction commonly attributed to Li Chunfeng. This shortened version includes only the station extensions in degrees, the terrestrial branch and a more detailed association with Chinese states, but without any astrological predictions (Ho, 1966: 113-120). We have checked the S.3326 extensions and found them almost exactly the same as those of the *Jinshu*, with only very minor one-degree variations in three cases (Table 1).

We also note that in five cases (Maps 1, 4, 5, 7 and 9), the texts refer to a lunar month different from the corresponding map, in accordance with the long astrological tradition of considering a 'shadow planet' moving in the opposite direction of Jupiter (see Needham, 1959: 402).

The astrological comments were found by previous authors analogous to texts in the section *Fenye Lueli* (分野略例) of the astronomical treatise (Chapter 64) of the later *Kaiyuan Zhanjing*. Based on this complementary information, a completed version in Chinese of the twelve calendar texts was produced, restoring the punctuation and the missing characters since some of the texts seem abbreviated in S.3326 (Deng, 1996: 58; Xi, 1966). The S.3326 texts appear therefore more developed than those found in *Jinshu*, and may be a somewhat earlier preliminary version of those in the *Kaiyuan Zhanjing*.

Analysis of the stations' equatorial extensions in S.3326 shows that their lengths are approximately equal, with a mean value of 29.0° and a total range from 27.1° to 31.4° (for an Equator at date +700). A major difference occurs, however, for the Jupiter stations *Chun Huo* (month 6) and *Chun Wei* (month 7) with respectively extensions of 36.7° and 19.7° (Table 1). There appears to be an error of 10° in the extension of the mansion *Zhang*, which is given as 18° whereas the mansion's total extension is only 8° (the effect of precession will not vary this value by more than a fraction of a degree even as far back as –500).

Table 1 shows that the correspondence between Jupiter stations and Chinese mansions on the Dunhuang Star Atlas is almost exactly the same as that found on Figure 91 and Table 34 in Needham (1959). Actually the repartition of the mansions with respect to the Jupiter stations is conventional and seems to go back to a very old tradition (de Saussure, 1930). Since these calendar texts are based on Jupiter's cyclic behaviour, they do not provide useful astronomical information on the production date of the document.

3.2.3 The Culmination Texts

At the bottom of the maps, an additional text gives the major annual landmarks associated with the lunar month. Together with the number of the lunar month, one reads the position of the Sun with respect to the mansions present on the map and the culminating constellations at dusk and at dawn during the month. The first map is labelled "12th lunar month". For three maps (8, 10 and 12), these indications are absent or have been erased.

Table 1: The Calendar Texts and Comparison to Needham (1959).

Map[1]	Month	S.3326 Jupiter stations	S.3326 Jupiter Station Extensions	S.3326 Chinese Mansions[2] (from West to East)	S.3326 Month/ Branch/ State[3]	Needham's Jupiter stations[4]	Needham's Lunar mansions[4]
1	12	*Xuan Xiao*	from 8th ° of *Nü* to 15th ° of *Wei*	*Xu*, *Wei* (12)	11 / *zi* / *Qi*	5. *Xuan Xiao*	*Nü*, *Xu*, *Wei*
2	1	*Zou Zi*	from 16th ° of *Wei* to 4th ° of *Kui*	*Shi*, *Bi* (14)	- / *hai*/ *Wei*	6. *Qu Zi*	*Shi*, *Bi*
3	2	*Jiang Lou*	from 5th ° of *Kui* to 6th ° of *Wei*	*Kui*, *Lou*	- / *xu*/ *Lu*	7. *Jiang Lou*	*Kui*, *Lou*
4	3	*Da Liang*	from 7th ° of *Wei* to 11th ° of *Bi*	*Mao*, *Bi* (19)	8 / *yu* / *Zhao*	8. *Da Liang*	*Wei*[5], *Mao*, *Bi*
5	4	*Shi Chen*	from 12th ° of *Bi* to 15th ° of *Jing*	*Zui*, *Shen*, *Jing*	7 / *shen*/ *Wei*	9. *Shi Chen*	*Zui*, *Shen*
6	5	*Chun Shou*	from 16th ° of *Jing* to 8th ° of *Liu*	*Gui*, *Liu*	- / *wei* / *Qin*	10. *Chun Shou*	*Jing*, *Gui*
7	6	*Chun Huo*	from 9th ° of *Liu* to 17th ° of *Zhang*[6]	*Xing*, *Zhang*	5 / *wu* / *Zhou*	11. *Chun Xin*	*Liu*, *Xing*, *Zhang*
8	7	*Chun Wei*	from 18th ° of *Zhang* to 11th ° of *Zhen*	*Yi*, *Zhen*	- / *si* / *Chu*	12. *Chun Wei*	*Yi*, *Zhen*
9	8	*Shou Xing*	from 12th ° of *Zhen* to 4th ° of *Di*	*Jiao*, *Kang*	3/ *chen*/ *Zheng*	1. *Shou Xing*	*Jiao*, *Kang*
10	9	*Da Huo*	from 5th ° of *Di* to 9th ° of *Wei*	*Di*, *Fang*, *Xin*, *Wei* (6)	- / *mao* / *Song*	2. *Da Huo*	*Di*, *Fang*, *Xin*
11	10	*Xi Mu*	from 10th ° of *Wei* to 12th ° of *Dou*[7]	*Ji*, *Dou*	- / *yin* / *Yan*	3. *Xi Mu*	*Wei*, *Ji*
12	11	*Xing Zhi*	from 12th ° of *Dou*[7] to 7th ° of *Nü*	*Niu*, *Nü*	-/ *chou*/ *Wu-Yue*	4. *Xing Ji*	*Dou*, *Niu*

1 The Dunhuang S.3326 maps are numbered 1 to 12, according to their order in the document, with Map 1 corresponding to the Winter solstice.

2 Chinese mansions (*xiu*) with the same pinyin names (such as *Bi* (14) and *Bi* (19)) are distinguished by their order number, as in Needham (1959: Figure 91 on page 243).

3 Lunar month used for predictions and the name of the corresponding state as indicated in the astrological text.

4 Correspondence between Jupiter stations (*ci*) and Chinese mansions (*xiu*) from Needham (1959: Figure 91 on page 243, and Table 34 on page 403).

5 The *xiu Wei* (17) is absent from the S.3326 map.

6 An apparent copyist error, introducing a very unequal station (see text).

7 Between months 10 and 11 the station extension is noted with the same degree on the map (from 12th ° of *Dou*) instead of increasing by one degree as in the other extensions.

Table 2: The Culmination Texts.

Map	1	2	3	4	5	6	7	8	9	10	11	12
Lunar Month	12	1	2	3	4	5	6	7	8	9	10	11
Major Western Constellations on S.3326	Cygnus Pegasus Aquarius	Andromeda Pegasus Pisces	Aries Cetus Andromeda	Perseus Taurus Eridanus	Auriga Orion Lepus	Cancer Canis Major Gemini	Leo Hydra	Virgo Corvus Canes Venatici	Bootes Virgo Lupus	Serpens Ophiuchus Scorpius	Herculus Ophiuchus Sagittarius	Lyra Aquila Capricornus
S.3326												
Chinese mansions (*xiu*)[1] on S.3326	*Xu* *Wei* (12)	*Shi* *Bi* (14)	*Kui* *Lou*	*Mao* *Bi* (19)	*Zui* *Shen* *Jing*	*Gui* *Liu*	*Xing* *Zhang*	*Yi* *Zhen*	*Jiao* *Kang*	*Di* *Fang* *Xin* *Wei* (6)	*Ji* *Dou*	*Niu* *Nü*
Sun conjunction	*Nü* *Xu*	*Shi*	*Kui*	*Wei* (17)[2] *Mao*	*Bi* (19) *Zui*	*Jing* *Gui*	*Xing*	*no text*	*Jiao*	*no text*	*Wei* (6) *Ji*	*no text*
Dusk culmination	*Kui* *Lou*	*Shen*	*Liu* *Xing*	*erased?*	*Yi*	??*Kang*	*Fang*	*no text*	*Niu*	*no text*	*Kang*[3]	*no text*
Dawn culmination	*Di*	*Wei* (6)	*Niu*	*erased?*	*Nü*	*Wei* (12)	*Kui*	*no text*	*Zui*	*no text*	*Xing*	*no text*
Yueling[4]												
Sun conjunction	*Nü*	*(Ying)* *Shi*	*Kui*	*Wei* (17)	*Bi* (19)	*Jing*	*Liu*	*Yi*	*Jiao*	*Fang*	*Wei* (6)	*Dou*
Dusk	*Lou*	*Shen*	??	*Xing*	*Yi*	*Kang*	*Huo* /*Xin*[5]	*JianXing*	*Niu*	*Xu*	*Wei* (12)	*Bi* (14)
Dawn	*Di*	*Wei* (6)	*Dou*	*Niu*	*Nü*	*Wei* (12)	*Kui*	*Bi* (14)	*Zui*	*Liu*	*Xing*	*Zhen*

1 Chinese mansions (*xiu*) in pinyin transcriptions are given from West to East on the maps (right to left). Mansions with the same pinyin names (such as *Bi* (14) and *Bi* (19)) are distinguished by their order number as in Needham (1959: Figure 91 on page 243).
2 *Wei* (17) is the only *xiu* missing graphically in the Star Atlas. A character in the eastern part of panel 3 could be *Wei* but with a mistake.
3 *Kang* does not correspond to a possible astronomical configuration; this is a possible copying error.
4 After Legge (1885); see, also, Couvreur (1913).
5 The term *huo* (火) also designates the *xiu xin* (心).

As an example, at the bottom of Map 1 (12th lunar month), one reads:

> The twelfth (lunar) month, the Sun meets the mansions *Nü* and *Xu*; at dusk the mansions *Kui* and *Lou* culminate; at dawn the mansion *Di* culminates.
> 十二月 - 日會女虛 - 昏奎婁中 - 旦氐中

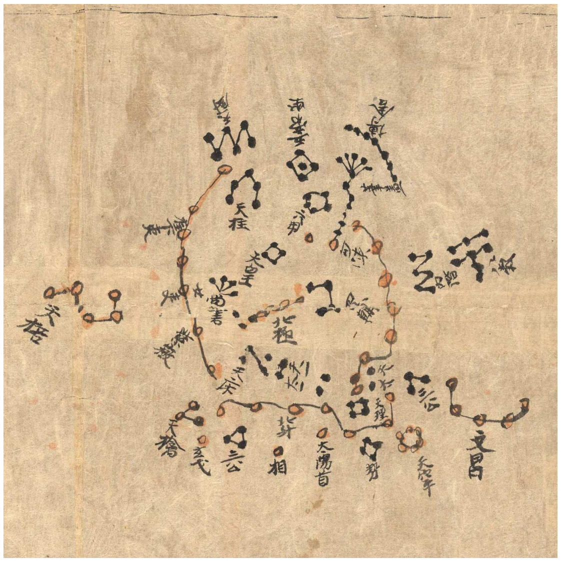


Figure 4: The North circumpolar region (Map 13). The map displays from the polar region down to a celestial latitude of about +50°.

The astronomical content of these texts is summarized in Table 2. According to different authors (Deng, 2002; Pan, 1989), these monthly texts are identical to those found in an early text, the *Monthly Ordinances* (*Yueling* 月令), that can be found both in the historical text *The Spring and Autumn Annals* (*Lüshi Chunqiu* 吕氏春秋), dated –240, and in a chapter of the *Classic of Rites* (*Liji* 礼记), dated approximately to the third or second century before the modern era. For comparison, the corresponding information from the *Yueling* texts is also given in Table 2, according to Legge's translation (Legge, 1885; see, also, Couvreur, 1913). Despite an overall similarity, there are notable small differences between *Yueling* and S.3326. For the culminations of mansions at dusk and dawn, the differences only affect months 2, 6 and 10 (out of the 9 months for which these texts are present in S.3326), with at least one obvious copying error (see Table 2).

Interestingly enough, for the solar conjunction with the mansions, the months 3, 4, 5, 10 and 12 are given with two mansions instead of one, the second one always with a higher right ascension than the mansions in *Yueling*. If interpreted as corrections to take into account the effect of precession for a period later than that of the *Yueling*, this is opposite to what would be expected. The culmination texts on the maps can however be dated by comparing them with known astronomical configurations (see Section 4.2).

3.3 The Pole Star

The circumpolar map is fully described in the Appendices (see Section 10.2) and is shown in Figure 4. As was usual in the Chinese sky representations, the north polar region features the central Purple Palace with the Celestial Emperor at the Pole, surrounded by his family, servants, military officers and the corresponding housing.

According to Gaubil (1819), and also quoted by de Saussure (1930), the star β Ursae Minoris was adopted as the Pole Star by the Chinese about –1000, and named *Di* (the first ancestor), but it was distant by 6° 30′ from the real Pole. Due to the precession of equinoxes, the astronomical North Pole describes a circle around the Ecliptic Pole in 25,800 years. Recognising the North Pole Star would therefore be a means of dating the sky map. On S.3326 the asterism *Beiji* is clearly drawn, with four red stars encircled by a black line (γ Ursae Minoris, β Ursae Minoris, 5 Ursae Minoris, and 4 Ursae Minoris). Another star is red and pale, not encircled in black, and is located near 4 Ursae Minoris. It is not easily identifiable in modern terms. The Pole Star is not indicated as such on the map. It could be that red pale spot, but it would be strange that the star figuring the supreme ruler should be so inconspicuous on the map. Quite different to the Suzhou sky map (see Section 5.2), on S.3326 the Pole Star cannot be seen within the asterism *Sifu* (the four advisors). We therefore conclude that for some reason the Pole Star is not shown on S.3326. However, the type of projection used to represent the polar region in S.3326 allows us to date the map, even if there is no graphical representation of the Pole itself (see Section 4.1).

4 SCIENTIFIC EVALUATION OF S.3326

4.1 Accuracy and Projection Study

S.3326 is a unique document as it presents a display of the full sky in a very 'modern' way, including a set of hour-angle maps in cylindrical-type projection, combined with a circumpolar map in azimuthal projection. This is the way most geographical maps are still presented today. Unlike most other ancient astronomical artefacts (i.e. the Denderah Zodiac or the Farnese Globe, see Section 5.2) which only show constellations figures without individual stars, it also provides a large number of star positions, grouped in asterisms each clearly labelled so that only a few ambiguities remain. In this sense, it can be considered as a scientific document and its accuracy can be tested.

To evaluate the accuracy of the star positions in the maps we made use of only the brightest stars (i.e. $m_v < 3$). Identifications were made using mainly the list provided from the study of the Han catalogues (Sun and Kistemaker, 1997: 44), but other traditional compilations (e.g. Ho, 1962) were also used as a check. We have further selected only the stars for which no ambiguity exists as to their identification by name, though in some cases slightly different positions are still possible, thereby adding probable systematic errors. The star positions on the maps were measured from the high-resolution scans provided by the British Library. A ruler is present in each scan that allows conversion to the physical size. The scan scale (204.8 pixel/cm) yields a precision an order of magnitude better than the size of the symbols on the maps. The typical size of the dots marking the stars (~0.2 cm) is indeed the limiting factor, so that the accuracy of the measurements can therefore be estimated to be <0.1 cm.

The star positions on the maps were compared to the stars' equatorial coordinates (right ascension and declination), corrected for proper motion and precessed to the date +700 (using ESA, 1997, for proper motions). As no absolute references are present in the document, the effect of precession is not fully relevant here (see, however, below for the position of the North Pole).

To evaluate the maps' accuracy, some assumption has to be made on the projection used. We tested the hour-angle maps with the two simplest versions of the cylindrical projection (pure-cylindrical and Mercator) and the circumpolar map with two azimuthal projections (equidistant and stereographic). In each case, the accuracy in the two coordinates (right ascension and declination) was evaluated separately to judge for the effect of different scales.

The best parameters of the projections consistent with the measured positions (X, Y) were determined by least-square fits with fitted function as:

For the hour-angle maps:

Pure-cylindrical projection:-

$$RA = a + b.X \text{ and} \tag{1}$$

$$DEC = c + d.Y \tag{2}$$

Cylindrical-Mercator projection:-

$$RA = a + b.X \text{ and} \tag{3}$$

$$DEC = c + d.\ln\left[tg\left(\frac{\pi}{4}+\frac{Y}{2}\right)\right] \tag{4}$$

For the circumpolar map:

Azimuthal equidistant:-

$$RA = a + b^{*}\text{arctg}(Y/X) \text{ and} \tag{5}$$

$$\frac{\pi}{2} - DEC = c + d.\left(X^2 + Y^2\right)^{\frac{1}{2}} \tag{6}$$

Azimuthal stereographic:-

$$RA = a + b^{*}\text{arctg}(Y/X) \text{ and} \tag{7}$$

$$tg\left(\frac{\pi}{2} - DEC\right) = c + d.\left(X^2 + Y^2\right)^{\frac{1}{2}} \tag{8}$$

where (RA and DEC) are the star's predicted position, (X and Y) the star's measured position, and (a and c) and (b and d) respectively the zero points and scale factors for each projection.

Table 3 gives representative results of the fits for three selected hour-angle maps (Maps 1, 2 and 5) and for the circumpolar map (Map 13).

The general quality of the document is illustrated by the mean residuals (in degrees) and values of R, the associated correlation coefficients.[13] For the hour-angle maps, the regression factor is always quite good, ranging from 0.91 to 0.99, with a markedly better correlation in the vertical (declination). The residuals are of the order of a few degrees only, with the best accuracy (~1.6°) achieved in Map 5. One notices also a significant difference between the horizontal (right ascension) and the vertical (declination) scales, the latter always being larger. This means that the projection is not strictly conformal (equal scales), but the scales are consistent from one map to another. The typical scale is ~4.5°/cm (horizontal) and ~5.5°/cm (vertical). The extensions and the geometrical centre of the maps have been computed from the star extreme fit positions. From one map to the other they are very similar (~50°) in right ascension but more variable in declination (70° to 100°), though more or less centred at the Equator. The comparison of the different types of projection, 'pure cylindrical' vs 'Mercator', does not yield a significant difference in the quality of the fit, as shown by the corresponding similar regression factors. Within the uncertainties, both projections are therefore in equal agreement with the maps. For illustration, Figures 5 and 6 give the correlation results for Map 5, as well as the reconstructed positions using the fitted scales.

Table 3: The Projection Results.

	Map 1	Map 2	Map 5	Map 13
Input stars[1]	19	12	17	22
Selected stars[2]	16	10	15	19
Right Ascension (RA) fit	*Horizontal*	*Horizontal*	*Horizontal*	*Azimuthal*
Scale factor (°/cm)	4.40	4.24	4.56	1.05
Mean residuals (°)	3.54	4.63	2.26	1.67
Correlation coefficient[3]	0.947	0.957	0.907	0.995
Declination (DEC) fit	*Vertical*	*Vertical*	*Vertical*	*Radial*
Scale factor (°/cm)	5.40	7.66	5.28	5.10
Mean residuals (°)	3.57	4.07	1.61	3.29
Correlation coefficient	0.974	0.975	0.996	0.919
Correlation coefficient Mercator	0.972	0.974	0.994	-
Correlation coefficient Stereographic	-	-	-	0.932
Map Dimensions				
Map centre (RA)	308°	344°	73°	-
Map limits (RA)	284 to 332°	321 to 366°	49 to 97°	-
Map extension (RA)	48°	45°	48°	-
Map centre (DEC)	+0.3°	+10°	+8°	+87.6°
Map limits (DEC)	−44° to +45	−41° to +61°	−27° to +43°	+90° to +52°
Map extension (DEC)	89°	102°	70°	48°
Geometrical centre (DEC)	–14°	–8°	+5°	

1 Input stars selected according to their magnitudes.
2 Selected stars for the fit after rejection of the largest deviations.
3 The correlation coefficient, R, is the Pearson least-squares fit parameter where R = 1 is a perfect fit and R = 0.76 and 0.68 for a random probability of 0.01% and 0.1% respectively.

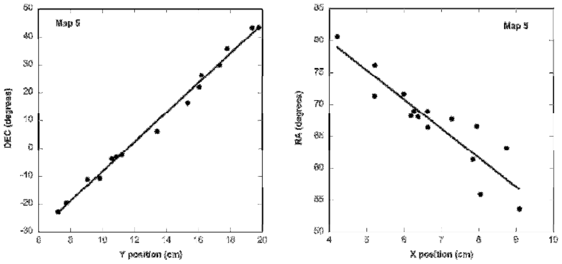


Figure 5: The regression factors and residuals (Orion, Map 5). Least-square fit of the measured *X-Y* positions with a pure cylindrical-projection. Note the very good correlation in the vertical scale (*Y*-declination).

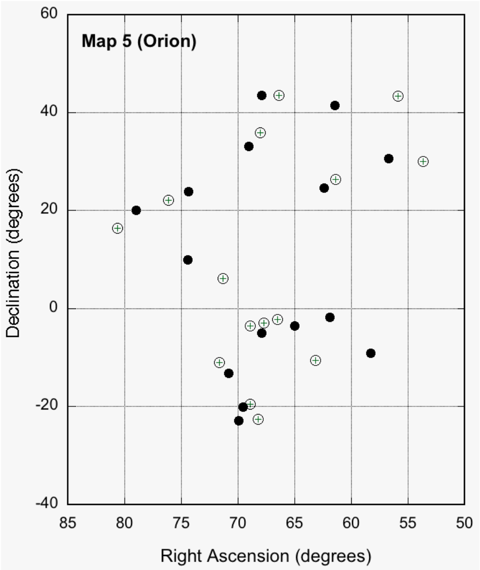


Figure 6: Computed vs measured positions (Orion, Map 5). The measured positions from the best fit cylindrical projection (filled circles) are compared to star positions for +700 (open circles with crosses). Note the good accuracy in declination.

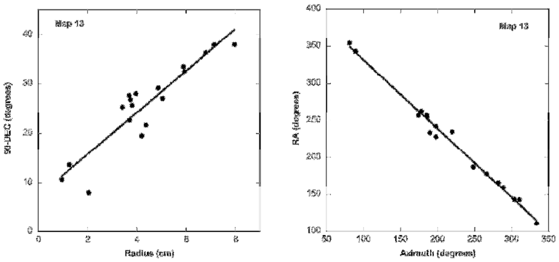


Figure 7: The regression factors and residuals (North polar region, Map 13). Least-square fit of the measured polar distance (radius) and azimuth with an azimuthal equidistant projection. Note the good azimuth correlation.

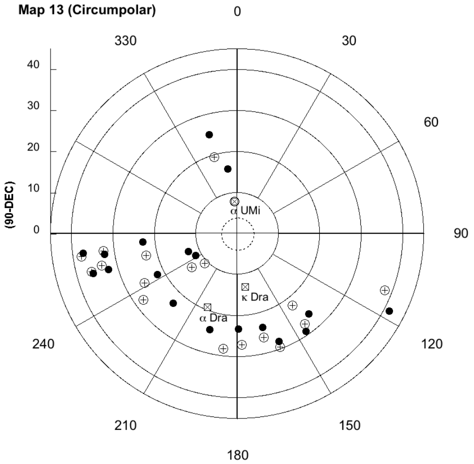


Figure 8: Computed vs measured positions (polar region, Map 13). The measured positions from the best fit azimuthal projection (filled circles) are compared to star positions for +700 (open circles with crosses). Also shown is the measured uncertainty in the Pole position from the best fit (dotted circle) and the different positions of the Pole (open squares with crosses) at dates of about +2000 (α Ursae Minoris), –1000 (κ Draconis) and –2500 (α Draconis).

For the circumpolar map (Map 13), the results are also given in Table 3 in terms of the azimuthal fit (hour-angle) and radial fit (polar distance). The azimuthal fit is extremely good, with a correlation coefficient of 0.995 and mean residuals of 1.7°. With a scale factor of 1.05 ± 0.03, there is also no significant distortion from the theoretical value (1.0) for the azimuthal projection. Comparatively, the radial fit is notably poorer (R = 0.92) with mean residuals of 3.3° and significant distortions in the polar distances (see Table 3 and Figure 7). The comparison of the 'pure equidistant' projection with the 'stereographic' projection gives a slightly better fit for the latter (R = 0.93), but strictly speaking this is not statistically significant. Although some distortions obviously exist (Figure 8; see, also, Section 10.2 in the Appendices), the overall accuracy of the projection is well preserved.

Interestingly, the correlation study also provides an indication of the expected position of the Pole on the map with respect to the reference position at date +700. The measured shift in polar distance of the Pole reference point (0,0 in Figure 8) between the S.3326 map and the sky at date +700 is only marginally significant with a difference of (3.9 ± 2.9)°. This position and the associated uncertainty is compared in Figure 8 with stars that were close to the Pole at different dates, namely α Ursae Minoris (~ +2000), κ Draconis or β Ursae Minoris (~ –1000) and α Draconis (~ –2500). Within the above uncertainties, the Pole is fully consistent with a +700 date.

The numerical study of the S.3326 document yields important results. The atlas is not a simple hastily hand-made reminder but was established according to precise geometrical rules. The projection methods used are consistent with either a pure-equidistant or the Mercator projection for the rectangular maps and with the azimuthal-equidistant or stereographic projection for the circular one. This is in line with similar results obtained on two later Song period maps, the Suzhou 苏州 Planisphere and the *Xin yixiang fayao* 新仪象法要 rectangular map (see Miyajima, 2002).

In all cases, the correlations are very good, which eliminates any random coincidence. Based on the brightest stars, the general positional accuracy of the maps is of the order of 1.5°-4°. The layout of the rectangular maps is reasonably good with similar scales from one to another, but with ±5° variation in the location of the Equator. The maps appear therefore as probable hand copies of a previous more accurate document, although the method of reproduction is not clear. The fineness of the original paper might have allowed for the maps to be traced from a clear original. It has nevertheless preserved a remarkable accuracy. It should be noted, however, that this accuracy study is based on selected bright stars only. The overall accuracy is well preserved, but there are local significant differences in the positions of some individual stars (e.g. β Canis Majoris in Map 5 and α Carinae (*Laoren*) in Map 6). In some parts, the geometrical shape of numerous asterisms appears also highly approximate and even fanciful.

4.2 Analysis of the Culmination Texts : An Attempt at Dating

Temporal information can also be extracted from the Dunhuang maps using the culmination data contained in the texts added to at least eight out of the twelve maps. In these texts, the given information is the number of the month, the name of the mansions through which the Sun passes during that month, and the names of the mansions which culminate (i.e. cross the meridian) at dusk and dawn during the month. This information does not change appreciably from one year to another, but over a longer time-scale the slow effect of the precession of the equinoxes introduces a significant shift in the position of the stars defining the mansions with respect to the Sun.

We have calculated the effect of precession in a period ranging from –500 to +900, which corresponds to the most likely interval when the information could have been produced. The definition of the mansions and more precisely their leading stars, have been taken from the list by Needham (1959: 234-237, Table 24). Standard precession has been applied without introducing proper motion, which is negligible for this list of stars.

The Sun's position along the Chinese zodiac formed by the mansions was computed for each chart at mid-month, and a common Chinese year starting on 5 February was assumed. This is the exact middle date for the variable Chinese luni-solar calendar (see Aslaksen, 2003: 27). For each month, the equatorial solar coordinates (right ascension and declination) were computed from astronomical formulae as well as using planetarium software (Voyager v. 4.0.3), and three different indicators were computed.

The Sun's position indicator, H_{sun}, was defined as the difference in right ascension between the Sun and the leading star of the mansions indicated in the map. In the case when two mansions are indicated in the map, the mean right ascension of the two mansions was used. Two other parameters, the rise (H_{rise}) and set (H_{set}) indicators, are defined as the difference in right ascension between the culminating right ascension and the mansions indicated respectively for the rising and setting time in the maps.

The culminating right ascension is simply the sidereal time (*ST*) at sunrise and sunset, and can be computed using standard formulae:

$$ST_{rise} = 24 - \frac{1}{15}\arccos\left[-tg\phi.tg(DEC)\right] + RA \tag{9}$$

$$ST_{set} = \frac{1}{15}\arccos\left[-tg\phi.tg(DEC)\right] + RA \tag{10}$$

where *RA* and *DEC* are the Sun's equatorial coordinates on the date and φ is the observer's latitude. In these equations a latitude of 34° was used, corresponding to the city of Chang'an (present-day Xi'an) but also compatible with Luoyang, the eastern capital of China. For each epoch, from –500 to +900 in 100-year steps, the indicators were computed for each month and their mean value and standard deviation for each epoch were evaluated.

The H_{sun} mean value is plotted in Figure 9 against time. Due to the effect of precession, it shows a continuous decrease, from +0.25 hr at –500 to –0.27hr at +900. A best date for a minimum shift can therefore be interpolated and is computed to be +85 with an interval (−40 to +220) according to the mean statistical errors. An important dispersion around the mean value is present from month to month (up to 0.5hr), which is reflected in the significant error bars.

Some caution has to be voiced about this absolute dating of the chart texts since there is no clear indication that our basic assumptions that the Sun's position is considered at mid-month and that the mansions are given by their leading stars (the starting points of the mansions) are correct. If the mansion positions were identified with their mid-extensions or the Sun was considered at the beginning of the month, the absolute dates will be shifted in the past by quite a large amount, not consistent with the supposed period.

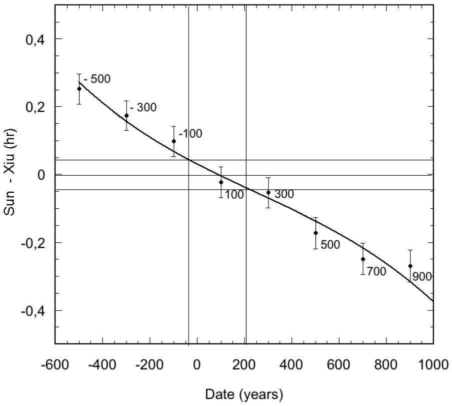


Figure 9: Dating from the culmination texts. The time difference between the Sun's position and the mansion (*xiu*) indicated in the culmination texts as a function of time. Shown is the mean Sun position indicator, H_{sun}, an average value over the 12 months for each epoch. Note the large error bars reflecting the important dispersion of the monthly values around the mean value. From a polynomial interpolation (thick line), the minimum difference is found at date ~+85 with an interval (−40 to +220) according to the mean errors (shown by vertical lines).

5 THE STATUS OF S.3326

5.1 Dating the Document

The exact dating of S.3326 is a difficult task. It is necessary to distinguish between the following factors:

(a) The date of the paper support itself. The nature of the paper makes it similar to those used in China up to and including the Tang Dynasty (+618-907), although its extreme thinness and long pure mulberry fibres make it an expensive paper, not an everyday paper. Such paper was almost certainly made in Central China and probably under Imperial order in the capital, Chang'an. More precise dating by means of radioactive carbon (C^{14}) should be possible but has not been attempted yet.

(b) The date indicated by its possible author. The scroll S.3326 lacks its original front cover that could have guided us for this purpose. However, there is a phrase in the initial uranomancy section which reads: "chen Chunfeng yan …" (臣淳风言). This translates literally as "your servant Chunfeng says …" It is a part of a paragraph (see Figure 2) which reads:

> Lü Buwei said that, as a general principle, when you approach a mound on a plain and there are air vapours in the shape of a staff reaching high up into the sky, straight and firm; if it is yellow, it is the colour of the Son of Heaven (i.e. the Emperor). Blue, red, white and black all mean the presence of tears and grief. Your servant Chunfeng says that as a general principle such prefectures and cities produce dukes and knights. With regard to colours, blue means deliverance from sickness, white that an army is being raised, black that robbers and thieves are increasing in the city.[14]

This is an argument for considering Chunfeng as a possible author of either the S.3326 manuscript itself or the original (if it is a copy). The only person mentioned in historical records at this time who had the right expertise with this name was Li Chunfeng, an outstanding figure in astronomy and mathematics. The phrase "Your servant … says …" is formulistic and the absence of the family name is a sign of modesty when referring to oneself in company with a famous man, here Lü Buwei, but it obviously makes the attribution to Li Chunfeng less certain. Moreover, this statement is extremely similar to the one used to introduce the commentaries by Li Chunfeng in the mathematical treatise *The Nine Chapters on the Mathematical Art* (Jiuzhang Suanshu, 九章算术).[15] As Li Chunfeng was also a highly-skilled mathematician, it is quite reasonable to think that he had the necessary expertise to design the projection methods used in the chart. The mention of Li Chunfeng would therefore put the period the document at about +650-670, when he was active.

(c) The date suggested by the style and form of the writing. Just as for European manuscripts, the style of the handwriting can be used to help date Chinese manuscripts. Pan (1989), in the article discussed above, suggested that the manuscript is a tenth-century copy, but I. Galambos (pers. comm., 2008) believes that the handwriting is more typical of an earlier period, fitting with a seventh or early eighth century date, and Ma (1983) in the article discussed above also follows this view. The handwriting is not that of a professional scribe, who would have written in a much neater and more regular hand and might, if required, have copied an earlier style. It is individualistic, and this suggests that the writer was using his own hand and was following the conventions of his time. This is relevant to the use of taboo characters, which are another clue to dating (see below).

(d) The date suggested by the taboo form or 'spelling' of the Chinese characters. Taboo characters are peculiar to Chinese texts (see Note 8). As discussed above, Ma (1983) points out the use in the Star Chart of the taboo form of '*min*', one part of emperor Taizong's personal name, confirming a date after the end of his reign (i.e. +649 onwards). He also points out that the character '*dan*', forming emperor Ruizong's personal name, is in its standard, non-taboo form. This suggests a date before this emperor came to the throne. Ma gives this as +710. However, Ruizong also ruled briefly in +684 (e.g. see Fairbank and Twitchett, 1979), and the taboo form should have been in effect from this earlier date. There are no other characters from later emperors' or empresses' names appearing in the manuscript in either standard or taboo form. This is fairly strong evidence that the manuscript dates from between +649 and +684. The individualistic style of the handwriting supports this conclusion: it is not the handwriting of a scribe paid to make an exact copy of an earlier manuscript. These two pieces of evidence seriously challenge Needham's +940 date.

(e) The date suggested by the drawing, which Ma Shichang argues is a style common during Empress Wu Zetian's reign. The clothing is fairly generic, but the official hat does provide some useful supporting evidence (see Figure 10). From the tenth century it became common for officials to starch their hat flaps so that they stuck out horizontally. This image shows unstarched hat flaps, also suggesting an earlier date.

(f) The date of the sky epoch as it is graphically represented in the maps. This is provided by the astronomical analysis presented here. The sky configuration may be dated using (a) the location of the Celestial Equator in the stellar maps, and (b) the position of the Pole in the circumpolar map. On the short stretch of each hour-angle map, the location of the Celestial Equator is too imprecise to be a useful constraint (see Table 3). However, the projection analysis of the circumpolar chart gives a meaningful constraint on the position of the Pole (Figure 8). The configuration is fully consistent with a date around +650.

(g) The date corresponding to the additional culmination texts. The analysis of the Sun's position among the mansions as indicated in the maps, points to a configuration at dates −40 and +220, which puts these texts at an earlier epoch than the maps. This suggests that the texts in the document may be a compilation from different sources.

From our analysis, it is likely that both the original document and its possible copies were produced in the interval +649-684, at the beginning of the Tang Dynasty, a period rich in significant works on astronomy. This precise date range is provided by the 'taboo characters' and is consistent with all other estimates. This date range encompasses a time contemporary with Li Chunfeng, and is earlier than the period when the important astronomical text *Kaiyuan Zhanjing* was produced. It also corresponds to the full apogee of the Tang domination in the Gobi region where the manuscript was found. The preliminary date of about +940 initially suggested by Needham—but on grounds that we were unable to trace—is certainly not confirmed by our analysis, although it is still compatible with the date at which the Dunhuang library was sealed (c. +1000). At this time China was divided and so the conditions were certainly less favourable for production of such a sophisticated scientific document.

5.2 A Comparison with Other Sources

It is outside the scope of this paper to review all the different sources where a pictorial representation of the sky is included, but what we will do here is consider S.3326 in relation to other important early artefacts with similar contents.

In China, before the Dunhuang Map, only a few documents or artefacts had graphical depictions of the sky, and none showed it in its entirety. Among the oldest such artefacts is a lacquered box found in 1978 in Sui County (Hubei), in the tomb of the Marquis of Yi. Dated from −430 (Warring States period), it is decorated with the first-known representation of the 28 mansions encircling the central *Bei Dou* (Ursa Major), but has no other detail on the sky (Li Changhao, 1987: 45; Rawson, 1997). Later sky representations were also found in the ceilings of different tombs such as the Jiatong Tomb, dated −25 (Stephenson, 1993) and the Luoyang Tomb, dated +526 (*Album of Ancient Relics* …, 1980), but all contain a very limited fraction of the sky. The closest comparable document to S.3326 is the already-cited *Bu Tian Ge* (Iannaccone, 2002; Zhou, 2004). This book, dating from +590-600, includes sky illustrations with stars and asterisms comparable to the Dunhuang Map, but limited only to the mansions at the Equator and the North circumpolar region. Although it may be considered as a preliminary version, it is by no means as complete and accurate as S.3326.[16]

Figure 10: The last section of the S.3326 document showing the image of a bowman in traditional clothes shooting an arrow. Judging by the caption to the right of the image, the figure is the god of lightning (Dian Shen 电神). The drawing is followed by what appears to be a title (to the left). The clothing is typical of an Imperial functionary and the official hat provides some evidence of the epoch. After the tenth century it became common for officials to starch their hat flaps so that they stuck out horizontally. This image shows unstarched hat flaps, which suggests an earlier date.

Later, i.e. after +700, the production of star atlases continued in China, Korea and finally in Europe, and different Chinese maps immediately followed S.3326. They of course largely benefited from the improvement in observational methods during the Song Dynasty (960-1279). Two outstanding Chinese star charts with a complete coverage of the observable sky are mentioned by Needham (1959: 277-279), and are still the only available ones from the Song period.

The Su Song Atlas, included in the book *Xin Yixiang Fa Yao* (新仪象法要, *New Design for an Armillary Clock*) by the astronomer Su Song, is dated to +1092 by Needham. It is a set of five maps, more elaborate and more complete (1,464 stars) than S.3326, and comprises two (instead of twelve) rectangular maps (where the mansions, the Celestial Equator and the Ecliptic are conspicuously drawn), one circumpolar map and two North and South polar projection maps. All five maps are reproduced in *Zhongguo Heng Xing Guance Shi (History of the Observation of Fixed Stars in China)* (Pan, 1989: 436-438).

The Suzhou Map (*Suzhou Tian Wen Tu* 苏州天文图) is a planisphere which was engraved in stone in +1247 and is still visible in a temple in Suzhou (Jiangsu). The astronomer Huang Shang prepared it in +1193 for the instruction of a future Emperor of the Song Dynasty. It is remarkable since it is accompanied by an explanatory text which is a full astronomical treatise. This text has been translated by Chavannes (1913). The Suzhou Planisphere is more elaborate than S.3326 in the sense that it shows radial grids converging on the North Pole and corresponding to the equatorial mansions. It also displays the Celestial Equator, the Ecliptic and the Milky Way. Like S.3326, it extends up to the declination limit beyond which stars are no longer visible from the observing site.

Those two star atlases allow an assessment of the astronomical quality of S.3326, which is 400 and 500 years earlier, respectively. It is interesting that all three maps are based on the same ‘Three Schools’ list of stars and asterisms. Progress in celestial observation under the Song—but within the context that the same objects were observed as before the Han—originates from documents like S.3326. It is a valuable witness to the advance of ancient Chinese astronomy.

In Western civilisations there are no known extant sky charts before the early Islamic work by the Persian astronomer, Al-Sufi (+903-986), the *Book of Fixed Stars*, illustrated with constellation pictures with stars (see Hafez, 2009). Unfortunately, apart from a unique copy kept in Oxford which possibly dates to +1009-1010 (Brend, 1994; Wellesh, 1959), no contemporary examples survived, and the earliest other copies are from the twelfth century. In these, the sky is displayed through independent panels showing stars in separate constellations, but without any indication of the constellations’ relative positions. Among the other related works in Europe, only the Farnese Globe is older than the above documents. It is considered to be a Roman copy from the second century AD of a Greek original dating from before the modern era (Duke, 2006; Schaefer, 2005). Although the major constellations of the Greek sky are carved on marble, no individual stars are positioned on the sphere; therefore it is hardly comparable to a full star atlas such as S.3326. Similarly, the other famous source, the Denderah Zodiac, dating to –50 (Aubourg, 1995) and preserved in the Louvre Museum, shows only constellations, with no identifications and no individual stars. In the same way, a Carolingian manuscript (dated +818), drawn according to Aratus, and sometimes referred as the earliest European star atlas, shows only naïve drawings of a few constellation figures, without stars (Whitfield, 1995).

The tradition of representing the sky finally came to Europe during the early Renaissance. The oldest true star atlas in Europe is probably the Vienna manuscript (Oesterreichische Nationalbibliotek MS 5415) dating to ca. +1440, which contains the main northern constellations and a limited number of stars. It is plotted in a polar projection from the ecliptic pole (Whitfield, 1995), and dates some seven centuries after the Dunhuang Star Atlas.

An extensive compendium of astronomical maps, mostly from the Western world, can be found in Gingerich (1983). Meanwhile, Chinese star atlases are listed by Feng Shi (2001).

5.3 The Purpose of S.3326

S.3326 lacks its cover and introduction which might have guided us as to its purpose. The first section of the extant document is concerned with uranomancy. The star atlas follows and completes the manuscript. The scroll also lacks its end sheet so we have no way of knowing whether it originally consisted of only these two texts or more. What could be the use of the star atlas which follows this first section of the manuscript? We can only make conjectures.

Dunhuang was an important strategic town for the Chinese during much of the first millennium and was administered by Imperially-appointed officials, the senior ones from Central China. The administrative office kept archives of important documents. It is hypothesized that, because of the shortage of paper during the Tibetan rule of Dunhuang (ca. +781-868), documents from the Chinese administrative archive were recycled—with Buddhist *sutras* being inscribed on the backs or versos. At other times, the backs of Buddhist texts were used. Such documents came to be stored in the Library Cave, a Buddhist library. Documents like S.3326, with no Buddhist text on the back, could have been kept there for future use.

A manuscript such as S.3326, however, contains very important and valued official knowledge. Astronomy in China was an essential Imperial science as divination based on events taking place in the celestial mirror image of the Empire was the way to rule the state. S.3326 was either copied in Dunhuang or originally produced at the Imperial Observatory and brought to Dunhuang. There is no evidence that Li Chunfeng, a possible author of the original version of S.3326, ever went to Dunhuang. As a high official during the early Tang Dynasty he would have lived in Chang’an, the capital. He remained in office at the Imperial Observatory until at least +664, occupying from about +648 the position of *Taishiling*, (太史令) i.e. Director of the Astrological Service (Chemla and Guo Shuchun, 2004; Deng Kehui, 2007).

We can also focus on the portable character of the document. It is possible that we have in hand not a scientific text intended for scientists only but a product of more popular use which existed in the form of several copies for several users. This would suggest that such texts could have been multicopied and that the version found in Dunhuang is merely one example from among others that were copied from the original. As we have noted, the calligraphy is not of Imperial standard. Since the manuscript found in Dunhuang has two consecutive sections on the same paper support, the purpose of such a scroll could have been for travellers or warriors on the Silk Road who needed predictions of the future to assist them with their travels, both with respect to clouds (hence the weather) and aspects of the night sky. But the high quality of the paper and the importance and sensitivity of the subject-matter argues against this. S.3326 is a mystery and, unless we discover similar documents, we might never know its original purpose.

6 CONCLUSION

At the end of this paper it is legitimate to again underline the importance of the Dunhuang Star Atlas, S.3326.

It has a special position in the history of astronomy, as it is the oldest extant graphical star atlas known from any civilisation. There is no equivalent either in Western Europe or in any other civilisation. Although it was found at the edge of the central Chinese Empire, a region open to different influences and not always controlled by the Chinese, this precious document was conceived in the purest Chinese astronomical tradition. It is probably a synthetic document that encompasses information of different origins for the use of scientific astronomy as well as divination purposes.

S3326 is the earliest known pictorial presentation of the traditional Chinese constellations. Individual stars, more numerous than in Ptolemy's catalogue, are represented and grouped into constellations. This star atlas gives us a full representation of the Chinese sky in strict accordance with all previously-known catalogues, retaining the old tradition of using different colours to identify asterisms named and described by the three earlier schools of the Chinese astronomy. The information on the star positions is delivered using a careful systematic method that makes use of accurate projection methods. This is unique considering the period of the document, and in all points is similar to present-day techniques. The overall accuracy (of the order of a few degrees) is surprising for a document from an early epoch and considering the relatively small dimensions of the paper roll.

The Dunhuang Star Atlas also includes additional texts with information relating to a conventional calendar (the position of each lunar month in the seasons and within the Jupiter cycle), as well as some specific astronomical conjunctions within each month. These texts are also part of the ancient Chinese astronomical tradition as they are only slightly different versions of known earlier sources, namely the *Yueling* (not older than –240), the *Jinshu* (with a redaction around +635), and probably the later source, *Kaiyuan Zhanjing* (dated +729).

The source of S.3326 is probably the early Chinese lists of stars such as those included in the third century Chen Zhuo catalogue. Based on different arguments, the dating of the star atlas (+649-684) shows that it could originally have been drawn by Li Chunfeng around +650, although the lack of a front cover and other evidence does not allow us to confirm this.

Nonetheless, the Dunhuang Star Atlas, as we have it today, was preserved by chance in a hidden cave for almost a millennium and this makes it a unique witness to the sky as it was seen during the Tang Dynasty.

7 NOTES

1. The International Dunhuang Project (IDP) was started in 1994 "… to promote the study and preservation of the archaeological legacy of the Eastern Silk Road through international cooperation." Its directorate is based at the British Library (see http://idp.bl.uk).
2. The dates in this paper are given in the so-called astronomical system where year –1 corresponds to 2 BC (or 2 BCE) and year +1 to AD 1 (or 1 CE).
3. The Chinese Government removed only the Chinese manuscripts leaving the remaining Tibetan manuscripts behind, and they are now in collections throughout Gansu Province. The Stein Collection was divided between the British Museum and the Government of India, co-sponsors of his expedition, and part of the Dunhuang Collection is in India's National Museum in New Delhi. The Japanese collections were dispersed and a large part is now in the National Museum of Korea in Seoul.
4. The manuscripts in the British Museum became part of the British Library collection with the establishment of the latter institution in 1972. S.3326 is now preserved in the Asian, Pacific and African Collections of the Library.
5. Re Giles's retirement in 1940, and the initial offering of the manuscript for publication in 1947, see Wood (1996).
6. Chinese characters are given here in their simplified form together with their standard 'pinyin' transcription in Latin letters (marked in italics).
7. Their precise origin is still an enigma and their relation to the Moon is not documented. However, these constellations were constantly used throughout Chinese history as precise markers of the positions of heavenly bodies during the seasons.
8. For those not familiar with the convention, during the reign of any emperor, characters that made up the emperor's personal name were not allowed to be used in their standard form. The characters were changed slightly—usually by omitting or adding a stroke. This is known as the 'taboo' form of the character. After the emperor's death, the 'taboo' forms of any of the characters in his name—not just his whole name—were used until the end of that dynasty. The consistent use of the taboo characters in *all* documents is not absolutely certain, but the fact that a taboo form is used in this document suggests that the rule was being followed.
9. From a study carried out by Anna-Grethe Rischel (National Museum of Denmark) who remarks that the fibres are "… particularly long and fine." Images of the manuscript and fibres are shown on IDP direct link http://idp.bl.uk/database/oo_loader.a4d?pm=Or.8210/S.3326
10. "The roller has been lined with acid-free Japanese tissue paper to protect the object from acid migration. The Kraft lining extends to both end maps. Due to the lack of written surviving documentation it is impossible to trace the history of conservation of the object, so our remarks can only be based on transmitted knowledge and visual observation. Using transmitted light it is possible to observe a long patch running along the whole length of the scroll. This patch has an irregular shape with non-defined margins. This might suggest that the patch is contemporary with the object, and was obviously not removed when the lining was applied. Other evidence to support this is represented by the fold lines, which can be observed in some areas. This fold runs through the patch and along the object in a continuous manner suggesting that the patch has indeed been in place for a long time although not conclusive in respect to a precise dating. There is evidence of other small patches along the manuscripts although some were removed as we could only observe their shape in the imprint they left in the paper." Description by Barbara Borghese, IDP UK and European Project Manager (private communication).

11. This title has been transliterated in some recent Chinese publications as "Qi jie meng ji dian jing yi juan", with the suggested translation of "Interpreting Dreams and Book of Lightning in One Chapter" (Deng and Liu, 2003). However, this interpretation is problematic. Firstly, it ignores the first character '*qi'*, which makes no sense in this context. Secondly, it reads the third character, which is in a non-standard form, as '*meng*' (= dreams) even though this is not an attested variant of '*meng*'. A more probable reading would be 蔑 or '*mie*' (= scorn, villify). And two titles like this joined with '*ji*' (and) is not a form seen in China.
12. The Chinese degrees are defined according to the mean year duration (325.25 days) and therefore 365.25 Chinese degrees corresponding to 360 European degrees.
13. The correlation coefficient, R, is the Pearson least-squares fit parameter with the value of R = 1 for a perfect fit and R = 0.76 and 0.68 for a random probability of 0.01% and 0.1% respectively.
14. Translation by Imre Galambos (British Library). He also notes that the first part of the compilation of *Lushu Chunqiu,* sponsored by Lü Buwei in the mid-third century BC, is concerned with the correlation of colours and the workings of the Universe.
15. The mention found here only differs from the one in *The Nine Chapters* by the use of '*yan*' (says) instead of '*an*' (comments) and the absence of 'with respect'. (K. Chemla, pers. comm.).
16. There is also a star catalogue forming part of Shi Shen's works which contains illustrations of asterisms within the Chinese mansions. A copy is preserved in Kyoto. We have not seen this manuscript and can merely cite Fung Kam Wing's (2003) paper.
17. An early discussion of ancient North Pole stars can be found in de Saussure (1930: 494-525).
18. No mention is made in the *Jinshu* (Ho, 1966) nor in the Han catalogues (Sun and Kistemaker*,* 1997).

8 ACKNOWLEDGEMENTS

We are indebted to Barbara Borghese, Karine Chemla, Vincent Durand-Dastets, Imre Galambos, Zhang Guangda, Isaia Iannaccone, Marc Kalinowski and Bernadette Zhu for their remarks and contributions.

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10 APPENDICES

10.1 The Orion Stellar Region (Map 5)

The sky region displayed on Map 5 (fourth lunar month) extends from –30° to +40° in declination (Figure 3 and Table 4). Right ascension increases from ~50 to 100°, right to left, i.e. west is to the right of the map, east to the left. This particular map is different from most of the other maps in that a major constellation can be recognised: *Shen* 参, or Orion, is a rare case where a constellation seen by the ancient Chinese is similar to what we are used to in the Western world.

The map contains 109 stars, grouped in 20 Chinese asterisms (see Table 4). The northern features are *Wuche* 五车 and *Sanzhu* 三炷, both forming Auriga. The two mansions *Zui* 觜 and *Jing* 井 are easily found south of it. *Shenqi* 参 旗 and, further South, *Shen* (also a *xiu*), comprise the brightest stars in Orion. Three not encircled, hazy, red stars form the group named *Fa* 伐, but here no label is present; they represent the multiple star θ Orionis, and maybe also M42 (The Great Orion Nebula), which is visible to the naked eye. To the southeast of *Shen*, but located too far north by about 10°, one finds the star *Yeji* (β Canis Majoris), surrounded by a crown of 11 stars. It is noticeable that this crown (asterism *Junshi* 军市) is formed of faint stars that a modern naked eye could hardly distinguish (visual magnitude around 6). However, the very bright star *Lang* 狼 (α Canis Majoris, or Sirius) is not related to *Yeji* and is found on Map 6. The modern constellation Lepus is here spread into several small asterisms, all at about the same declination, which is not correct. Finally two groups of two stars (*Zi* 子 and *Zhangren* 丈人) are identified as belonging to the constellation of Columba, but in this case they are also drawn too far north as compared to *Ce* 厕, *Junjing* 军井 and *Ping* 屏.

This chart, the drawing of which is quite clear, shows nevertheless that the author had difficulties positioning the southernmost stars of the zone. The constellations which are best represented are those along the Celestial Equator (declination 0°). Several stars and asterisms which are described in the *Jinshu* are absent from this map: within *Wuche* the asterisms *Tianhuang* 天潢 and *Xianchi* 咸池; south of *Wuche* the star *Tianguan* 天关; and the asterisms *Siguai* 司怪 and *Wuzhuhou* 五渚候.

Calendar text (2 columns, left)

From the 12th degree of *Bi* to the 15th degree of *Jing*, the astral position is *Shen*. It is *Shichen*, the sinking (or fructification). It is said that at the 7th lunar month, ten thousands creatures are full of force and blossoming, the yin spirits deepen and are heavy; the ten thousands creatures fructify. For this, it is called *Shichen*. It is part (of the state) of *Wei*.
自毕(?) 十二度 至井十五度

Culmination text (3 columns, bottom)

The fourth (lunar) month, the Sun meets the mansions *Bi* and *Zhu*, at dusk the mansion *Yi* culminates, at dawn the mansion *Nü* culminates.
四月 - 日會畢觜 - 昏翼中 - 旦女中

10.2 The Circumpolar Map (Map 13)

The circumpolar map (Figure 4) is a rich one in that it displays 144 stars. This indicates the attention with which Chinese astronomers observed this northern part of the sky, which was supposed to be the seat of the Emperor, his family, the court and the officials. On the Dunhuang maps, the names of all asterisms are easily read therefore identification is not dubious, inasmuch as the author of the map is correct.

The map extends over 40° in declination (from about 50° to 90°). A major role is played by the Pole (or pivot) Star, around which the sky seems to revolve. On the S.3326 map, this star is not specially indicated. A red hazy spot, not encircled in black, could be it. The asterism *Sifu* 四辅, a group of four stars representing the four advisors to the Emperor, is close to this spot, on its western side, but does not surround it. The Emperor sits in the Purple Palace (*Zigong*). The Palace is surrounded by an eastern wall (7 stars, left on the map) and a western wall (8 stars, right on the map) constituting *Ziwei*, one of the three enclosures (*yuan*) of the Chinese sky. A number of high officials, commodities such as grains, or rooms such as kitchens or bedrooms, are also represented in the sky (see Table 5). Of the three asterisms named kitchen (*chu*) in the Chinese sky, two are found on the circumpolar map: *Tianchu* 天厨 and *Neichu* 内厨 (but the latter is without a name on the map; see below).

Table 4: Content of Map 5 (The Orion Region).

Map: 5
Month: 4 (*wu yue*)
Xiu: *Zhi*, *Shen*, *Jing*
(The fourth lunar month), the Sun meets with the mansions (*xiu*) *Bi* and *Zhi* (*Zui*); at dusk the mansion *Yi* culminates; at dawn the mansion *Nü* culminates.
Totals: 20 asterisms and 109 stars.

	Asterism[1] (pinyin) by RA and from N to S	Asterism (common Chinese name)	IAU[2] Constel -lation	Identifi-cation in SXC[3]	Colour (R, B, W)[4] on map	Nb[5] of *[6] (SXC)	Nb of * on map	Ident. of one star (SXC)	Remarks (between quotes are comments by SXC)	Conf. Index[7] (ident.)
1	*Wuche* + *Sanzhu*	Five chariots+ three poles	Aur	I 37	R	14	14	ι Aur		5
2	*Zhuwang*	Several princes		II 60	R	6	5	τ Tau	"6 * S of *Wuche*."	5
3	*Zuoqi*	Left banner	Aur	II 62	B	9	8	κ Aur	"9 * NE of *Siguai*."	5
4	*Tian zun*	Celestial wine cup	Gem	II 59	B	3	3	δ Gem	"3 * N of *xiu Jing*, E of *Zuoqi*."	1
5	*Tiangao*	Celestial high terrace	Tau	II 63	W	4	4	97 Tau	"4 * close to *xiu Bi*." Note that *Bi* is on S 3326 Map 4.	4
6	*Jing*	Eastern well	Gem	I 114	W	8	8	μ Gem		5
7	*Shenqi*	Shen banner	Ori	I 82	R	9	6	π Ori		5
8	*Zui*	Bird beak	Ori	I 112	W	3	3	φ Ori		5
9	*Shuifu*	Water palace	Mon	II 106	B	4	4	ν Ori	"4 * S of *xiu Jing*." Labels are inter-changed for *Shuifu* and *Sidu*.	4
10	*Sidu*	Four rivers	Ori	II 107	B	4	4	ε Mon	"4 * S of *xiu Jing*." Labels are inter-changed for *Shuifu* and *Sidu*.	4
11	*Shen*	Warrior-hunter	Ori	I 113	R circled black and red alone	10	10	δ Ori	No label for *Shen* on the map. The three hazy red stars are *Fa*, the dagger (no specific label).	5
12	*Jiuliu*	Nine flags	Ori	I 104	B	9	9	54 Eri?	"9 * SW of Yujing." No label on the map.	5
13	*Yujing*	Jade well		I 83	R	4	4	β Eri	A circle of stars close to β Ori.	5
14	*Yeji*	Pheasant cock	C Ma	I 88	R	1	1	β C Ma		5
15	*Junshi*	Soldiers market	Lep	I 87	R	13	11	17 Lep	Surrounds *Yeji*.	5
16	*Ping*	Toilet screen		I 84	W	2	2	μ Lep	The group is labelled but not at its place; should be S of *Junjing*.	2
17	*Junjing*	Soldiers well	Lep	II 105	B	4	4	κ Lep	"4 * SE of *Yujing*."	2
18	*Ce*	Toilet with a shed	Lep	I 85	W	4	4	β Lep		5
19	*Zhangren*	Husband man	Col	II 110	B	2	2	ε Col	"2 *SW of *Junshi*." *Zhangren* and *Zi* should be more S of *Ce* and *Junjing*.	5
20	*Zi*	Son	Col	II 111	W	2	2	β Col	"2 * E of *Zhangren*." *Zhangren* and *Zi* should be more S of *Ce* and *Junjing*.	5

1 Asterisms are listed from North to South and from West to East (i.e. in increasing right ascension).
2 IAU = International Astronomical Union.
3 The lists, labelled I, II and III, are found in Sun Xiaochun and Kistemaker (1997). This book name is abbreviated as SXC.
4 R = red, list of Shi shi (I); B= black, list of Gan shi (II); W = white, list of Wu Xian shi (III).
5 NI = Unidentified.
6 * means star.
7 Confidence index: from 1 to 5; 5 = very good, 1 = bad.

Table 5: Contents of Map 13 (The Northern Circumpolar Region).

Map: 13
Month: North cicumpolar zone
Xiu:
Totals: 34 asterisms (1 of which is unidentified) and 142 stars (+ 3 in *Beiji*). All stars on this circumpolar map belong to *Shi Shi* or *Gan Shi*.

	Asterism[1] (pinyin) by RA and from N to S	Asterism (common Chinese name)	IAU[2] Constel-lation	Identifi-cation in SXC[3]	Colour (R, B, W)[4] on map	Nb[5] of *[6] (SXC)	Nb of * on map	Ident. of one star (SXC)	Remarks (between quotes are comments by SXC)	Conf. Index[7] (ident.)
1	*Tianchu*	Celestial kitchen	Dra	II 15	B	5	6	δ Dra	"5 * outside the NE wall of *Ziwe*i."	5
2	*Wudizuo*	Seats of five *Di*	Cep	II 4	B	5	5	γ Cep?	"5 * inside *Ziwei* below *Huagai*; rather E of *Huagai*."	5
3	Chuanshe	Guest rooms		II 17	B	9	7	3947 Cam	"9 * above *Huagai*."	5
4	*Tianzhu*	Celestial pillars	Dra	II 6	B	5	5	? Dra	"5 * inside *Ziwei* close to the Eastern wall."	5
5	*Liujia*	Six *jia*	Cam	II 5	B	6	5	? Cep	"6 * inside *Ziwei* near the handle of *Huagai*."	5
6	*Huagai*	Canopy of the Emperor	Cas	II 3	B	7	7 (+ 6)	? Cas	"7 * above *Tianhuang*." What is 6? Is it *Gang*? But character for *Gang* is absent; see also below.	4
7	*Gouchen*		U Mi	I 60	R	5	6		Classified with *Beiji* by SXC; could be the handle of U Mi in modern terms, ending with α U Mi, or the handle of *Huagai*.	5
8	*NI 1*		U Mi		R		1		1 * without character East of *Gouchen*; could be δ U Mi.	
9	*Tianhuang*	High God of Heaven	U Mi	II 1	B	1	4	? U Mi	"1* inside *Gouchen*"; here 4 * two of which belonging to U Mi.	3
10	*Ziwei*	Celestial Purple Palace wall	Dra	I 59	14 R, 1 B	15	15	κ Dra	Two walls, E and W, just as for *Taiwei*.	5
11	*Zhuxiashi*	Officer in charge of communi-cation	Dra	II 7	R	1	1	χ Dra	"1 star inside *Ziwei* N-E of *Beiji*."	5
12	*Nüshi*	Woman officer	Dra	II 8	R	1	1	φ Dra	"1 * N of *Zhuxiashi*"; it is rather W of *Zhuxiashi*.	5
13	*Tianpei*	Celestial flail	Dra	I 7	5 R, 1B?	5	5 or 6	ι Her	Asterism to the extreme left (E) of the map.	5
14	*Shangshu*	Secretary	Dra	II 9	B	5	5	15 Dra	"5 * in the SE of *Ziwei*."	5
15	*Beiji*	North Pole Office	U Mi	I 60	R	5	4	β U Mi	*Beiji* continues with 3 * drawn in B, without characters. Moreover a R non-encircled star slightly erased could be the Pole star.	4
16	*Sifu*	Four advisors	Cam and U Mi	II 2	B	4	4	? U Ma	"4 * surrounding the N Pole"; is the N. Pole visible?	5
17	*Neijie*	Inner steps	U Ma	II 14	B	6	6	2 Dra	"6 * N of *Wenchang*"; asterism outside *Ziwei* to the right of the map (W).	5
18	*Bagu*	Eight species of grains	Cam	II 65	B	8	8	β Cam	"8 * N of *Wuche*"; the character after *Ba* is not easily read; *Wuche* is not on this map.	3

19	*Tianchuang*	Celestial bed	Dra	II 11	B	6	4	? Dra	"6 * outside the doors of *Zi gong* (= *Ziwei*)"; SXC likely include the 2 * which we identify as *Taiyi* and *Tianyi*. The latter may be located further right, just above δ U Ma.	3-4
20	*Taiyi*	Supreme unity		I 62	B	1	1	8 Dra	Unambiguous character. But may be wrong position. Star discussed by de Saussure (1930).	3-4
21	*Tianyi*	Heavenly unity		I 61	B	1	1	7 Dra	Unambiguous character. But may be wrong position. Star discussed by de Saussure (1930).	3-4 cf supra
22	*Tai*			Not in SXC	B		1	?	1 character, 1* near the S border of the W part of *Ziwei*.	
23	*Tian*			Not in SXC	B		1	?	On the *Suzhou* map, these two stars are *Taiyi* and *Tianyi*.	
24	*Sangong(2)*	Three excellencies	U Ma	Not in SXC	B		3	?	East of Wenchang. Unambiguous character.	5
25	*Tianqiang*	Celestial spear	Boo	I 6	R	3	3	κ Boo		5
26	*Beidou*	Northern Dipper	U Ma	I 58	R	8	7	α U Ma		5
27	*Tianli*	Great Judge for Nobility	U Ma	II 12	B	4	4	? U Ma	"4 * inside the scoop of *Beidou*."	5
28	*Wenchang*	Administrative center	U Ma	I 57	R	6	5	ο U Ma	Note: ο U Ma is not on the map.	5
29	*Xuange*	Halberd	Boo	I 5	R	1	1	λ Boo	Small problem of declination on the map between η et ξ U Ma.	5
30	*Sangong(1)*	Three excellencies	C Vn	II 39	B	3	3	24 C Vn	"3 * S of the handle of *Beidou*."	5
31	*Xiang*	Prime Minister	U Ma	I 54	R	1	1	χ U Ma	Identification as χ U Ma not correct; should be S of γ U Ma.	5
32	*Taiyang-shou*	General in charge of the *yang valve*	U Ma	I 55	R	1	1	ψ U Ma	Identification of SXC as ψ U Ma dubious, ψ U Ma should be S of β U Ma.	?
33	*Shi*	Eunuch official	U Ma	II 55	B	4	4	? U Ma	"4 * N of *Taiyangshou*"; this star is not N of *Taiyangshou*, but W.	5
34	*Tianlao*	Celestial prison	U Ma	I 56	R	6	6	44 U Ma		5

1 Asterisms are listed from North to South and from West to East (i.e. in increasing right ascension).
2 IAU = International Astronomical Union.
3 The lists, labelled I, II and III, are found in Sun Xiaochun and Kistemaker (1997). This book name is abbreviated as SXC.
4 R = red, list of Shi shi (I); B= black, list of Gan shi (II); W = white, list of Wu Xian shi (III).
5 NI = Unidentified.
6 * means star.
7 Confidence index: from 1 to 5; 5 = very good, 1 = bad.

The Northern Dipper (*Beidou,* 北斗) is well recognised at the bottom of the map. Contrary to the situation corresponding to the present epoch, the alignment between α and β Ursae Majoris does not point to the Pole Star and does not even enter the *Ziwei* region. Some ambiguity also exists for the one-star asterisms *Xiang* 相 and *Taiyangshou* 太陽首, which are not located accurately south of the Dipper if they are identified with χ and ψ Ursae Majoris respectively, as suggested by Sun & Kistemaker (1997). They are better identified respectively with 5 Canum Venaticorum and χ Ursae Majoris, as proposed by Ho (1966).

Near the Southern Gate of *Ziwei*, a group of six stars raises a question: they are labelled *Tianyi* (天一) and *Taiyi* (太一), *Tian* (天) and *Tai* (太), plus two unnamed stars just 'above' δ Ursae Majoris which we identify with *Neichu* (内厨). The stars *Tianyi* and *Taiyi*, North of ε Ursae Majoris, translated literally as "celestial unique or celestial unity" and "great unique or supreme unity" respectively. Their names refer to a supreme quality, indicating they were once Pole Stars.[18] Two stars, *Tai* and *Tian*, northeast of ε Ursae Majoris, are not mentioned in previous catalogues.[17] Is the confusion on the Dunhuang atlas a copying error? Suggestions have been made of an inversion with two other asterisms, and also of a misinterpretation with two different positions of the Pole in the past (Maeyama, 2002).

An unnamed asterism is located between *Tianhuang* 天皇 and *Gouchen* 狗陈 (in the upper part of the map); it is red and circled in black. Thus it may belong to the Shi Shi Catalogue, and is likely δ Ursae Minoris. The name *Gouchen* on the map refers to a single star (in red), α Ursae Minoris (the present-day Pole Star) and not, as usual, to an asterism of five stars. Within *Beiji* 北极 (an important asterism since it represents the North Pole office) the second red star, named *Di* (Emperor) by the Chinese, but without a name on the map, is identified with β Ursae Minoris*,* which was also once approximately the Pole Star (together with κ Draconis) around –1000.

Altogether, the S.3326 circumpolar map is well documented. There are, however, several imperfections:

(a) The shape of *Beidou* with respect to the *Ziwei* walls differs from that displayed on the Suzhou Map or on any modern map of the sky. The largest displacements affect the extreme stars, η Ursae Majoris and α Ursae Majoris (see Figure 6b). It is because of this wrong position that the alignment α - β Ursae Majoris is poorly oriented.

(b) The asterism *Gouchen* is not represented in full, and the star that we identify with α Ursae Minoris is here the bottom star of the handle (Gang) of *Huagai* 華蓋 instead of being the brightest star of *Gouchen*. Some asterisms (*Wudi* 五帝, *Zhaofu*) also listed in the *Jinshu* are absent on S.3326.

Jean-Marc Bonnet-Bidaud is an astrophysicist in the Astrophysical Department of the French Atomic Energy Commission (C.E.A.), and specialises in high energy astrophysics and in the study of highly condensed stars in the Galaxy. He is also deeply interested in the history and popularization of astronomy. He is currently the scientific adviser of the French astronomy magazine *Ciel et Espace* and has published numerous articles in different magazines and newspapers. He is mainly interested in the history of modern cosmology and in the roots of ancient astronomy in China and Africa.

Dr Françoise Praderie, an outstanding European astronomer, passed away on 28 January 2009, before this paper was published. Prior to that she was an Honorary Astronomer at the Paris Observatory. She was a former Vice-President of the Paris Observatory and former Editor of *Astronomy and Astrophysics*. She contributed to the creation of the trans-disciplinary European association 'Euroscience', where she served as its first Secretary General. Her main research interests are in stellar seismology, and she was the author of the book *The Stars* (which was co-authored with E. Schatzman).

Dr Susan Whitfield is Director of the International Dunhuang Project at the British Library and an historian and writer on China and the Silk Road. She is interested in cross-disciplinary research, combining history, archaeology, art history, the history of religions and science in her study of manuscripts and artefacts from the eastern Silk Road. She has published extensively, lectures worldwide and also has curated several exhibitions, including a display of historical star charts in the collections of the British Library.

Journal of Astronomical History and Heritage, 12(1), 60 (2009).

DOCTORAL DEGREES IN HISTORY OF ASTRONOMY AT JAMES COOK UNIVERSITY

History of astronomy was introduced as a JCU Doctoral option in 2005, and we now have eighteen students enrolled in this area, ten from the USA, six from Australia, and one each from Lebanon and South Africa. Some of the students are studying full-time and others part-time, and all are off-campus. Between them, they are pursuing a fascinating array of projects. The various thesis topics are listed below, along with the names of the associated students.

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- Abdul Rahman al-Sufi and *The Book of the Stars*: A Journey of Re-discovery (Ihsan Hafez)
- Amateur-Professional Collaboration in Astronomy: A History of South Africa's Earliest Astronomical Societies (Wynand Pretorius)
- Comets, Eclipses and Transits of Venus in the 1870s and 80s and their Role in the Popularization of Astronomy in the USA (Stella Cottam)
- Contribution of the Division of Radiophysics Penrith and Dapto Field Stations to International Solar Radio Astronomy (Ron Stewart)
- Contribution of the Division of Radiophysics Potts Hill Field Station to International Radio Astronomy (Harry Wendt)
- Early Pulsar Research and the Roles of the Molonglo Radio Telescope, Parkes and the Culgoora Circular Array (Peter Stark)
- John Bolton and the Enigma of the 'Radio Stars' (Peter Robertson)
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Journal of Astronomical History and Heritage, 12(1), 61-65 (2009).

SOME EARLY ASTRONOMICAL SITES IN THE KASHMIR REGION

Naseer Iqbal
Department of Physics, University of Kashmir, Srinagar, India 190006.
E-mail: naseerphysics@kashmiruniversity.net

M.N. Vahia
Tata Institute of Fundamental Research, Mumbai, India 400005.
E-mail: Vahia@tifr.res.in

Tabasum Masood and Aijaz Ahmad
Department of Physics, University of Kashmir, Srinagar, India 190006.
E-mails: Tabasum_phd@rediffmail.com
ajaz_dr@yahoomail.com

Abstract: We discuss a number of early rock art sites in the Kashmir Valley in northern India and neighbouring Pakistan, and suggest that some of these contain depictions of astronomical objects or events. The sites are in the Srinagar and Sopore regions and in or near the Ladakh region, and date to Neolithic or Upper Paleolithic times. Our studies suggest that during this period some of the ancient astronomers recorded supernovae, meteorite impacts, the Sun, the Moon and the seasons in their rock art.

Key words: Ancient astronomy; stone carvings; supernovae; meteorite impacts.

1 INTRODUCTION

Archaeoastronomy is the study of ancient or traditional astronomies in their cultural context, utilizing archaeological evidence. The subject uses historical records of heavenly events to infer the astronomical knowledge of our ancestors. Archaeoastronomy also uses monuments and written records to evaluate astronomical traditions. The importance of archaeoastronomy is that it allows us to understand something about prehistoric times and the knowledge of astronomy that flourished. In other words, archaeoastronomy can be used to identify prehistoric astronomical practices. There are a number of ways of studying archaeoastronomy, including through

1) the architecture of ancient monuments (e.g., see Menon, 2007);
2) simulations of ancient observatories and situations (e.g., see Hrishikesh et al., n.d.);
3) Harappan script pattern recognition (e.g., see Yadav and Vahia, n.d.); and
4) stone carvings (e.g., see Masood, 2007).

The Kashmir region of India (Figure 1) is rich in stone carvings. Stone carvings often have abstract representations, and large numbers of poorly-understood stone carvings raise interesting issues about the history of civilization. These mysteries pose important questions and lead to new answers about the people of the ancient world, including their culture, language, architecture, astronomy and religion. Ancient people viewed heavenly objects as unknowns and sometimes expressed their state of knowledge through their stone carvings.

Figure 1: Map showing the locations of Kashmir and Ladakh in northern India (blue and purple), and the neighbouring regions of Pakistan (green).

Various carvings found in Kashmir and in the areas of Drass in Ladakh and Chillas (bordering Ladakh, in Pakistan) indicate that there was a tradition of recording astronomical events in prehistoric times. In this paper, we discuss sites in three different areas of Kashmir that appear to present evidence of this type.

2 ANCIENT ASTRONOMICAL ROCK ART SITES

On the basis of visiting various sites and studying their astronomical aspects, we believe that the following sites were used by ancient peoples from time to time for astronomical observations and therefore are the oldest 'observatories' in Kashmir.

Figure 2a: Stone carving located at Bomai Sopore in the Baramulla District of Kashmir.

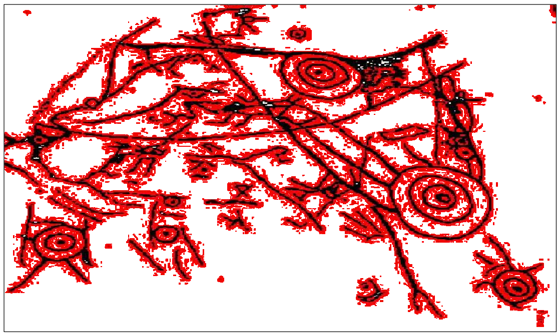

Figure 2b: Drawing showing the concentric circles of different sizes in Figure 2(a).

2.1 Bomai Sopore (Baramulla-Kashmir)

In northern Kashmir there is a place called Bomai Sopore ~70km northwest of Srinagar. This region was occupied during the Upper Paleolithic period, from ~20,000 to 6,000 BP. There is a conspicuous rock carving in this area situated at 74° 30′ longitude and +34° 22′ latitude, at the northwest end of a 3,000m high plateau with peaks to the southeast rising to ~3,500m. The rock surface has multiple concentric circles (Figures 2a and 2b), and is situated on the side of a mountain ~100m from the fields, and overlooking the eastern side of the famous Wular Lake. We believe that this rock carving depicts a meteorite impact that occurred some time between 40,000 BP and 6,000 BP (Vahia et al., n.d.). It has already been observed that when it impacts a meteorite can deform the surface on which it lands. Such fractures can take the form of concentric rings around an impact crater. The impact of a massive meteorite or a small asteroid can also induce volcanic activity if the area it strikes contains hot lava that can rise up through the crust (Gibilisco, 2003). We believe that the astronomical interpretation of this stone carving is consistent with this interpretation because the carving has multiple concentric circles distributed across the entire picture (see Figure 2a and 2b). Vahia et al. (n.d.) have already postulated that a single meteoroid may have splintered into several pieces as it penetrated the atmosphere and that if any of the larger fragments landed they would have formed craters or pits.

There are four lakes in this region—which appear to correspond to the four circles in the drawing—and several smaller water bodies, all consistent with a multiple impact event. Also, the orientation of the lakes indicates that the meteoroid entered the region from the northwest and fell in a southeasterly direction. Three of the circles in Figure 2a are collinear and three of the lakes are also aligned in the same direction. In this scenario (see Iqbal et al., 2008 for details), Wular Lake (the largest in India) can be associated with the top-most circle; the second circle relates to Manasbal Lake; the third circle to Dal Lake; and the fourth circle to Hokerser Lake. The small circle between the two larger circles corresponds to the small water bodies which exist between these lakes. We believe that the line adjacent to the three collinear circles indicates the flight path of the meteoroid, or the associated (smoke) trail, and the relative sizes of these three circles indicate the changing brightness of the object. All this seems consistent with a meteorite impact. In order to examine this hypothesis, we reviewed the relevant geological literature and also carried out our own research around Dal Lake. We found the following evidence that, in our view, supports a meteorite impact:

1. Dal Lake was originally a basin-like structure, but has been deformed through erosion since its formation.
2. Coulomb excitation measures of different samples taken from Dal Lake revealed the presence of those same elements found at Lonar Lake, which is known to be associated with a meteorite impact (see Chowdhury and Handa, 1978). About 70% of the Dal Lake samples matched the elemental abundance levels obtained at Lonar Lake.
3. Wadia (1953) reports evidence of shock metamorphism in the vicinity of Dal Lake.
4. Jeelani and Shah (2006) report the presence of basalts and breccias in the vicinity of Dal Lake.
5. The pH value of the water at a depth of 2m in the Lake, and from the surrounding mountains averages >9.7.

2.2 Burzahama (Srinagar-Kashmir)

The site of Burzahama is located in the Kashmir Valley at 74° 54′ longitude and +34° 10′ latitude and is 17km northeast of Srinagar. To its east is the glaciated peak of Mahadev Mountain, while the glittering waters of Dal Lake lie to the south; there are also mountain ranges to the west. Among dozens of flat rectangular stones found at Burzahama are two bearing engravings. One of these has a base width of 70cm and contains a really impressive example of Neolithic art. The engraved portion is divided into two parts. The upper part shows an animal on the right and on the left depictions of two Suns, one with sixteen radiating lines while the other is somewhat damaged. Below these three elements are another animal (with antlers) and two hunters (see Figure 3a). It would seem that the picture depicts a hunting scene, but Hrishikesh et al. (n.d.) postulate that this is not a terrestrial hunting scene but actually represents a sky map and the locations of prominent constellations and the Moon on the night when a supernova (SN) was observed (see Figure 3b). In this scenario, the hunter on the left in the figure represents Orion, the central animal is Taurus, the hunter on the right may have been formed from stars in Cetus, and the other animal on the right may be Andromeda or Pegasus.

The latitude of Burzahama (34° N) and its geographical setting in the foothills of the Himalayas constrained the number of possible SNe that would have been visible in the past, given the presence of mountains up to 4,000m high both to the north and the east. A further constraint is the age of the site, which on the basis of radio-carbon dating we know to have been utilized between about 5,000 BP and 3,500 BP (Agrawal and Kusumgar, 1965; Pande, 1971). A search of the relevant literature (Green, 2004; Xu et al., 2005) revealed the existence of five different SNe closer than ~5 kpc[1] (and therefore conspicuous at maximum light) that erupted during this period,[2] but three of these had southern declinations and were not easily observed from Burzahama. This left just two viable candidates, HB9 and G182.4+4.3, and these are compared in Table 1.

This Table shows that G182.4+4.3 erupted around 3,800 BP, and at a distance of ~3 kpc would have reached an apparent magnitude of between –7 and –5 at maximum (see Kothes et al., 1998). The other candidate, HB9, exploded some time between 7,000 and 4,000 BP. The distance of this SN is given as 1.1 kpc by Touhy et al. (1979) and 0.8 ± 0.4 kpc by Laehy and Tian (2007), so at maximum it would have reached between –10 and –7.5 apparent magnitude (Laehy and Aschenbach, 1995; Xu et al., 2005).

Both SNe would have been readily visible from Burzahama and very conspicuous to naked eye observers, so which SN is more likely represented on the rock engraving? If one of the concentric circles represents the Moon and discloses the location of the ecliptic, we believe that the positioning of the various elements in the drawing better supports HB9. If HB9 is indicated by the damaged concentric circles in the upper left part of Figure 3b and the Moon's position is marked by the larger concentric circles to the right, then the long curved line in the carving—traditionally interpreted as a spear—is actually an arc of bright stars, and the figure on the left is Orion. To check on this assumption, the relative distances of various stars in the rock engraving were compared with the actual angular separations of the stars in the sky, and there was a reasonable fit (Hrishikesh et al., n.d.). On the basis of the accumulated evidence we suggest that the rock engraving depicts a major astronomical event which took place more than 4,000 years ago.

In a recent study of this site we noted a number of additional points of interest:

1. Two of the stones are still *in situ* but are leaning (see Figure 4) while the rest have fallen, but all can be categorized as 'megaliths'.
2. When all of the fallen and standing stones at this are considered together, they form a rough circle which may also have astronomical connotations.
3. There seems to be more to these monuments than local people attribute to them now. Of particular interest is a mound located due east of the stones.
4. Some of the stones seem to have been erected on artificially-constructed mounds, judging by the placement of rocks as a sort of retaining structure exposed in one of the excavations.

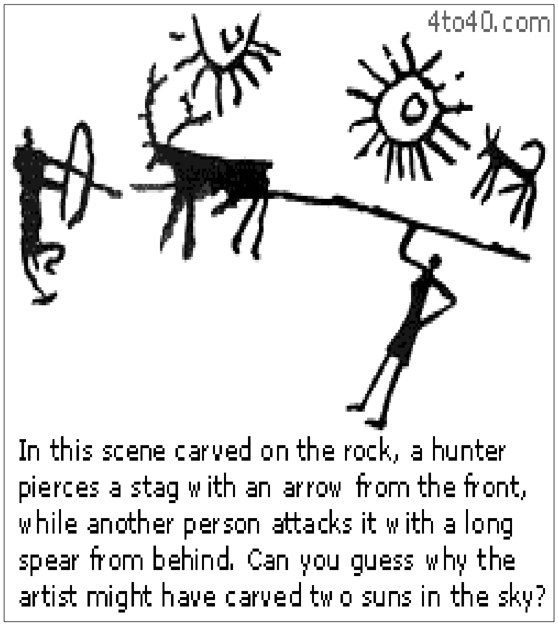

Figure 3a: Rock carving found at Burzahama.

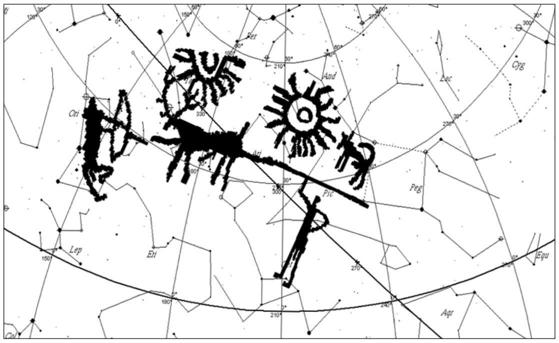

Figure 3b: Sky map showing the region of HB9 in 5,000 BP. To facilitate easy comparison with the drawing, rough patterns are drawn in the map. The large circle in the centre is the full Moon in the month of August in roughly 5,000 BP, and the smaller damaged circle to its left marks the position of HB9.

5. 'Cup marks', which are known to have astronomical connotations elsewhere (Ruggles, 1999), were observed on two of the fallen stones.
6. A view of the eastern horizon is blocked to a large extent by mountains, but the western horizon is largely unobstructed.

Table 1: A comparison of the two SN candidates.

SN Name	*l* (°)	*b* (°)	Date (BP)	Dist. (kpc)	Max. m_v
HB9 (G160.9+2.6)	160.9	+2.6	7,000 - 4,000	0.8 – 1	–10 to –7.5
G182.4+4.3	182.4	+4.3	3,800	3	–7 to –5

Figure 4: Panoramic view of the Burzahama from the northwest.

2.3 Chillas and Drass (Ladakh)

Chillas is a small town located near the Drass belt in the Ladakh region. It is at 74° longitude and +35° latitude, on the upper reaches of the Indus River, under the shadow of the famous Nanga Parbat, the ninth highest mountain on Earth. Archaeological surveys have revealed the existence of ~20,000 rock art sites and petroglyphs along the Karakorum Highway in northern areas of Pakistan, left by various invaders, traders and pilgrims who passed along this popular trade route.

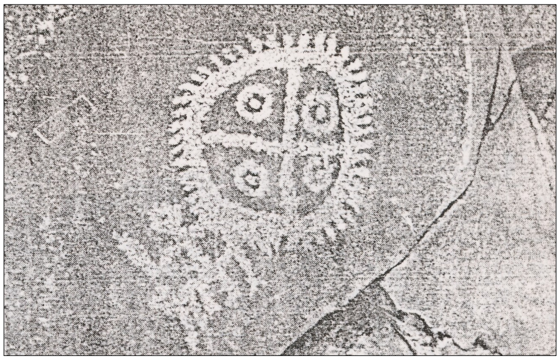

Figure 5(a): A horse rider pulling a circle showing four seasons.

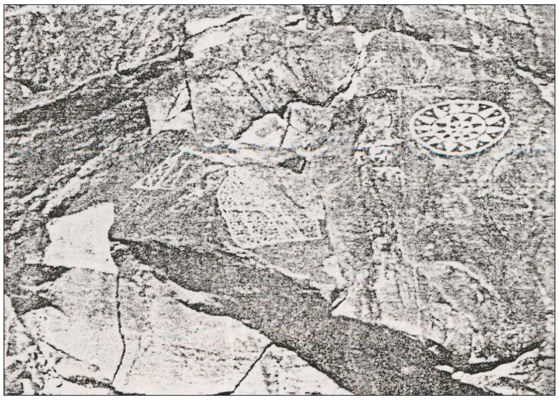

Figure 5b: Solar symbol that has in it 12 triangles possibly showing 12 months.

The earliest sites date between 7,000 and 3,000 BP, and include pictures of animals as well as circular motifs. These latter carvings were pecked into the rock with stone tools, and some may have astronomical significance. Figures 5a and 5b show two different kinds of circular motifs, and as an initial interpretation we propose that they may represent the changing of the seasons, the calendar and radiating objects. These interesting rock engravings clearly warrant further investigation.

3 CONCLUDING REMARKS

The overall investigations in this paper are summarized briefly as follows. Observation of the sky and astronomical bodies has been of worldwide interest since prehistoric times, irrespective of the cultures involved. Kashmir, too, was an important place for celestial observations during the Paleolithic and Neolithic periods. In this paper we discussed the northwestern part of Kashmir, and gained the impression that the ancient inhabitants definitely noted different celestial events, despite the fact that they were merely hunters and gatherers and could only use stone tools to record their observations.

Two of the sites we discussed, Sopore and Burzahama, have already attracted international attention because of their archaeoastronomical features, but some of the sites near Chillas also need to be carefully investigated from an archaeoastronomical point of view. Collectively, these Kashmir sites appear to depict meteorite impacts, a supernova, various constellations, and possibly the changing of the seasons. This northwestern sector of Kashmir offers a route that was popular with ancient travelers, and some of them made astronomical observations and left records of these in their rock art. Water would have been essential for the survival of these early ‘astronomers’, and when the various sites were studied in detail we noticed that all of them were situated on the banks of lakes, rivers or other bodies of water. Those sites that we have identified appear to provide a new perspective on the archaeoastronomical potential of Kashmir.

4 NOTES

1. Distances to supernova remnants (SNRs) can be estimated from (1) optical expansions and proper motions, (2) 21cm H-line absorption spectra, (3) neutral hydrogen column densities, (4) association with neutral hydrogen or CO features in the surrounding interstellar medium, or (5) associations with other objects of known distance. But Green (2004: 348) reminds us that each of these “… is subject to their own uncertainties …” Consequently, astronomers tend to rely

> … on the surface-brightness/diameter, or ‘Σ–D’ relation to derive distances for individual SNRs from their observed flux densities and angular sizes. For remnants with known distances (d), and hence known diameters (D), physically large SNRs are fainter (i.e. they have a lower surface brightness) than small remnants. Using this correlation between Σ and D for remnants with known distances, a physical diameter is deduced from the distance-independent *observed* surface brightness of any remnant. Then a distance to the remnant can be deduced from this diameter and the observed angular size of the remnant. (Green, 2004: 350).

Thus, since

$$\Sigma \propto S/\theta^2 \quad \text{and} \quad L \propto Sd^2 \tag{1, 2}$$

then

$$\Sigma \propto L/(\theta d)^2 \;\; or \;\; \Sigma \propto L/D^2 \qquad (3, 4)$$

where Σ is the surface brightness, S is the flux density, θ is the angular size and L is the luminosity.

2. As Green and Orchiston (2004: 111) stress, "… it is not easy to definitively determine the age of an SNR from available observations." Physical size, surface brightness and morphology can all be used as indicators, but each has its inherent problems. Meanwhile, the age of an SNR containing a pulsar can be calculated from the pulsar period and time derivative of the period (Dickel, 2006: 62). However, HB9 and G182.4+4.3 are shell-type SNRs (see Green, 2004: 367) and as such lack pulsars.

5 ACKNOWLEDGEMENTS

The authors are grateful to the Jemsethji Tata Trust in Mumbai for funding the TIFR archaeoastronomy project. Two of us (N.I. and A.A.) are grateful to the IUCAA (Pune) for their support and for facilities to carry out this research. We also want to thank S. Menon (University of Manipal) and Dr Aijaz Ahmad and Mumtaz Ahmad (University of Kashmir) for their assistance. Finally, we wish to thank Dr Hilmar Duerbeck (University of Muenster) and Dr Wayne Orchiston (James Cook University) for their helpful comments on earlier drafts of this paper.

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Dr Naseer Iqbal is a senior Assistant Professor in the Department of Physics at the University of Kashmir in Srinagar and a Research Associate at the Interuniversity Center of Astronomy and Astrophysics Pune (India). His main research interests lie in the large scale structure of the Universe and he has published six research papers in this field. He has visited three foreign countries for collaborative research work and has presented many research papers at national and international conferences. He is one of the members of group working on "Archaeoastronomy in Indian Context." He has guided three research students for their M. Phil. degrees and two doctoral students are presently working with him.

Mayank N Vahia is a Professor in the Department of Astronomy and Astrophysics at the Tata Institute of Fundamental Research (TIFR) in Mumbai, India. His main research interests are in solar physics, stellar physics, computer simulations of astrophysical environments, and the history of astronomy in India. He is a member of the Astronomical Society of India and General Secretary of the Indian Physics Association. He has published more than 150 papers in national and international journals, and is a member of various scientific organizing committees.

Tabasum Masood is a doctoral student in the Department of Physics at the University of Kashmir in Srinagar and is working on "Analysis of Prehistoric Astronomical Records and their Dating" under the supervision of Dr Iqbal and Professor Vahia. She has participated in national seminars on archaeoastronomy.

Aijaz Ahmad is a Research Fellow in the Department of Physics at the University of Kashmir in Srinagar, and has worked in the field of archaeoastronomy for the past two years. He recently identified some new astronomical sites in the Ladakh belt of Jammu and Kashmir State.

Journal of Astronomical History and Heritage, 12(1), 66-71 (2009).

THE NAMING OF NEPTUNE

Nicholas Kollerstrom
9 Primrose Gardens, London, NW3 4UJ, England.
E-mail: nk@astro3.demon.co.uk

Abstract: Le Verrier chose the name of Neptune immediately after hearing of the correctness of his prediction. This fact soon became obscured by François Arago's pledge made before the French Académie des Sciences, claiming that Le Verrier had entrusted him with the naming of the new planet. Then, British and German sources weighed in with differing names, and Britain's claim to co-prediction of the planet's position was expressed by their proposal of the name, 'Oceanus'. Eventually in February of 1847 Airy urged upon Le Verrier that the name he had originally proposed, namely 'Neptune', should be accepted, because it was the only one that could secure consensus.

Keywords: Neptune, Urbain Le Verrier, Sir John Herschel, François Arago

> *"And what do you think of Le Verrier's sudden determination to call Uranus by no other name than 'Herschel?'"* (Richarda Airy to Adam Sedgwick, January 1847).

1 INTRODUCTION

The discovery of Neptune in Berlin in September 1846 was hailed as a triumph of theoretical astronomy, and the predictor, Urbain Le Verrier (Figure 1),[1] was soon showered with honours. A crisis arose over the naming of the new sphere, finally requiring a consensus of European astronomers to agree. Its predictor, who had located it by theoretical calculations to within one degree, found himself in an emotional crisis and was strangely paralysed when asked for his opinion over what the name ought to be, while a plethora of classical names were propounded by other astronomers. When a consensus did finally start to emerge, it impinged upon the name which astronomers had given to another new planet, 'Herschel' (Uranus). The belated British claim to have co-predicted the new sphere, which took place in the months following its discovery, also contributed to Le Verrier's stress and the complications in agreeing upon a name.

Concerning the name of the planet Uranus, discovered in 1781 by William Herschel, the annual French *Connaissance des Temps* called the new sphere 'Herschel' until 1813, when it changed over to the name, 'Uranus.' The Royal Astronomical Society's *Monthly Notices* had used the latter name from 1836, whereas the *Nautical Almanac* called it 'The Georgian' right up until 1851, when it finally switched over to 'Uranus'.

2 THE DISCOVERY

Neptune's discovery generated a sense of wonder unmatched in the annals of astronomy, as the following account by Benjamin Gould (1850: 21) indicates:

> The remembrance of the enthusiasm excited by the discovery, of the amazement with which the tidings were received, not only by astronomers, but by almost all classes of the community, and of the homage paid to the genius of Le Verrier, is still fresh in the memory of all. Nations vied with one another in the expressions of their admiration.

But, there swiftly followed challenges to Le Verrier's achievement, both from the English claim of co-prediction by John Couch Adams at Cambridge (Kollerstrom, 2006a) and the growing American scepticism over the computations:

> The strange series of wonderful occurrences of which I am to speak is utterly unparalleled in the whole history of science; - the brilliant analysis which was the direct occasion of the search for a trans-Uranian planet, – the actual detection of an exterior planet in almost precisely the direction indicated, – the immediate and most unexpected claim to an equal share of merit in the investigation, made on behalf of a mathematician till then unknown to the scientific world, – and finally the startling discovery, that, in spite of all this, the orbit of the new planet was totally irreconcilable with those computations which had led immediately to its detection, and that, although found in the direction predicted, it was by no means in the predicted place, nor yet in the predicted orb. (Gould, 1850: 3).

The turbulent national rivalries here involved played a part in the endeavour to choose a name that would generate consensus.

On the evening of 25 September, 1846, a euphoric astronomer, Johann Galle at the Berlin Observatory, sat down to pen a letter to Urbain Le Verrier in Paris. "La planète, dont vous avez signalé la position, *réellement existe …",* it began. He had spotted it just after midnight on the night of the 23/24 September, and then confirmed it on the next night's viewing with the Berlin Observatory's telescope. As the person who had had the honour of first *seeing* it, Galle evidently felt that he had a right to propose a name: let it be *Janus,* he wrote, "… the most ancient deity of the Romans, whose double face signifies its position at the frontier of the solar system." (Galle, 1846).

Le Verrier received Galle's letter on 28 September, but he was just too late to announce it at the weekly Académie des Sciences meeting that same day (Foucault, 1846a). Instead, he at once gave his story to two French newspapers, the *National* and the *Journal des Débats,* which published it on 30 September (Foucault, 1846b). In his report Le Verrier proposed the name, 'Neptune'. He thus proposed and published its name before anyone in England (with the sole exception of John Hind) had even heard of its discovery. This primary nomenclatural act seems to have been omitted from all English-language histories of the discovery. Léon Foucault (of pendulum fame) was the young reporter working for the *Journal des Débats* whose story carried this name. The news broke in England on 1 October when Hind's letter about 'Le Verrier's planet' was published in *The Times* newspaper.

The term 'discovery' was at once attributed to Le Verrier: Galle in his letter merely said he had 'found' ('trouvé') the planet, while a letter dated 28 September from Heinrich Schumacher (1846: 22), editor of *Astronomische Nachrichten*, to Le Verrier alluded to

"… votre brillante découverte. C'est le triomphe le plus noble de la théorie que je connaisse."

3 LE VERRIER CHOOSES A NAME

On 1 October, Le Verrier sent letters to three European observatories, proposing this name *and* the symbol of the Trident for the new planet. His letter of gratitude to Galle in Berlin rejected the name Janus: "… the name of Janus would indicate that this planet is the last of the solar system, which there is no reason to believe …". He wrote similar letters to George Biddell Airy and to Wilhelm Struve, Directors of the Greenwich and Pulkovo Observatories. In these letters Le Verrier averred rather strangely that the Bureau des Longitudes had already made the decision: "Le Bureau des Longitudes s'est prononcé ici pour Neptune. Le signe un trident."[2]

The Bureau des Longitudes published the yearly *Connaissance des Temps*, and to that extent decisions over nomenclature did fall within its provenance. But it had no occasion to meet, let alone reach any such decision, during those three days. It may not have been in Le Verrier's nature to say "I have decided …" or "What I want is …", which would have been the truth, and he sought instead for a more impersonal phrase. This caused trouble later, with the Bureau explicitly repudiating Le Verrier's statement at a subsequent meeting (Grosser, 1962: 124) and insisting that it had had nothing to do with the name, and it even threatened legal action on this matter.[3] Le Verrier's initial suggestion, published in the two French newspapers, made no mention of the Bureau.

Sir Henry Holland paid a visit to the Berlin Observatory after the discovery, and spent an evening in conversation with Encke, the Director of the Observatory, and with Galle (who first saw the new planet). He was fortunate enough to be present when the letter from Le Verrier arrived:

> Among other things discussed while thus sitting together in a sort of tremulous impatience, was the name to be given to the new planet. Encke told me he had thought of Vulcan, but deemed it right to remit the choice to Le Verrier, then supposed the sole indicator of the planet and its place in the heavens; adding that he expected Le Verrier's answer by the first post. Not an hour had elapsed before a knock at the door of the observatory announced the letter expected. Encke read it aloud; and, coming to the passage where Le Verrier proposed the name of 'Neptune', exclaimed, '*So lass den Namen Neptun sein*' It was a midnight scene not easily to be forgotten. A royal baptism, with its long array of titles, would ill compare with this simple naming of the remote and solitary planet thus wonderfully discovered. (Holland, 1872: 298-299).

4 THE PLEDGE OF ARAGO

In Paris, the following week's dramatic meeting of the Académie des Sciences (on 5 October) was packed with crowds endeavouring to catch a glimpse of Le Verrier, and the new planet was debated. The most eminent of French astronomers, François Arago, rather ruined the prospect of scientific debate with a pledge that he made. As Director of the Paris Observatory and perpetual Secretary of the Académie, he had received from LeVerrier "… une délégation très-flatteuse: le droit de nommer la planète nouvelle"[4]—a rather startling claim as the latter had already sent out letters and given newspaper reports suggesting a name for the new planet. As comets are named after their discoverers, such as Halley, Encke or Biela, Arago explained, how much more should planets be so nameable. "Herschel déthronera Uranus …" he exclaimed: the name of 'Herschel' would replace that of Uranus. Dramatically, he pledged "… de ne jamais appeler la nouvelle planète, que du nom de Planète de Le Verrier."

Figure 1: Urbain Jean Joseph Le Verrier, 1811-1877 (courtesy Observatoire de Paris).

This was, he averred, "… a legitimate national sentiment." (Arago, 1846). Arago was not proposing a name to the French Académie des Sciences as a basis for discussion, he was imperiously informing them that he would use no name other than one which he personally chose, irrespective of anyone else's view!

Scholars have surmised that LeVerrier had requested Arago to adopt this position (e.g. see Danjon, 1946: 273; Grosser, 1962: 125 and Standage, 2000: 111), but one may doubt this for two reasons. Firstly, the account of the Académie des Sciences' meeting has Arago describing how *of his own volition*, he reached this decision; and, secondly, when, after some months, it was becoming evident across Europe that his name was not going to be accepted, and even when a row may have taken place between Arago and Le Verrier (the substance of which we are, alas, unable to apprehend),[5] Arago does not ever blame Le Verrier, or even hint that it was anything other than his own initiative. During the few months that Le Verrier was a member of the Bureau des Longitudes, it evidently decided in favour of Arago's chosen name, 'Le Verrier', and its symbol (which combined an 'L' and 'V' design) appeared in its early-1847 volume (tables for the year 1849). This symbol is also depicted here in Figure 1.

5 THE BRITISH PROPOSAL

On 14 October, Professor James Challis, Director of the Cambridge Observatory, and his young Cambridge protégé, John Couch Adams, wrote to *The Athenaeum* proposing the name 'Oceanus'. Their letter was published on 17 October, at which time the world had yet to be informed of the predictions supposedly made by Adams concerning the new planet's position, and how near they might have been (see Kollerstrom, 2006a). This London weekly subsequently served as the central forum for British debate over the priority dispute. On the same day of this publication, the Astronomer Royal, Airy, wrote to Le Verrier objecting that the name he had proposed, 'Neptune', "… somewhat disturbs my mythological ideas". The name 'Oceanus' would, he explained, be better received! (Airy, 1846a).[6] At the stormy meeting of the Académie on the following Monday, Arago (1846c) responded with sarcasm to this British proposal:

> M.Challis s'exagère tellement le mérite du travail *clandestin* de M. Adams, qu'il attribue, jusqu'à un certain point, au jeune géomètre de Cambridge le droit de nommer le nouvel astre. Cette prétention ne sera pas accueillie. La public ne doit rien à qui ne lui a rien appris, à qui ne lui a rendu aucun service. Quoi! (Arago, 1846c).

Airy exerted an extraordinarily wide influence upon European astronomy and there was no person living for whom Le Verrier had greater respect. Following this letter, one is perplexed to find Le Verrier behaving as if he had never proposed the name of 'Neptune'.

In their *Athenaeum* letter, Challis and Adams published the first realistic estimate of the distance of the planet from the Sun as 30.05 astronomical units, which was considerably less than Adams and Le Verrier had earlier assumed. From a six-week sky-search which Challis had made with the Cambridge Observatory telescope, two pre-discovery observations of Neptune were identified, and these enabled Adams to compute the planet's speed and thus its "… present distance." This, presumably, gave the two astronomers enough confidence to propose a name. Meanwhile, John Hind (whose observatory was located in Regent's Park, London) objected: "… it appears to me intrusive in the Cambridge people to urge a name for the planet on astronomers, and one too which is no more likely to succeed with the French (who have the only right to name it) than if it had been dubbed 'Wellington'." (Hind, 1846).

6 THE DILEMMA OF LE VERRIER

Some light upon the dilemma faced by Le Verrier is cast by a letter he wrote to Schumacher on 25 November 1846:

> I have been valiantly defended by M. Arago. In another epoch I would perhaps have fended off the honour which he wanted me to have in giving my name to the planet; but the singular pretensions of the British have decided me to accept his friendly gesture. I would assure you that even the adoption by the Board of Longitude, to which I was not party, of the name of Neptune which I had not proposed, has not a little contributed to making me find this name detestable. (Le Verrier, 1846b, my translation).

Le Verrier here appears to be trapped in a Hamlet-like paralysis of indecision. This letter does not, I suggest, support the thesis that he had asked Arago to make the proposal in the first place.

Three days later, on 28 November 1846, Le Verrier (1846c) wrote a letter to John Herschel, signing it as being from "U J LeVerrier and Mr Thomas of Hell No 5", as if some tormented *alter ego* were appearing. This letter concerned Herschel's agreement to represent him at a forthcoming Royal Society meeting and receive on his behalf its prestigious Copley Medal, a cheerful enough occasion, one would have thought. Le Verrier also presented Herschel with a memoir entitled 'Researches on the Movements of Uranus', but he changed its title so that it read 'Herschel' instead of 'Uranus' (in honour of John Herschel's father William, who was the discoverer of Uranus). In the Introduction, Le Verrier (1846d) explained:

> In my future publications, I shall consider it my strict duty to eliminate the name Uranus completely, and to call the planet only by the name Herschel. I deeply regret that the printing of this work is already so far advanced that I am unable to adhere to a vow that I shall observe religiously in the future.

It is noteworthy that 'Uranus' is used throughout the text of this memoir and it is only on the title page that the name of the planet has been changed! An inappropriate degree of fervour has crept in here, where Le Verrier and Arago appear to be trying to put the clock back by several decades, 1812 being the last time that the *Connaissance des Temps* had alluded to this outer planet as 'Herschel'. Sir John thanked Le Verrier for the volume, and whilst appreciating the honour intended for his father he declined to concur because "I have personally committed myself to a mythological name, a few years ago, on the occasion of the reform of our Nautical Almanac." (Herschel, 1847a; cf. Kollerstrom, 2006b).

On 7 January 1847, Le Verrier confided to Airy about his state of depression: "I have been completely unaware of all that was done and said, in France or elsewhere, about the poor planet. I have been troubled here in many ways. I would not advise anyone who likes peace to deal with astronomy in France." He was not able to comment upon the 'Account' which Airy had read out at the RAS—this being the main British statement concerning the discovery of Neptune—because, "… having withdrawn myself from the matter I have not seen the communications or documents." (Le Verrier, 1847a). The combination of having an Englishman steal his glory, having Arago proclaim that the planet be named after him, and *then* having that name be not accepted by European astronomers, was all just too much!

In his reply, Airy (1847a) discreetly indicated that the name proposed by Arago was not being well received and begged him to accept the name of Neptune. Was Le Verrier glad at hearing the name proposed, which he himself had originally advocated? He sent off a tormented reply on 26 February, after a two-week delay, signed as being from "U J Le Verrier and Mr Thomas of Hell no. 6." (Le Verrier, 1847b) This infernal concordance of two of his letters to England has not hitherto been noticed, except by the present writer in the process of collating the letters. What caused the man who found Neptune, then receiving supreme accolades from kings, learned societies and astronomical observatories around the world, to descend in his moods thus, through the circles of Hell? This letter added that he had "… finally resigned from being a functioning member of the Bureau of Longitude [which he joined in October]. I am no longer part of the Observatory." This does not sound quite like glory being awarded to France's greatest astronomer. In this reply, Le Verrier makes a last-ditch plea to have the new planet named after himself. The two letters expressing hellish angst are about nomenclature and Le Verrier's own involvement therein, both being concerned with name-changes to "… this unfortunate planet." (Le Verrier, 1847a).

James Challis received a letter dated 4 February 1847 from Wilhelm Struve declaring that the name 'Le Verrier' would be "… against historical truth, as it cannot be denied that Mr Adams has been the first theoretical discoverer of that body …" (Struve, 1847). Thus the claim for joint co-prediction of the new planet worked against its being named after an individual. Tactfully, Sir John Herschel (1847b) proposed a diplomatic exit from Arago's pledge:

> I observe that Arago calls the new Planet not 'Le Verrier' but 'Planète de Le Verrier' … Now this is rather a description than a name. Those who think it 'Le Verrier's Planet' may yet *call* it Neptune without compromise ...

Sir John was quite forthcoming with suitable names: 'Demogorgon' and 'Minerva' (Herschel, 1846a). Later he suggested 'Hyperion' (Herschel, 1846b), which in Greek, meant "… the transcender …", a son of Uranus and Terra, "… the inhabitants of terra having come to its knowledge by means of Uranus." (Herschel, 1847b; for further details see Kollerstrom, 2006b). But as the Edinburgh Professor of Latin, J. Pillans (1847a) pointed out, some questioned the right of a Frenchman to name the planet because, had not a German, Johann Galle, first seen it? Meanwhile, Pillans found literary reasons for preferring 'Janus' to 'Neptune' (cf. Pillans, 1847b). Thus, by the end of 1847 a plethora of different names had been proposed for 'Neptune', mirroring the variety of names then in use for Uranus ('Herschel', 'The Georgian', '*Georgium Sidus*', and 'Uranus').

7 AIRY'S DECISION

Airy broke the stalemate of nomenclature in his letter of 28 February 1847 to Le Verrier: after explaining "… the difficulty in which I found myself, and in which nearly all the astronomers of Europe found themselves, with regard to the name of the new planet …"—viz, there was no-one who liked Arago's proposal—he then added, "I had hoped that perhaps you might give me some sanction for the adoption of a mythological name" (Airy, 1847c). Because Le Verrier was, for whatever reason, unable to do this, Airy felt compelled to act: he had received "… the reports of the principal astronomers of the North of Europe … [and] I therefore definitely adopted the name of Neptune." It would seem, therefore, that 28 February 1847 is a key date for the accepting of the new planet's name. No-one especially liked the new name, but it emerged as a default position, others being too partisan.

The letter of 28 February echoed Airy's note a week earlier to *The Athenaeum*, based on the view that Le Verrier had not *himself* expressed approval of any name, for the new planet: "It is proper, however, to add, that M Le Verrier himself did not distinctively express either approval or disapproval of the name Neptune." As for Arago's proposal, Airy (1847b) propounded a somewhat subtle argument, whereby "… the decision of a deputy is far less binding than that of the original discoverer." He described Arago's proposal—in a move which he acutely regretted, as soon as he had put the letter in the post—as "… an attempt (which I must characterise as indelicate) ..."

This single word fractured his good relations with Arago, for as Sir Roderick Murchison (1847) explained, use of such a term was "…*an unpardonable offence* in the eyes of a Frenchman." Ten months later, Airy alluded to "… the grief which I have felt ever since …" (Airy, 1847d) over this (indelicate, one might say) phrase. A published apology turned out to be the only answer; even though this, he explained to George Peacock the Dean of Ely, would

> … probably be interpreted as retracting a great deal more than I have any intention to retract. [After all, there was no doubt that] … Arago had done greviously wrong: he had mingled great violence with a sort of craftiness entirely setting aside common rules of propriety, and it was necessary that an objection should be made by the proper persons.

It was hard for Airy to put his finger on exactly what was wrong, whereby Arago had named the planet after the person who had assigned to him the right to choose the name. Nor are we, alas, able to clarify for the reader, in what way Arago had perpetrated 'great violence' and 'craftiness.' The *Athenaeum* eventually published his apology. (Airy, 1847e).

In the British debate, a widely-held consensus emerged that comets could be named after their discoverers, whereas planets needed more Olympian names.[7] This (we may conjecture) obliged British astronomers to re-examine their own preferences for national names for Uranus. On 28 April 1847, Adams wrote to Airy that this would be an appropriate time for the name of the 'Georgian' in the *Nautical Almanac* to be changed to 'Uranus', "… in order to conform to the general usage among astronomers." Usage of the name 'Herschel' may have persisted for some more years out of respect for the Herschel family. On both sides of the Channel, personal names for the two outermost planets came to be renounced, with their connotations of national prestige, in favour of those from Graeco-Roman mythology.

In the summer of 1847, the Bureau des Longitudes wanted to clarify its position, and stated:

> Le Bureau des Longitudes n'avait pas jusqu'à présent aucune décision relativement au nom qu'il convenerait de donner à la nouvelle planète: celui de Neptune ayant aujourd'hui prévalu parmi les astronomes, le Bureau se décide à l'adopter. (*Connaissance des Temps,* 1847).

Arago had, it added, refrained from voting on this matter. It there employed the trident glyph of Neptune, instead of the earlier 'LV' symbol; Le Verrier's name had remained attached to the planet for one year!

8 CONCLUDING REMARKS

French theory and British data were married together in the quest for Neptune. Sir John Herschel wrote:

> I regard the discovery whether made by Leverrier or Adams or both as in the main of French origin. The analytical theory of the Planetary Perturbation which alone render it *possible* is almost exclusively French. Clairaut, Laplace, Lagrange, Pontécoulant and Poisson are the authors of those formulae which, used as tools or as *telescopes of the intellect* have done the thing and we owe them this national recognition. (Herschel, 1847b).

Both parties, Adams and Le Verrier, used a similar theory of planetary perturbations—indeed, they used the same textbook on perturbation theory (Pontécoulant, 1840). The theory describing planetary perturbations was largely French in formation, by the late eighteenth century, because French use of the Leibnizian differential calculus in that century had been more productive than the rather abortive British endeavour to use Newtonian fluxions (see Grattan-Guinness, 1990). But equally, both parties used British data, Greenwich being the source of the best positional-astronomy data for Uranus.[8] The discovery thus involved Anglo-French collaboration, and it is therefore appropriate that its name should have emerged from a sometimes stormy cross-Channel debate.

9 NOTES

1. To inspect the Leverrier correspondence, on which this article is based, go to www.dioi.org/search.php. Inserting 'Le Verrier' will bring up a couple of dozen letters from him, and a similar number to him. For other Neptune articles by the author of this paper, see www.dioi.org/kn/index.htm.
2. At the time Le Verrier was not even a member of the Bureau. He was only nominated on 14 October, and remained a member for just four months. However, as early as 1841 one finds Le Verrier being alluded to as a member ("… on songeait à lui comme membre du Bureau des Longitudes …") with J-B. Biot (1841) writing to the Bureau's President requesting that he be affiliated.
3. Danjon (1946: 273) notes that "Le fait [i.e. that the Bureau de Longitude had chosen the name] fut contesté formellement dans la suite et les procès-verbaux des séances n'en conservent aucune trace."
4. Le Verrier (1846a) said: "J'ai prié mon illustre ami M Arago de se charger du soin de choisir un nom pour la planète. J'ai été un peu confus de la decision qu'il a prise dans le sein de l'Académie."
5. In his 1846b letter to Herschel, Arago refers to Le Verrier as "… my young friend …" with no hint of a falling-out, so any possible row between these two scientists must have occurred at a later date.
6. Rawlins (1999) expressed the opinion that "The Oceanus letter to Le Verrier has got to be THE nuttiest notion of Airy's long and illustrious career."
7. For instance, J. Lee wrote to Airy (1847) reporting on the RAS's dinner-club discussion of 13 January 1847, where the majority wished that "… a mythological or archetypal name should be given to the new planet …"
8. Airy had sent his Greenwich Uranus positional data to Eugène Bouvard in Paris, in a series of five letters dated 1838-1844, which the latter used for improving his uncle Alexis Bouvard's tables of Uranus, to which Le Verrier had access. Also, both parties used the seventeen prediscovery observations of Uranus published in Bouvard's *Tables* (Paris, 1821), derived from Flamsteed and Le Monnier.

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The following abbreviations are used:

IoA = The Institute of Astronomy (Challis' Collection) at the University Library, Cambridge.
McA = The McAlister Collection at St John's College, Cambridge (copies of originals).
RAS MSS = The Royal Astronomical Society's manuscript collection.
RGON = The RGO's Neptune File at the University of Cambridge Library.
RS:HS = The Royal Society's Herschel Collection.

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Until recently, Dr Nicholas Kollerstrom was on the staff of the Science and Technology Studies Department at University College, London, and he is now an independent researcher based in north London. He is a founding member of the Society for History of Astronomy, an IAU member and a Fellow of the Royal Astronomical Society (from which he received a grant to collate the British Neptune-discovery correspondence). His Ph.D. in 1995 was on Newton's 1702 lunar theory, and he has an essay on Newton in the *Biographical Encyclopeadia of Astronomers* (Springer, 2007). His forthcoming article on the 'Reception of Newton's lunar theory on the Continent' is due to be published later this year in *Newton in Europe* (edited by Pulte and Mandelbrot, Springer, 2009).

Journal of Astronomical History and Heritage, 12(1), 72-80 (2009).

V.M. SLIPHER'S DISCOVERY OF THE ROTATION OF SPIRAL NEBULAE AND THE CONTROVERSY WITH BERTIL LINDBLAD

Alain G. Brémond

Laboratory for the Study of the Scientific Phenomenon (EA 4148 LEPS),
Université Lyon 1, 38 boulevard Niels Bohr, 69622 Villeurbanne Cedex, France.
E-mail: alain.bremond@neuf.fr

Abstract: A study of the Lowell Observatory Archives has revealed that, starting in 1917, V.M. Slipher worked out a coherent hypothesis concerning the rotation of spiral nebulae. When Hubble became interested in the question in 1932, he discovered Slipher's work, studied it and concluded, according to his own observations, that Slipher was right. Slipher's conclusions concerning the dynamics of the spirals were only called into question in 1940 when Lindblad claimed that the spiral arms were 'leading'. Hubble defended Slipher's conclusion, and Slipher himself intervened in the debate in 1944 with only a short note. The debate ended in part with the evolution of Lindblad's work and with the development of the density wave theory in the 1970s.

Keywords: galaxies, rotation, V.M. Slipher, Edwin Hubble, Bertil Lindblad

1 INTRODUCTION

In the middle of the nineteenth century the drawings made by William Parsons, 3rd Earl of Rosse (Parsons, 1926), showed that among the nebulae there was a particular group that he called spiral nebulae. Before 1912, those images of the spiral nebulae and the first photographs by I. Roberts and J.E. Keeler encouraged astronomers to interpret their appearance as the consequence of rotational motion. The English astronomer and photographer, Isaac Roberts (1829–1904) was the first to 'observe' an apparent rotation when he compared two successive photographic plates of the same nebula. Nevertheless he soon came to recognize that this visualization did not justify deducing any rotation (Turner, 1900).

The proper motions of the spiral nebulae were also questioned by Adriaan van Maanen (1884–1946). These issues, which have been studied by many historians of astronomy (e.g. see Berendzen and Hart, 1973; Berendzen, Hart, and Seeley, 1976; Brashear and Hetherington, 1991; Crowe, 1994; Fernie, 1970; Hetherington, 1971, 1972; Smith, 1982, 2008), are well known and they will not be discussed in detail in this paper.

The question of rotation of this particular kind of nebula, the 'spirals', involves rotational velocity and motion of the spiral arms, and observation of the latter requires a careful orientation of the nebula in the line of sight. A controversy took place between V.M. Slipher (1875–1969), Edwin Hubble (1889–1953) and Bertil Lindblad (1882–1965) in the 1930s (see Oort, 1966). This purely observational discussion was important because of its consequences on the hypothesis concerning the dynamics of the spiral arms in what are now called galaxies. The debate on the position of the spiral and elliptical nebulae in relation to our Galaxy was closed by the successful measurements of their distances by Hubble in 1924 (Berendzen and Hoskin, 1971).

Much has been written about Slipher's measurements of radial velocities but little about this controversy. It was only discovered when we were studying the archives[1] at the Lowell Observatory and, more specifically, the letters that were exchanged between Slipher and Hubble.

Vesto Melvin Slipher (but always known simply as V.M. Slipher), was an astronomer educated at Indiana University at Bloomington (for biographical details see Hart and Berendzen, 1970; Hoyt, 1980). As a favour to Wilbur Cogshall (one of Slipher's teachers), Percival Lowell (1855–1916)[2] recruited Slipher for the Lowell Observatory, and he arrived in Flagstaff in August 1901. All his research would be devoted to spectroscopy. After working on planets and stars, he obtained his first nebular spectrum of Messier 31 in November 1910 (Slipher, 1910). He soon discovered that this object had a high velocity in the line of sight (Slipher, 1912), and he announced this result to William Wallace Campbell (1862–1938), Director of the Lick Observatory, and then published it (Slipher, 1913a, 1913b).

2 THE DISCOVERY OF SPIRAL ROTATION

After generating the spectra of spiral nebulae, Slipher realized very quickly—by 1912—that the lines were inclined. He had already encountered this phenomenon when he had studied the planets using spectroscopy to measure their velocities of rotation. In a manuscript he wrote:

> … the lines of the spectrograms of the Virgo nebula NGC 4594 are inclined. The inclination recalls that shown by a spectrogram of Jupiter made with the spectrographic slit on the equatorial diameter. (Slipher 1914b).[3]

Thus, it was quite natural for him to apply the same method to determine the velocities of rotation of the spirals. While he initiated this approach in 1912 using a spectrum of the Andromeda Nebula, his study of the rotation of nebulae started in earnest with NGC 4594. In April 1913 he noted: "By its inclined lines this plate furnished direct evidence that nebulae rotate …", and he went on to offer a systematic analysis of the phenomenon based on many spectral lines for each spiral (Slipher, 1913c).

2.1 Technical Aspects

Slipher's observations for the study of nebulae were made using a 24-inch refractor with a single prism spectrograph (Figure 1). A typed manuscript, copiously annotated by hand, details the problems that he encountered as well as the solutions he found (Slipher, n.d.(b)). While this paper is not dated, we know that it was written after January 1916 since it includes data obtained at the end of 1915. This interesting paper was never published.

Slipher carried out several experiments between 12 January and 7 October 1915 to determine the optimal instrumental configuration for recording the spectra. From these experiments, he concluded that the best results were obtained using the single prism spectrograph, except in the case of the most luminous nebulae where two prisms gave a better dispersion (Slipher, n.d.(a)). The iron-vanadium spectrum was used for comparison (Figure 2).

The method used to generate the spectrum for the study of nebular rotation consisted of placing the slit along the large axis of a tilted spiral. With this configuration, the central part of the nebula showed a shift corresponding to the radial speed of the nebula as a whole. Furthermore, the part that moved away in the line of sight showed a redshift relative to the center of the nebula, while the part that approached the observer exhibited a relative blueshift. Slipher described his method of data reduction for determining the rotation of the planets in two papers published in 1903 and 1904. The inclination of the lines was measured using a Hartmann microscope.

2.2 Results

In his presentation at the 17th Meeting of the American Astronomical Association (henceforth AAS) at Evanston in late August 1914, Slipher (1914b) indicated that, for NGC 4594 (located in Virgo), the slope was of approximately four degrees and that it corresponded to a circular speed of approximately 100 km/s, at 20″ from the centre of the nebula. A note drawn from his working papers illustrates this discovery:

> … and as the lines appeared inclined a third spectrogram was made in 1913. While it did not, unfortunately, receive the exposure intended, it nevertheless completely verified the earlier ones both as regards the exceptional displacement and the inclination of the nuclear lines. (Slipher, 1913d).

The first publication on nebular rotation in the *Lowell Observatory Bulletin* (Slipher, 1914a) carries the date of May 1914. In this short article Slipher concluded from his study of NGC 4594 that the nebula rotated and he noted that although most observers, starting with Laplace, had thought that nebulae rotated, it was the first time that this phenomenon had been verified.[4] The following month, a similar paper was published in *Scientific American*, and Slipher (1914c) was enthusiastic: "If Laplace could have seen this nebula as it really is, he might have found in it a satisfactory illustration of his nebular hypothesis." In addition, Slipher believed that this discovery introduced an excellent method for studying stellar and nebular evolution within the framework of the theory of a protostellar nebula similar to that worked out for the Solar System.

Starting at the end of 1915, Slipher entered into discussion with Campbell over the rotation of spiral nebulae, a question that interested the Director of the Lick Observatory. In a letter dated 4 December 1915, Slipher (1915a) told Campbell that he had obtained plates of the Andromeda Nebula showing rotation and that other studies in progress confirmed this phenomenon. He also posed the problem of determining which edge was nearer to the observer because the spiral rotation trajectory depended on the location of this edge.[5] In his reply, Campbell (1915) did not provide an answer to these questions, but instead urged Slipher to publish this work without delay. Instead, the 19th Meeting of the AAS, held in Swarthmore in September 1915, provided the opportunity for Slipher to present his results.

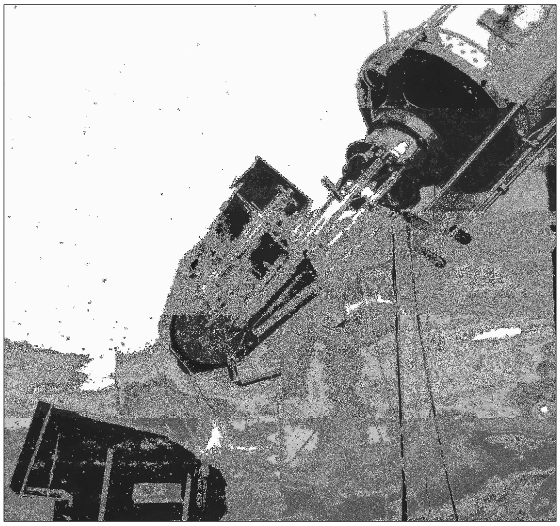

Figure 1: The 24-inch telescope and Slipher's spectrograph (courtesy: Lowell Observatory).

In his working papers, Slipher (1915b) noted the increasing number of photographs of spectra, with analyses that he found encouraging:

> … additional cases of rotating nebulae have been met with in the and. Neb.[,] M65, M66 and less incidentally in still other cases. The form of the spectral lines of the andromeda nebula in particular denotes a greater irregular velocity near the nucleus than further ant., but measures for these are difficult and not precise enough to express the motion quantitatively. This type of rotation or internal motion promises to be more common than the planetary disk line rotation shown by the Virgo nebula 4594.

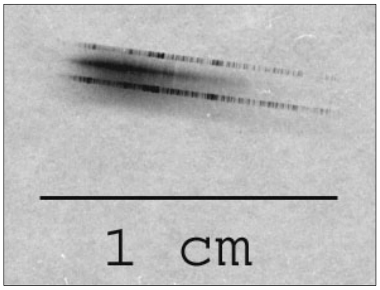

Figure 2: A spectrum of the Andromeda Nebula with the comparison spectra (courtesy: Lowell Observatory).

In 1917 Slipher observed the rotation of six spirals: NGC 224, 2683, 3623, 3627, 4594 and 5005. In December of that year he published new results for NGC 1068 (M77), which according to his calculations rotated at a velocity of 300 km/s 1′ from the centre (Slipher, 1917c). In 1921, his paper presented at the 25th Meeting of the AAS included observations of rotation of NGC 221, 224, 1068, 2683, 3623, and 4594. In all six he found "The direction is that in which the arbor of a spiral spring turns when the spring is being wound up." (Slipher, 1921). Despite the growing number of spirals he had observed, Slipher (n.d.(b); 1915d) only had velocity measurements for three of these: NGC 224 (Messier 31), NGC 1068 (Messier 77) and NGC 4594 (which are the ones with the highest surface brightness, and probably the most easily-measurable spectra).

Figure 3: The edge-on galaxy NGC 4565 in Coma (courtesy: Bruce Hugo and Leslie Gaul, Adam Block, NOAO, AURA, NFS).

These observations were verified by Francis Pease (1881–1938), an astronomer at the Mount Wilson Observatory with an interest in the rotation of spiral nebulae (Adams, 1938). Slipher found out about Pease's interest in July 1916 through his correspondence with John Duncan (1882–1962), and took it as a confirmation of the interest of his recent spectral discoveries (Duncan 1916). After 80 hours of exposure, Pease obtained a spectrum for NGC 4594 that enabled him to calculate a rotation velocity of 330 km/s at 2′ from the centre, and he proceeded to publish his results (Pease, 1916). Based on twelve measurements, Pease determined that there was a linear relation between the velocity (V_{rot}) and the distance from the centre of the nebula (r):

$$V_{\text{rot}} = 2.78r + 1180 \qquad (1)$$

where V_{rot} is in km/s and r in seconds of arc. The radial velocity of the spiral at the centre (i.e. 0 second of arc) is 1180 km/s.

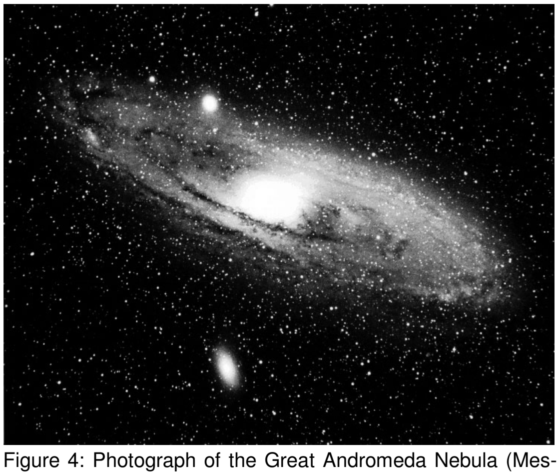

Figure 4: Photograph of the Great Andromeda Nebula (Messier 31) with its dark bands (courtesy and copyright: Jason Ware).

In his data reduction methods, Pease took into account the tilt of the spiral in the plane of the sky. The determination of this linear relation raised several questions. It was clear, for example, that the nebula could not be a solid body in rotation because no such body could possibly be stable at such high speeds. Pease considered the possibility of some (unknown) law that would give a linear velocity-distance relation. Furthermore, the relation made the presence of planets around the centre of the nebula impossible because the linear velocity of such objects would increase as they become closer to the centre (just like the planets of the Solar System), leading to impossibly high velocities.

A little later, Pease (1918) made the same study of Messier 31 and found a velocity of 58 km/s at 2′ from the centre and a similar linear relation:

$$V_{\text{rot}} = -\,0.48r - 316 \qquad (2)$$

The observations made by Slipher (n.d.(b)) led him to a different result: "Angular velocity of Andromeda apparently decreases outward. Linear velocity one minute from nucleus estimated 50 miles." Applying Pease's formula would give a velocity of 30 km/s whereas Slipher determined it to be 80 km/s. The inaccuracy of the measurements of rotational velocity can probably explain the difference,[6] and in this context it is important to note that all these measurements—of Pease and Slipher—only relate to the central part of the core and not to the spiral arms of the Nebula. For example, the measurements made by Pease on NGC 4594 (The Sombrero Galaxy) involved "… approximately the central half of the nebula …" (Pease, 1916) and in Messier 31 it reached 2.5′.[7] In 1939, Horace Babcock (1912–2003), with the same method, published results of the same order of magnitude as those of Slipher and Pease for the Andromeda Nebula with a velocity at 2.5′ of 100 km/s, instead of 70 km/s with Pease's formula (see Babcock, 1939).

These measurements were then combined with the proper motions measured by van Maanen, assuming that the spirals seen edgewise and those seen front-view had the same velocities, and Pease (1916) deriveed a parallax of 0.00013″ (7,700 parsecs) for NGC 4594.

The reception of these results by other astronomers was excellent. One of the most prominent astronomers of that time, W.W. Campbell, wrote to Slipher in 1914: "The rotation observed in NGC 4594 is especially interesting and important … I hope you will be able to get additional observations of the same kind." He often used Slipher's data in his lectures, such as those to the National Academy of Sciences (ibid). As we will see further on, Heber D. Curtis (1872–1942)[8] was also highly favourable to the rotation theory and wrote that he always preferred Slipher's views to those of van Maanen. However, in his 1919 review, "On the existence of external galaxies", Harlow Shapley did not even mention the papers by Slipher or Pease. All his discussion on rotation velocities was based on van Maanen's publications on Messier 101, and it is only twenty-four years later, in his book, *Galaxies*, that he briefly acknowledged the importance of "… spectroscopically determined rotation …" (Shapley, 1943: 118).

Although the rotation of the spiral nebulae had been established, the question of the direction of rotation remained open. As we have already noted, to make this determination it is necessary to know which side of the nebula is nearer to the observer.

3 THE CONTROVERSY

3.1 Slipher's Reasoning

As was the case for all his research, Slipher (1915c) communicated his discovery to John Miller (1859–1946), one of his teachers from his university years, and asked his opinion:

> If we knew which edge of the nebula is toward us then from the inclination of the lines we could say which way they are turning with reference to the curvature of the branches of the spiral. To get that by parallax measures seems now impossible.

Slipher (ibid.) proposed an hypothesis that could extricate him from this situation:

> We know that for the great majority of the spindle-edge-on spirals there is a dark lane on their long diameter obviously due to absorbing or occulting material on the nearer edge of the nebula. Imagine we are looking at the great dark-lane spindle of Coma [NGC 4565; see Figure 3 here], and while we are looking we are rising out of its plane. As we pass out of the shadow of the absorbing material, the dark lane will lose intensity and prominence[13] and the spiral branches begin to show themselves and the dark lane remains only as darker rifts between the arms of the spirals on one side of the nucleus. If we stopped when about 25° above the plane our view of this spindle, it is imaginable that then this nebula might resemble the great Andromeda spiral [see Figure 4], which has much more intense rifts between the spiral arms on one than on the other side. In short, I assume that edge of a spiral which has the darker rifts is the edge nearer to us.

One hypothesis proposed by Pease (1916) was that the dark streak in NGC 4594 could be the "… unilluminated edge of the thin disk surrounding the brilliant nucleus." This opinion was also advocated by Slipher (1917b), who reasoned that the dark lane would seem less dark and prominent if looked at from an upper position.

Based on these assumptions, Slipher (1915c) reached the conclusion that "… the Andromeda nebula is turning into the spiral arms i.e. in the direction we turn a spool to wind the thread onto it." To test this hypothesis, he searched for a sufficient number of spirals with the appropriate characteristics. These studies proved long and difficult, but despite numerous problems, the three or four cases he was able to exploit seemed to agree with his winding-up theory. While Miller expressed his interest in Slipher's discovery, he, like Campbell before him, voiced no opinion on the question of the orientation of the nebular rotation (see Miller, 1915).

At the 25th Meeting of the AAS at the end of December 1920, Slipher presented his latest conclusions concerning the rotation of spiral nebulae. They were based on his measurements of rotation linked to an indicator of the spiral's orientation, which in turn allowed him to determine the direction of the movement:

> Considering then that side of the inclined spiral having the darker rifts and deficient illumination to be the one nearer us, we can interpret the direction of the rotation, shown by the spectrograph, relative to the curvature of the spiral arms where arms are recognizable. In every case the spectrographic results were got independently of any knowledge as to the nearer edge of the spiral and the location of the spiral arms, and likewise these data as to orientation were determined quite independently of the rotation shown by the spectrograph. (Slipher, 1921).

The six nebulae discussed all agreed in showing rotation in the same direction relative to the spiral arms. The direction was that in which the arbor of a spiral spring turned when the spring was being wound up.

A copy of Slipher's (1917b) synthesis of this work preserved at the Lowell Observatory archives contains a typed note from him (Slipher, 1917a). It tells us that, thanks to Walter S. Adams, he had been able to examine an excellent picture of NGC 4594 taken at Mount Wilson Observatory, which revealed fine spiral arms (see Figure 5). This plate allowed him to validate his assumption concerning the rotation of this nebula, but in that case he deduced that the spiral was expanding:

> With Professor Adams, I have examined an excellent Mount Wilson photograph of this nebula, which reveals faintly the spiral arms. The shape of the arms allows my spectrographic rotation of the nebula to be interpreted as to direction. It comes out that the object is rotating in the same sense relative to the curvature of the spiral arms as the above discussed spirals were found to be turning.
>
> It thus is reasonably certain that we can generally decide (in the manner described above) from the appearance of spiral nebulae which edge of the nebula is the nearer to us. Hence it follows that the unsymmetrical aspect of the two edges of a spiral is chiefly dependant upon the direction from which we view the nebula. And this, in turn, has its bearing upon the question of the physical nature and the illumination of the spirals in general. (Slipher, 1917a).

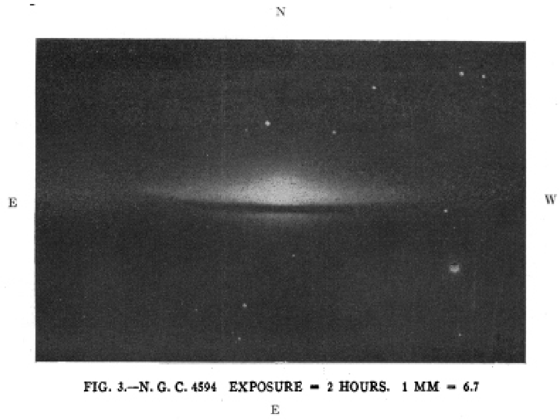

Figure 5: NGC 4594 with dark band and fine spiral arms (after Pease, 1916).

From the high velocity measured for this Nebula, Slipher deduced that some spirals were expanding and matter was being thrown out by the rotation. We must remember that at this time one hypothesis about spiral nebulae was that they were Solar Systems in formation, the central bulge being a new star surrounded by condensed matter.[9] Instead, Slipher thought about spirals as objects which were expanding, and he called the former hypothesis an old one:

> The high velocity of rotation argues that in some cases, at least, - as NGC 4594, for instance - the nebula is, in consequence of rotation, expanding. Indeed the disk-form and the spiral arms of these nebulae imply action, past or present, of expansive forces. The evidence from these observations, and from other sources, to my mind, makes clear the need of our entertaining the view that systems exist which are undergoing expansion. The old theory of condensation of nebulae into stars is today insufficient because one-sided and hence should share the field with the view of the expansion of denser systems into more tenuous ones. In a universe so vast in space and time, its components must be variously circumstanced and it is hardly to be thought that the different forces with expansive tendencies will always be overpowered by those with condensing tendencies. (Slipher, 1917a).

Thus, Slipher (1921), in light of his work on NGC 4594 and with his proposed orientation of the spiral, concluded that for all the spirals he had studied the arms turned like "… a winding spring … [or a] reel on which one rolls up a wire."

In 1924, Curtis wrote to Slipher in connection with the IAU Commission on Nebulae and took the opportunity to express his own point of view on the rotation of the spirals:

> Your results are uniformly to the effect that the motion is in the "direction of the arbor of a spiral spring when it is wound up". Similarly, Pease on the Andromeda nebula, states, "Whether the motion of the nebula is inward or outward along the arms of the spiral depends upon the inclination of the nebula." Referring to his diagram, we find, if we assume as you did in your work that if the "lane" side of the nebula is the nearer, its direction of motion is that found by you. Van Maanen's motions are prevailing outward along the arms of the spiral. Whereas, if the "lane" side is the nearer to us, it seems to me that the spectrographic results directly contradict those secured by van Maanen. Further, I can see no way in reason to put the "lane" side anywhere than on the side toward us. I have never been able to accept VM's results; my feeling is a mixed one of admiration for careful and honest measures on the most difficult subjects, of "watchful waiting" for additional evidence on "being on the fence" and from Missouri, and some measure of total disbelief that the motions he found exist at all in the quantities he gives. One thing that bolsters my attitude with regard to accepting his measures has been what seemed to me the absolute contradiction in the direction of motion given by the spectrographic results, which, per se, appear to me to be worthy of far more confidence.

Curtis' position was confirmed later on, in 1926, in correspondence with Slipher.

In these two letters, Curtis considered that what was contradictory between van Maanen's observations, on the one hand, and those of Slipher and Pease on the other, was the direction of the motion of the spiral arms. For van Maanen, the spirals seemed to unwind, while for Slipher they were winding up. Curtis could not see how to interpret the position of the dark lanes differently from Slipher, and for this reason he was obliged to accept his demonstration. As for the velocities, it was possible to admit that they could be in accord if it was assumed that the distance of the spiral was not more than 35,000 light-years. By the time Curtis wrote his 1926 letter Hubble had measured distances to three spiral nebulae (i.e. NGC 6822, M31 and M33) and shown that each was much farther away than 35,000 light-years (which definitely contradicted van Maanen's hypothesis), but Curtis did not mentions this fact in his letter.

3.2 A Different Point of View from Bertil Lindblad

Bertil Lindblad was a Swedish astronomer and a graduate of Uppsala University (see Öhman, 1970; Oort, 1966). He began his studies on galactic rotation in 1925 with the paper "Star-streaming and the structure of the stellar system", and never stopped them until his death in June 1965. Lindblad was the Director of the Stockholm Observatory from 1927 to 1965, and he spent two years (1920-1922) in the United States, at Lick Observatory and at Mount Wilson.

From his work on Messier 31, Lindblad concluded that its orientation was the opposite of that proposed by Slipher. In 1946 Lindblad published a paper in the *Astrophysical Journal* with his assistant, Rolfe Brahde (Lindblad and Brahde, 1946), where he outlined his observations and assumptions. Here he addressed the question of the bands that darken certain parts of the spiral arms, suggesting that the matter responsible for these dark bands was located in both their convex and their concave parts. He based this argument on the face-on spiral, Messier 51, which also presented dark zones in the concave part of the arms. Lindblad concluded that matter was homogeneously distributed throughout the arms, and he suggested that if an observer were to move away from the plane of the spiral, the most distant dark zones would be more apparent than the closer ones. This reasoning led him to the conclusion that "… the part of the nebula which shows heavy obscuration is in all probability farther from us …", and then he logically deduced the result that "… the direction of rotation found by Slipher and by Pease will be the direction in which the spiral arms wind outward, in accordance with our theoretical rule." In this paper (ibid.), Lindblad also confirmed his earlier conclusion that "… the spiral arms open up in the direction of rotation …"

Thus Lindblad's position concerning the rotation of these spiral nebulae was the opposite of Slipher's. During the same period, Babcock (1939) studied the Andromeda Nebula and confirmed Slipher's point of view, and Erik Holmberg (1908–2000) also positioned himself on this side of the debate (Holmberg, 1939). Edwin Hubble was also interested in the rotation of spiral nebulae, and in order to determine which interpretation should prevail he decided to undertake a new study.

3.3 Hubble's Point of View

In July 1932, Hubble asked Slipher whether he was still interested in this subject, because he believed that there was an "… outstanding need in nebular research." In response, Slipher (1932) sent Hubble his results and later on they exchanged spectrographic plates (see Hubble, 1941a), and discussed the issue of rotation:

> Thank you for your letter on the rotation of spirals. I am sending you prints of 3190 and 4594 as you request, and will be very glad to send others if you wish them. The expression "trail their arms" is ambiguous as you point out. I was careful, in the brief paper for the Academy, to use the expression "the arms trail", for the analogy is with the pin-wheel and the direction is that which you stated in your 1917 paper. (ibid.).

Hubble, who had read Lindblad's publications in the *Astrophysical Journal*, considered publishing on the rotation of the spirals, and he asked Slipher to read his manuscript (Hubble, 1941b). In September 1941 Slipher sent him a long answer as well as his notes on the manuscript itself, and Hubble submitted his revised paper to the *Astrophysical Journal*. It was published in the March 1943 issue (Hubble, 1943), and in this paper Hubble cited Slipher's work at length and he discussed Lindblad's alternative assumptions.

After a clear recapitulation of the various aspects of the problem, Hubble presented two methods for determining the orientation of the spirals. When the spiral is observed edge-on and a dark band passes in front of the central core, its orientation is not debatable, and this is the primary criterion for determining the orienttation. In less inclined spirals, this dark band is no longer directly in front of the core but, as long as it is *projected* in front of the core, the orientation is also unambiguous. But when the inclination is insufficient for such a projection then its orientation cannot be determined with any certainty. Hubble then turned to a consideration of secondary criterion for determining the orientation, which he took from Slipher. If the observer could move off the plane of the spiral, he would see the band move away and deviate laterally, making the spiral asymmetrical. In this case, the nearer side is the one without a dark band (e.g., see Figure 4). If we consider the observation of a nebula with a quite visible band barring the core edge-on, when the tilt decreases, the dark band should move away from the core just before the spiral arms become visible. However, if there are any interior bands present, they should remain behind the peripheral band. This is what Hubble observed in three nebulae—NGC 4216, 4258 and 4527—which he compared with NGC 3190 where the primary criterion was present. Hubble also offered a critical analysis of the spirals described by Slipher, and concluded that they contained only one indisputable case, that of NGC 2683. Next, he considered the photographic catalogue of the Mount Wilson Observatory. His first table summarized the results for fifteen well-observed nebulae, all of which satisfied the criteria defined by Hubble. In all these cases the rotation of the arms was in the direction described by Slipher. Hubble added another eight more doubtful cases, which all rotated "… trailing their arm." Finally he criticized Lindblad's criterion as being erroneous, arguing that the asymmetrical concentration of globular clusters and novae showed that the darkening matter was distributed asymmetrically in nebulae seen edge-on and not symmetrically as Lindblad had supposed.

But Lindblad was not convinced, as is shown by his 1946 paper (Lindblad and Brahde, 1946). Using photometric and color measurements, he concluded: "The results indicate that the dissolution of a system into spiral structure proceeds in such a way that the arms open up in the direction of rotation."

3.4 Slipher's Reactions

We know about Slipher's reaction to Hubble's arguments thanks to papers that are housed in the archives of the Lowell Observatory. The documents on this topic are gathered together under the rubric of "Working papers" in a folder containing a series of notes on the question of the rotation of the spirals (see Slipher, 1946a). Another source of information is the series of letters on the subject exchanged between Hubble and Slipher.

Slipher appears to have been a little irritated by Hubble's article, which he believed did not give enough space to his own work on the subject. Indeed, in an undated note, which was probably penned in 1944, Slipher (n.d.(c)) wrote "Hubble has added nothing in the matter." Moreover, he did not agree with Hubble that NGC 3190 constituted "… the first non-ambiguous spiral." (ibid.). Indeed, he believed that there were many spirals among those that he had published presenting sufficient criteria to reliably orientate them in space. He continued his criticism in the following terms: "Hubble seems to call dark lane of slightly inclined spirals a "new? criterion" which means he did not understand/read the method here formulated 25 years ago…" (ibid.). In fact, Hubble only used the term "new" for the secondary criteria of tilt that were much more detailed in his paper than in Slipher's earlier ones. But, as we have already stated, he did present all of Slipher's results in detail.

In 1944 Slipher published a note in *Science*, where he insisted on the priority of his work (Slipher, 1944). He then went and detailed his argument in a text dated 2 December 1946, probably with the intention of publishing a more complete paper. Two letters to Hubble, one dated 3 December 1946 and the other undated (but probably written in 1947), show that Slipher (1946b; n.d.(d)) wished to develop his point of view in a more detailed article and in particular to argue against Lindblad's proposal, but this article was never published. In spite of these disagreements, the relations between Hubble and Slipher remained excellent, as is clear from their subsequent epistolary exchanges. Slipher possessed excellent human qualities. He was always courteous and gave his results, slides and plates to all those who asked him for them, as is attested by letters from Campbell, Eddington, Pease, Strömberg and others in the Lowell Observatory Archives. Slipher had helped Hubble, whose personal relationships with other astronomers were sometimes difficult (e.g., see Sandage, 2004: 521, 529, and Brashear and Hetherington, 1991: 240), and he tried to honestly present all of his ideas to a young Edwin Hubble who was not well known at that time and not even a member of the IAU Commission on Nebulae (of which Slipher had been President from 1922 to 1928).[10]

3.5 How Did the Controversy End?

Lindblad, himself, contributed to the evolution of the spiral dynamics question. He spent a sabbatical period at Mount Wilson and Palomar, where he met Hubble and was able to use detailed photographs of spiral nebulae taken with the largest telescopes in the world. His studies showed (Lindblad, 1963; 1964) that the matter in the centre of a galaxy rotated more quickly than the spiral arms, meaning that the external parts would 'trail'. He also showed that, at a certain distance from the centre, one could observe a co-rotational resonance (known as 'Lindblad resonance') between the stars and the nebula. Finally, Lindblad also introduced the concept of internal and external zones of instability. Later, between 1964 and 1970, Lin and Shu (1964) went on to develop the density wave theory. At the observational level, the velocity curves of many galaxies have been measured since 1954 thanks to new techniques in radio astronomy, particularly the study of the 21-cm emission line of neutral hydrogen. Today, astronomers consider the direction of rotation of the spiral nebulae to be well established.

4 CONCLUDING REMARKS

From 1930, the rotation of spiral nebulae was an important issue, mainly because of its implications for the theories of the dynamics of these objects. V.M. Slipher's role in the detection of the rotation and in the determination of the direction of motion of the arms in nebulae attracted the interest of some prominent astronomers, including Hubble. But although he had good intuition, made precise observations and derived interesting hypotheses, Slipher's ideas were not widely known. This illustrates one of the major problems with Slipher: he was reluctant to publish, and most of his papers appeared in the *Lowell Observatory Bulletin* or in *Popular Astronomy*. In contrast, Francis Pease published his results in the *Proceeding of the National Academy of Science*, and Hubble's and Bertil Lindblad's papers appeared in the *Astrophysical Journal*. In contrast, the long paper that Slipher planned to write on the rotation of nebulae never appeared, and partly because of this his work was not very well known and was not widely quoted. Nevertheless, his work, and the controversy which resulted from it, stimulated further research on the dynamics of the spiral arms of galaxies.

5 ACKNOWLEDGEMENTS

It is my pleasure to thank Antoinette Beiser for her help in my research in the archives of the Lowell Observatory; Kevin Schindler from the Lowell Observatory; Hugues Chabot and Jonathan Simon from the LEPS (Laboratory for the Study of Scientific Phenomenon) and Georges Paturel, astronomer at the Lyon Observatory, for his stimulating discussion and pertinent criticism.

6 NOTES

1. The letters are preserved in boxes with one or two folders for each correspondent of V.M. Slipher. They are in alphabetic order. When the letter has no date on it, the year in brackets was given by the context. The *working papers* are classified by subject and by year. This dating was done by W. Hoyt and by A. Beiser.
2. See Putnam (1994) for an account of Percival Lowell and a history of the Lowell Observatory. For more on the Observatory see Slipher (1927) and for a biography of Lowell see Strauss (2001).
3. In this paper we present all the texts as they actually appear in the manuscripts, without any corrections.
4. It is Campbell who, in November 1914, reported to him a similar observation by Wolf: "The rotation observed in NGC 4594 is especially interesting and important. Wolf observed a similar effect in M 81, as reported by Turner in the Oxford Note Book recently. I hope you will be able to get additional observations of the same kind." The printed version was quoted by Slipher (1914d) as "*Gesellschaft* 48 *Jahrgang p 162*", which actually refers to Wolf's annual report of 1913, published in 1914 in *Vierteljahrsschrift der Astronomischen Gesellschaft*, 49, 151-163, and specifically to page 162.
5. The image of a winding spring was used by the astronomers at that time. The measurements with the Doppler effect only give information on velocity but it is necessary to find an orientation for the spiral nebula to determine the direction of its arms.
6. Thanks to radio astronomy, we now know that the velocity quickly increases linearly from the centre and then plateaus or decreases slightly after the maximum. This was also noted by Vera Rubin in 1970 from spectroscopy of emission regions (see Rubin and Ford, 1970).
7. The unresolved central part of the nebula was estimated by Hubble (1929) to be $10' \times 30'$.
8. Heber D. Curtis worked at the Lick Observatory until 1920 where he was recruited as Director of the Allegheny Observatory. In 1930 he moved to the University of Michigan. He was involved with Shapley in the 'Great Debate' (see Smith, 1982).
9. Prior to 1917 this was the view of Campbell and Slipher.
10. See the letters exchanged between V.M. Slipher and Edwin Hubble during the period 1922 to 1927, as well as with other participants during the same interval, and manuscripts of Slipher's reports to the IAU in the Lowell Observatory Archives. During his Presidency, Slipher did not succeed in getting the Nebula Commission to accept Hubble's classification of nebulae, which was rejected because of its evolutionary nature. However, Hubble "... also thought that a decision on the exact scheme of classification of the nebulae to be used in the catalogue had better await the completion of the survey ..." (Meeting of the Commission, 1928).

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Alain Brémond has a doctorate in history and philosophy of science and is Professor Emeritus at the Claude-Bernard University in Lyon (France). His main research interest is in the field of nebulae, through the life and work of V.M. Slipher. He is also working on the history of the Lyon Observatory, and particularly its instruments. Among these is a coudé telescope (in a perfect state of preservation), and there are many other telescopes and older instruments from the eighteenth century whose histories can to be traced through the archival records. In addition to carrying out historical research, he also hopes to develop a museum of astronomy.

Journal of Astronomical History and Heritage, 12(1), 81-83 (2009).

DR MARY BRÜCK (1925-2008)

It is with great regret that we report the death of astronomer and eminent historian of astronomy Dr Mary Brück (Figure 1) on 11 December 2008 at the age of eighty-three after a short illness. Dr Brück will be no stranger to readers of this journal, as a member of its Editorial Board since its founding and a regular contributor.

Figure 1: Dr Máire (Mary) Teresa Brück (1925-2008).

Máire Teresa Brück née Conway (she often used the Anglicised form of her first name outside Ireland) was born on 29 May 1925 in Ballivor, Co. Meath in the Irish Republic. She was the daughter of Thomas and Margaret Conway, the oldest of their eight children. She attended St Louis Convent in Monaghan and sat her Leaving Certificate examination at the age of sixteen. A talented and determined pupil she showed an early aptitude for mathematics and the physical sciences. She was also musically gifted, becoming an accomplished pianist who could tackle Liszt and Chopin, though he younger brothers preferred her renditions of ragtime.

After school she attended University College Dublin where she studied physics. She later remarked that the physics syllabus at this time was almost entirely classical, with no mention of relativity or quantum mechanics and only a brief treatment of radioactivity.

From Dublin she moved across the Irish Sea to the University of Edinburgh, where normal academic life was resuming after the war. Here she pursued doctoral research in solar physics under Dr M.A. Ellison. This work resulted in the thesis *Studies of $H\alpha$ Line Profiles in Prominences*, for which a Ph.D. was awarded in 1950. Her first professional publications appeared during this time, two contributions to *The Observatory* reporting solar flares. Her doctoral work was later published in the *Monthly Notices of the Royal Astronom-cal Society*. Following the award of her doctorate she returned to Dublin, taking up an appointment at the Dunsink Observatory (Figures 2 and 3), then, as now, part of the Dublin Institute for Advanced Studies, where she continued her solar work. While at Dunsink, Mary Conway, as she then was, met her future husband, Professor Hermann Alexander Brück, then Director of the Observatory. They married in 1951 and she acquired an instant family as Professor Brück was a widower and had two children from his first marriage.

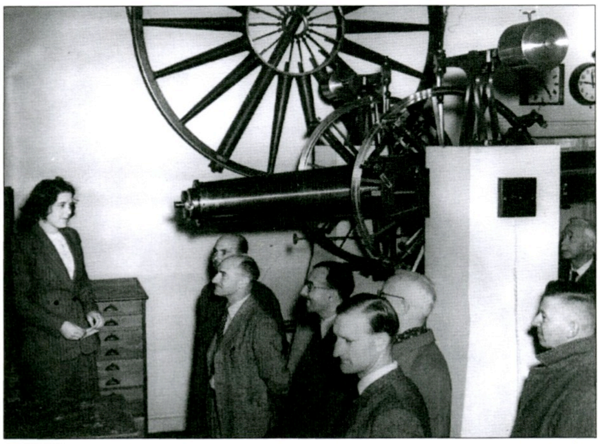

Figure 2: Mary Conway demonstrating equipment at the Dunsink Observatory to members of the Royal Astronomical Society during their meeting in Dublin in 1950.

While at Dunsink Mary Brück made her first foray into popular astronomy, broadcasting a series of radio programmes for children, *The Sun, Moon and Stars*, on Radio Éireann (now Radio Telefís Éireann) in the mid-1950s. These broadcasts were the first popular astronomy programmes in Ireland and found a receptive audience. In the early 1960s she broadcast a second series on the then-new topic of *Spaceflight*.

In 1957 Professor Brück was appointed Astronomer Royal for Scotland, Regius Professor of Astronomy at the University of Edinburgh and Director of the Royal Observatory Edinburgh (ROE), posts which he held until his retirement in 1975. His family relocated to Scotland with him, moving into the purpose-built residence for the Astronomer Royal in the grounds of the ROE on Blackford Hill in Edinburgh. They were the last Director's family to live 'on the hill'; subsequent to Professor Brück's retirement all of the residential accommodation was converted into offices.

Figure 3: In 1954 the Dunsink Observatory mounted an expedition to observe the 30 June total solar eclipse from Öland in Sweden. Mary Brück is captured here preparing for the eclipse. On the day, heavy clouds prevented observations from being made.

Figure 4: A meteor shower over a country town. One of the illustrations in *The Night Sky* (1965), Mary Brück's introductory astronomy book for younger children.

Although she now had three children of her own as well as two step-children Mary Brück continued to pursue an academic career. In 1962 she was appointed a part-time Lecturer at the University of Edinburgh, later becoming full-time and retiring as a Senior Lecturer in 1984. From 1984 to 1987 she was a Fellow of the University and more recently an Honorary Fellow. As a lecturer she taught generations of students and was well-loved for the care she showed her charges. Her first book, however, was aimed at a younger audience. In 1965 she published *The Night Sky* in the popular Ladybird series for young children (see Figure 4). This charming book introduced the constellations and various types of astronomical objects, from meteors and comets to galaxies.

Figure 5: Professor Hermann Brück (left), Mary Brück and Professor Malcolm Longair on the occasion of Professor Brück's 80th Birthday in 1985. At the time Professor Longair was the Astronomer Royal of Scotland.

During this period she switched from solar to stellar research, pursuing a programme of three-colour photometry, initially largely of southern galactic clusters. Later she concentrated on the Magellanic Clouds, in the 1970s utilising the then-new UK Schmidt Telescope (UKST) on Siding Spring Mountain in New South Wales and the COSMOS fast microdensitometer in Edinburgh. She became an expert on the Nebeculae and was an invited speaker at IAU Symposium 108 on "Structure and Evolution of the Magellanic Clouds" in 1983.

Her teaching and research interests coalesced in the Edinburgh astronomy teaching packages, first released in 1984. These packs contained a series of practical exercises for undergraduates. They were used in conjunction with professional-quality film reproductions of UKST photographs and allowed students to use the techniques of professional astronomers with professional material but without requiring specialised measuring machines. A later development of this approach was the book *Exercises in Practical Astronomy using Photographs* (1990). Here the measurements were made on photographs reproduced in the book without requiring separate films.

Figure 6: The opening of the extension to the Crawford Room at the ROE in 1988. Professor Brück and Mary Brück are first and second from the right, respectively.

Following his retirement in 1975 Professor Brück (Figure 5) took up the study of history of astronomy, largely, though not exclusively, working on the earlier history of the institution he had directed. Initially Mary Brück collaborated in this work, but she was to become an eminent and respected historian of astronomy in her own right. The collaboration led to *The Peripatetic Astronomer* (1988), the definitive biography of Piazzi Smyth, the second Astronomer Royal for Scotland. In later years, Professor Brück's health declined and Mary Brück looked after him through his final years until his death in 2000.

Mary Brück's own particular interest was women in astronomy and much of her work subsequent to *The Peripatetic Astronomer* was in this area. However, she also maintained her interest in the history of the ROE and its magnificent Crawford Collection of historic astronomical texts (see Figure 6). In 2002 she published *Agnes Mary Clerke and the Rise of Astrophysics*, a masterly piece of work which is likely to remain the definitive study of this subject. When Miss Clerke's *Popular History of Astronomy During the Nineteenth Century* was republished in 2003 it was natural that Mary Brück should provide the Foreword. Her final book, *Stars and Satellites*, is to be published posthumously later in 2009. Each of its chapters contains biographical essays on various women astronomers. It will stand as her last word on the subject.

Mary Brück never lost sight of her Irish roots, writing two chapters for *Stars, Shells and Bluebells* (1997) published under the auspices of the Irish WITS (Women In Technology and Science) initiative and celebrating the achievements of early women pioneers in science in that country. Its forthcoming companion volume, *Lab Coats and Lace*, to which she also contributed, is dedicated to her memory. She also contributed to the *Irish Astronomical Journal* until it ceased publication.

Figure 7: Mary Brück (left) receiving the Lorimer Medal from Lorna McCalman (the then-President of the Edinburgh Astronomical Society) and Dr David Gavine in 2001 for her efforts to popularise astronomy.

She wrote entries for the *Oxford Dictionary of National Biography* and published numerous papers and book reviews, not least in this journal. When the newly-formed Society for the History of Astronomy (SHA) launched its journal, *The Antiquarian Astronomer* (*AA*), she contributed what became the first paper in the inaugural issue. Later she would join the SHA and become a member of the *AA*'s Editorial Board. In recent years she has also returned to solar work, collaborating with Jay Pasachoff and his colleagues. She was instrumental in setting up the ROE History Project to document the recent past of that institution.

Mary Brück was a Fellow of the Royal Astronomical Society and an Honorary Member of the Irish Astronomical Society. In 2001 she was awarded the Lorimer Medal by the Astronomical Society of Edinburgh for her work in popularising astronomy (Figure 7) and was made an Honorary Member of that Society. The ROE held a short workshop in her honour on the occasion of her 80th birthday in 2005 (Figure 8).

She remained active until shortly before the end, regularly attending meetings and giving talks. In 2002, despite being almost immobile following a hip operation, she was determined to honour an invitation as the Guest Speaker at the Scottish Astronomy Weekend in Dundee and gave an acclaimed talk on "Spectra of the Stars". As recently as May 2008 she gave a well-received public lecture to the RAS in London on "The Fascination of the Heavens", which was about pioneering women astronomers. In addition to the book *Stars and Satellites*, she also has a paper in press in the *AA*. Co-authored by David Gavine, it documents the Reverend Hector MacPherson, a populariser of astronomy in early twentieth-century Edinburgh.

Figure 8: Mary Brück at the ROE in May 2005 for the Workshop celebrating her 80th Birthday. With her are her brother, Loman Conway and his son, Turlough Conway.

In her youth, Mary Brück imbibed the deep Catholic faith of her parents, and it sustained and underpinned her throughout her life. Always modest and self-effacing, she maintained that being a wife and mother was much more difficult than her academic work. She was unfailingly generous and helpful to her colleagues, and generations of students have benefited from her advice and assistance. She is survived by her children, Anne, Catherine and Andrew, and her step-children, Mary and Peter.

Clive Davenhall

Journal of Astronomical History and Heritage, 12(1), 84-87 (2009).

BOOK REVIEWS

***Astronomy, Weather, and Calendars in the Ancient World.* Parapegmata *and Related Texts in Classical and Near-Eastern Societies*, by Daryn Lehoux (Cambridge, Cambridge University Press, 2007), pp. xiv + 566, ISBN 978-0-521-85181-7 (hardback), US$131, 247 x 174 mm.**

Professor Lehoux laudably serves scholars and all others with an interest in ancient astronomy and calendrics in the first large-scale study of parapegmata to appear in over half a century (see Figure 1). But first things first: I read the Ph.D. dissertation on which the book is based (University of Toronto, 2000, under the supervision of Alexander Jones) and then waited months for my pre-ordered copy of the book to arrive. When it did, I was heartened to receive much more than a reupholstered doctoral thesis.

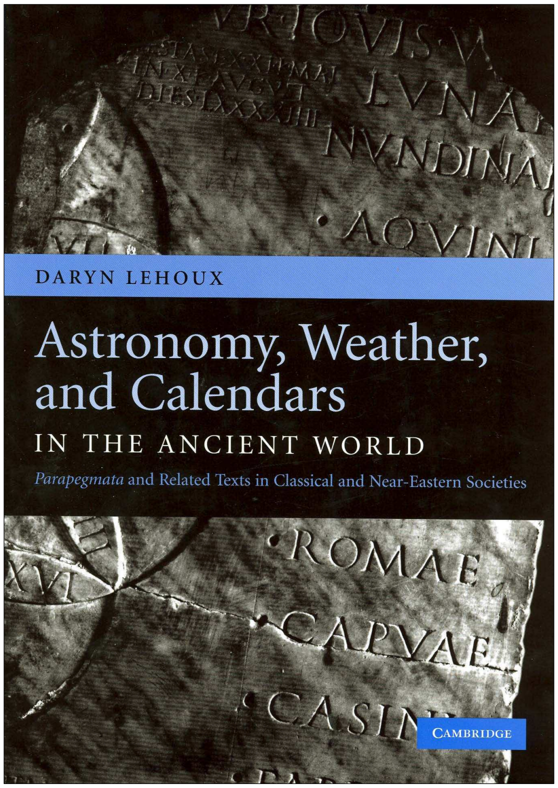

Figure 1: The front cover of Daryn Lehoux's book.

From the Greek "… to put a peg beside something …" (*parapegnumi*), a *parapegma* is an instrument or inscription that tracks the passage of time with movable pegs, or a literary text with a similar aim. It resembles a calendar or (as Lehoux notes) a farmer's almanac:

> But the fact that parapegmata sometimes incorporate calendars does not mean they *are* calendars. They may contain calendrical information, but they are not conventions for the dating of events. They are rather tools for keeping track of phenomena (astronomical, meteorological) and cycles (astrometeorological, hebdomadal, nundinal, lunar), and, specifically, our current position in those cycles. (Page 91).

Lehoux's study is divided into two parts. Part I consists of a collection of fairly individualized essays written in a fluid and (usually refreshingly) colloquial style—much of one was published as a stand-alone article in 2004. Here, there is something for everyone—from the serious historian of calendrics to your run-of-the-mill Egyptologist. The first chapter is titled "The rain in Attica falls mainly under Sagitta" and presents *inter alia* an introductory discussion of parapegmatic texts and instruments as well as the relevant naked-eye astronomy (e.g., stellar phases). In Chapter Two, "Spelt and Spica", Lehoux situates Greek and Roman parapegmata within the context of ancient agricultural practice, with particular emphasis on Rome. In the next chapter, *De signis* (literally "On the signs"), Lehoux illuminatingly fleshes out the role of observation in the construction and use of classical parapegmata. Chapter Four, "When are thirty days not a month?", consists of a largely technical discussion of calendar systems and luni-solar cycles in Greece and Rome, and of what parapegmata can (and cannot) add to debates on the origins of ancient calendars. The next two chapters deal with texts that look like (but which Lehoux does not call) parapegmata from Mesopotamia ("Calendars, weather, and stars in Babylon") and Egypt ("Egyptian astrometeorology"), such as hemerologies, menologies, and lists of lucky and unlucky days. In light of these two chapters, I think a few more words on ancient brontologia and seismologia as well as a description of the meteorological tablets in the Enuma Anu Enlil, though not necessary, would probably not have been out of place—they are all clearly 'related texts'.

After a short conclusion to Part I, there follows in Part II 346 pages of "all extant" parapegmata which Lehoux has catalogued, translated, and in many cases reproduced in the original. These originals-cum-translations include Ptolemy's *Phaseis*, Clodius Tuscus' *Ephemeris* (pp. 343-375) and over sixty others. The classification scheme Lehoux devises for cataloguing these sources is based principally on usage: the 'astrometeorological' texts and inscriptions relate astronomical events to meteorological events; 'astrological' ones track astrological phenomena—e.g., zodiacal signs—and similarly for 'astronomical' parapegmata which mark for example the phases of fixed stars. Even though Lehoux has not re-edited the texts, his commentaries, divergent readings and textual criticisms, and translations—especially for the Greek and Latin astrometeorological parapegmata—are of tremendous value. This is reason alone for those who even peripherally come into contact with these texts to have this book at their disposal. The remaining classes are 'other' (e.g., fragmentary), 'reports of' (parapegmata), 'related texts' and 'dubia'. The study ends with two short appendices of authorities cited and a table of correspondences; a bibliography (pp. 499-518), updated since 2000; an 'astrometeorological' index (pp. 519-547); and a general index (pp. 548-566).

Although I managed to stumble across a few minor errors (e.g., "a brontologia" (p. 392) should be "a brontologion", while Marino (2000) (p. 12) and Boll (1910b) (p. 404) are not in the bibliography), I highly recommend this useful work. It will make a valuable addition to any university's research library.

Jefferson Sauter
Centre for Astronomy, James Cook University, Australia

The Astrolabe, by James E. Morrison (Rehoboth Beach (USA), Janus, 2007), pp. xiv + 438, ISBN 978-0-939320-30-1 (softcover), US$60, 276 x 213 mm.

The title of this book is *The Astrolabe* (Figure 2) without any subtitle. Yes, this fact agrees with my conclusion as well as the author's intention. This book is a comprehensive and lucid treatise on the astrolabe itself.

Beginning with the history and principle of the 'planispheric astrolabe' (ordinary astrolabe), this book explains several related astronomical instruments. The planispheric astrolabe is an astronomical instrument which is based on the stereographic projection of the celestial sphere on the equatorial plane, and was invented in the Hellenistic world (around the fourth century AD), and largely developed in the Islamic world. It was also used in medieval Europe, India, etc.

Regarding the astronomical and mathematical principles of the planispheric astrolabe, this work is almost self-contained, and readers will be able to construct their own astrolabes after reading this book. The principle of the stereographic projection is lucidly explained, and each component of the planispheric astrolabe is minutely explained with several figures and formulae. This book is not a description of particular existing astrolabes, but a comprehensive and balanced description of several variations of astrolabes. So, readers who want to analyze specific astrolabes will easily be able to get useful information regarding the theory of the instrument from this book.

The author then proceeds to explain the 'universal astrolabe'. The ordinary planispheric astrolabe is projected from the celestial South Pole (or North Pole in the case of the astrolabe for southern latitudes), and its plate can only be used at a particular terrestrial latitude. So, travellers had to possess several plates for different latitudes. The 'universal astrolabe' is projected from the point of the equinox by stereographic projection (or projected by orthographic projection etc.), and can be used at any terrestrial latitude.

Next the author explains 'quadrants'. A quadrant is one-fourth of a circle, and there are several versions of this instrument. The reverse sides of astrolabes were sometimes divided into four parts, and some of them were used as quadrants. There are also several independent quadrants. The simplest quadrant was used to measure the altitude of heavenly bodies. More complicated quadrants were used for graphical calculation of astronomical problems. Some of them are quite ingenious and interesting.

The author explains other stereographic and related instruments. He then discusses basic spherical astronomy and how to design personal astrolabes using computers.

It must be stressed that this book is a treatise on the principle of the astrolabe, and not a compendium of specific specimens. For the latest information regarding historical specimens see King (2005).

The author conducted a useful survey of the literature on Islamic and European astrolabes, but I would like to provide some additional information. Several Indian astrolabes are described by Kaye (1918) and Sarma (2003; 2008), while Ôhashi (1997) discusses literature (particularly Sanskrit literature) about the astrolabe in India. Readers may also be interested in these Eastern astrolabes.

Although the astrolabe is an historical instrument of the past, it is a very useful educational tool nowadays. As it can be designed with a ruler and compasses (or, of course, with a personal computer), paper models can easily be made in the classroom, and the rotation of the celestial sphere is represented clearly. Educators should recognize the importance of the astrolabe and other historical astronomical instruments.

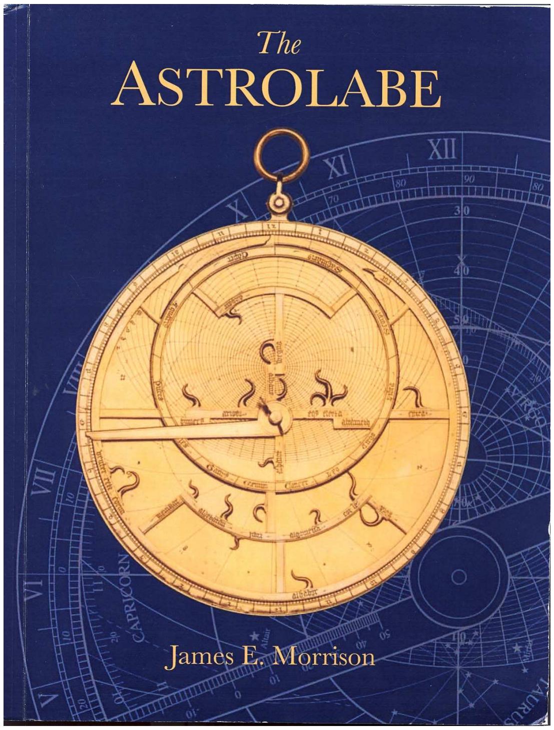

Figure 2: The front cover of *The Astrolabe*.

In future bibliographies relating to the astrolabe, I think that Morrison's book should be listed in the section on primary sources (rather than secondary sources). This is a very impressive book, which shows that the astrolabe is still living!

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Yukio Ôhashi
Tokyo, Japan

Shrouds of the Night. Masks of the Milky Way and Our Awesome New View of Galaxies, by David L. Block and Kenneth Freeman (New York, Springer, 2008), pp. 441, ISBN: 978-0-387-7894-3 (hardcover), US$39:95, 240 x 310 mm.

This is a beautiful large-format book (Figure 3), written by two astronomers who have each spent a lifetime studying 'dark matter'. The Preface is by the renowned Vera Rubin, Senior Fellow at the Carnegie Institute of Washington, who briefly tells the reader about what they are going to read and enjoy.

Early civilizations explained their curiosity about the Universe with stories, myths and legends about its origin, how the Milky Way was formed, the rising and setting of the Sun and the Moon, etc. These stories were handed down through the generations. As tools and understanding progressed, some of the questions were answered, but new discoveries and new questions arose to take their place. Before 1946, the discoveries were largely restricted to observations made in visible light, with or without telescopes or cameras. From this date, however, we have seen the remarkable growth of radio astronomy and more recently ultra-violet, infrared, X-ray and gamma-ray astronomy.

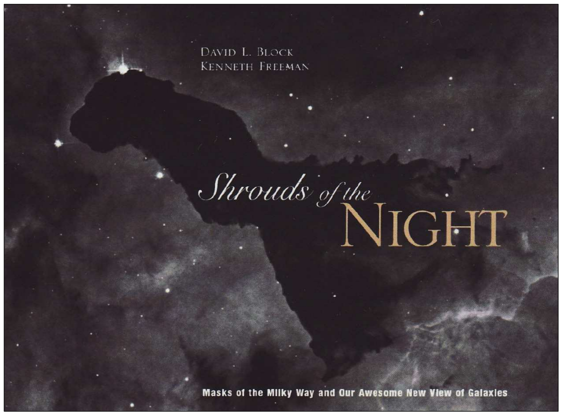

Figure 3: The front cover of *Shrouds of the Night* …

The first five chapters in *Shrouds of the Night* … cover the period from Galileo in 1609 to Sir John Herschel in 1847. During this interval observations of the heavens were recorded in written descriptions and hand drawings. Both authors expressed their tremendous joy at personally being able to hold and examine many of the Herschels' drawings of nebulae housed in the archives of the Royal Astronomical Society in London. William and John Herschel discovered an astonishing 4,630 objects.

Chapter 6 on "The Dawning of the Photographic Era", describes the transformation from hand drawings to Fritz Zwicky's well known research in the 1940's and the rise of photography as a handmaiden of astronomy. The first recognizable image formed by a *camera obscura* was obtained by Joseph N. Niepce in 1826. In 1833 W.H.F. Talbot made sketches of the scenery at Lake Como (Italy) using a *camera obscura*, and in 1835 he exposed the earliest-known surviving photographic negative on sensitized paper, which had been washed in salt and silver solutions. The photograph was fixed by a liquid solution devised by Sir John Herschel. Thus it is to Herschel that we owe the word *photography*, from the Greek *photos* (light) and *graphos* (to write). In this book, the early development of astronomical photography is discussed in detail.

Enter Edward Emerson Barnard, one of the most admired astrophotographers of all time, who was inspired by the Reverend Thomas Dick's description of the heavens. To support his widowed mother, Barnard took a job at nine years of age, directing a solar camera used to develop photographic enlargements. To pay his way through Vanderbilt University, Barnard successfully searched for comets, receiving a prize of $200 for each new one he discovered. For me personally, Barnard is best remembered for *A Photographic Atlas of Selected Regions of the Milky Way* which was published in 1927, four years after his death. It contained the best seven hundred photographs from a lifetime total of 35,700 that Barnard took.

Chapter 7 opens the discussion on the classification of spiral galaxies with the contribution made by Edwin Hubble. Mention is also made of Herber D. Curtis and John Reynolds. Reynolds became a wealthy industrialist making cut nails for the American market. Taking an interest in astronomy, he purchased a 30-inch mirror from Andrew A. Common and helped design a reflector telescope which eventually was installed in Egypt and became operational in 1907. Reynolds then decided to build his own observatory and made his own 28 inch mirror. After an upgrade in Egypt, the 30 inch mirror was returned to Reynolds, who installed it in his own telescope. He then donated the telescope to the Commonwealth Solar Observatory (later Mount Stromlo and Siding Spring Observatories) in Canberra, Australia, where for many years it was a stalwart of the astrophysical research program. Amongst those who used this telescope was Ken Freeman, one of the authors of this book. Block and Freeman end Chapter 7 by reproducing extracts from previously-unpublished letters between Reynolds and some of the leading astronomers of the day. In 1899, at just 25 years of age, Reynolds was elected a Fellow of the Royal Astronomical Society, and he served as President of the Society from 1935 to 1937.

Chapter 8, "The Dust Penetrated Universe: Hidden Symmetries", opens with an analogy of our view of the Universe to a ship entering a strange harbour at night in a fog. The captain's view of the harbour is misleading, because of the light beaming from the lighthouse and the fog enveloping the actual lighthouse. Compare this view to the full Moon masking the presence of fainter stars. This chapter shows how our view of the Universe changed markedly with the advent of new technology.

The final chapters highlight the philosophy of astronomy and religion, starting with music played by a string trio in the famed Carnegie Hall. The authors view spiral galaxies as "… great stringed instruments, instruments being plucked or bowed, in which the strings of gas and dust typically measure some 100,000 light years across." They talk about "Penetrating the Mask of Time" and move forward to the "Eyes of the Future". There is also a short chapter on "Planets Orbiting other Stars".

Meanwhile, the religious aspect opens with a discussion on the insignificance of man. In this regard, Bernard de Fontenelle (1657–1757) said: "Behold a Universe so immense that I am lost in it. I no longer know where I am. I am just nothing at all. Our world is terrifying in its insignificance." Block and Freeman then ask the audacious question, "Does God exist?", and is the language of the Universe one of eternal silence? To answer this question Block prepared a questionnaire and sent it to many of his colleagues. Readers of this book will be very surprised by the answers he received.

This is a 'must-have' book for those interested in the history of astronomy, and an ideal gift for any young aspiring astronomer.

Colin Montgomery
Centre for Astronomy, James Cook University, Australia

***The Greatest Comets in History. Broom Stars and Celestial Scimitars*, by David Seargent (New York, Springer, 2009), pp. xx + 260, ISBN: 978-0-387-09512-7 (paperback), €24:95, 235 x 155 mm.**

As an authority on comets, a successful searcher for new comets, and the author of other books about comets, Dr Seargent is ideally placed to pen a book on the 'greatest comets' (see Figure 4). Whilst many comets can be designated 'great comets' and have made their mark in history, what Seargent is concerned with in this particular book are "… the greatest of the great, the cream of the comet world. We are looking for nothing less than cometary royalty." (page vii).

For those with an historical interest in comets, this is a compelling book in that it succinctly presents an overview of almost fifty truly amazing comets, all in the span of about 230 pages. But first, Seargent assigns 30 pages to Chapter 1, where he discusses "The Nature of Comets" and provides a useful anatomical exploration of these broom stars and celestial scimitars. Then follow chapters on "Halley's Comet Through the Ages"; "The Greatest Comets of Ancient Times" (from 372 BC to AD 905); "The Greatest Comets from A.D. 1000 to 1800"; "The Greatest Comets from 1800 to Present Times", the final candidate being C/2006 P1 (McNaught); "Kamikaze Comets: The Kreutz Sungrazers"; and "Daylight Comets". The final 20 pages of the book contain a glossary, a very short list of "Further Reading", a table summarizing information on comets discussed in the book, and name and subject indexes.

Each chapter is easy reading, and embellished throughout with a brilliant selection of drawings and photographs. Seargent draws freely on archival material, and also incorporates data supplied by astronomical and lay informants. When dealing with comets of the last three to four decades, the fact that he often knew the astronomers responsible for their discoveries and actually observed many of these objects brings a refreshingly personal touch to the accounts. Meanwhile, those wanting further details on individual comets can always resort to Kronk's excellent *Cometography* series (the fourth volume of which has just been published).

The one challenge when writing a book like this is to decide which comets to include and which to omit, and as Seargent says in the Preface, "… it is quite possible that I have missed some comets that should have been included, and I may have included one or two that should not be here." (page x). Clearly this involves a personal choice and I suspect that each author would come up with a slightly different list. Certainly, if I had written this book I would have included C/1881 K1 (Tebbutt), which is also known as the Great Comet of 1881. This comet fulfils all of Seargent's selection criteria (it had a bright nucleus, an impressive tail, and was a conspicuous naked eye object that attracted the attention of non-astronomers), but it also arrived at a critical time in the emergence of astrophysics. As such, it was the first comet to be successfully photographed and the first comet that was subjected to detailed spectroscopic investigation (see Orchiston, 1999). In this regard, I believe that it really deserves to be a member of cometary's 'royal family'.

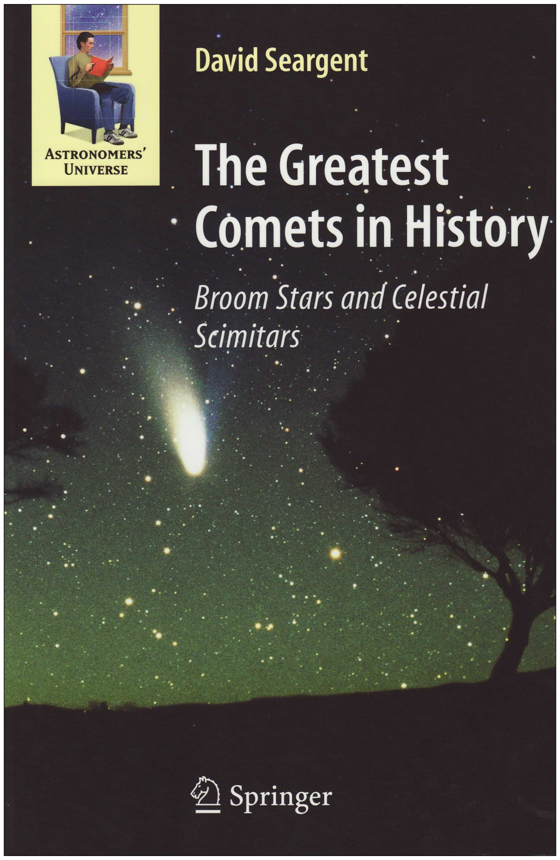

Figure 4: The front cover of David Seargent's book.

Notwithstanding this personal aside, *The Greatest Comets in History* … is an excellent book. It is totally affordable, and belongs in the library of all those with a passion for comets and cometary history.

Reference

Orchiston, W., 1999. C/1881 K1: a forgotten "Great Comet" of the nineteenth century. *Irish Astronomical Journal*, 26, 33-44.

Wayne Orchiston
Centre for Astronomy, James Cook University, Australia

CONTENTS

Christiansen Papers

Other Papers

Obituary

Book Reviews

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