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COVER IMAGE

Comet Donati (C/1858 L1) as observed (and drawn) by C.F. Fearnley on 26, 27, 29 September and 1 October 1858 (right to left). Observations made with various refractors from the University Observatory at Christiana (former name of Oslo) are described by Bjørn Ragnvald Pettersen from p. 98. The measurements, which include polarization determinations, were recently recovered and have not been published until now. The drawings attest to Fearnley's observing and drafting skill (north is up - for orientation, note the seven stars of the Big Dipper [or Plough] along the top).

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EDITORIAL

Dear Readers of *JAHH*,

It is with great pleasure that we welcome a new Associate Editor to the Editorial team: Dr Duane Hamacher from the University of New South Wales in Sydney, Australia.

Duane will be known to many readers of *JAHH* through the research papers on Aboriginal Australian astronomy that he has published in the journal in recent years, and for serving as the Guest Editor of the July/August 2014 Special Issue of *JAHH* on the 'Ethnoastronomy of Aboriginal Australians'.

American by birth, Duane received a B.Sc. in Physics from the University of Missouri in 2004, then moved to Australia and completed an M.Sc. in Astrophysics from the University of New South Wales in 2006. He then completed a Ph.D. in Indigenous Studies at Macquarie University (also in Sydney) in 2012, with a thesis on Aboriginal Australian astronomy. His supervisors were astrophysicist Professor Ray Norris from CSIRO Astronomy and Space Science, anthropologist Dr Kristina Everett from Macquarie University and retired University of Sydney prehistorian John Clegg.

After graduating, Duane moved back to the University of New South Wales, not to the Astrophysics Department, but to the Nura Gili Indigenous Programs Unit, where he is a Lecturer and ARC Discovery Early Career Research Fellow. Duane won a major DECRA grant from the Australian Research Council to study Torres Strait Islander astronomy, and he quickly built up a group of staff and graduate students studying various aspects of Australian Indigenous astronomy. Two of these graduate students are Trevor Leaman and Robert Fuller, both of whom have published papers in *JAHH* in the past year.

In addition to supervising Honours, Masters and Ph.D. students, Duane developed and teaches undergraduate courses on Australian Indigenous Astronomy (ATSI 3006) and Indigenous Science (ATSI 2015), which are especially popular with overseas students studying at the University.

In 2011, Duane married Tui Britton, a New Zealander completing a Ph.D. in astrophysics at Macquarie University. Just like one of us (W.O.), Tui has Maori ancestry, so recently she and Duane teamed together to write a paper on Maori astronomy.

Duane and Tui also are committed to taking astronomy to the public, and for several years they worked as Astronomy Educators at Sydney Observatory.

With the three of us beyond the traditional retirement age, it is a great pleasure to have someone much younger join the Editorial team. We look forward to publishing further papers by Duane, his graduate students, and Ray Norris, in *JAHH*, and it will be very helpful to have him assess and referee papers we receive on ethnoastronomy and archaeoastronomy. These are now well-established niche areas that we regularly publish papers on in *JAHH*.

We look forward to working closely with Duane.

Wayne Orchiston
Joseph S. Tenn
Richard Strom

THE HISTORY OF EARLY LOW FREQUENCY RADIO ASTRONOMY IN AUSTRALIA. 1: THE CSIRO DIVISION OF RADIOPHYSICS

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Abstract: During the 1950s and 1960s Australia was a world leader in the specialised field of low frequency radio astronomy, with two geographically-distinct areas of activity. One was in the Sydney region and the other in the island of Tasmania to the south of the Australian mainland. Research in the Sydney region began in 1949 through the CSIRO's Division of Radiophysics, and initially was carried out at the Hornsby Valley field station before later transferring to the Fleurs field station. In this paper we summarise the low frequency radio telescopes and research programs associated with the historic Hornsby Valley and Fleurs sites.

Keywords: Australian low frequency radio astronomy, CSIRO Division of Radiophysics, Alex Shain, Hornsby Valley, Fleurs, Tasmania.

1 INTRODUCTION

A revolution began in astronomy in 1931 when the American physicist Karl Guthe Jansky (1905–1950) first detected what he termed 'cosmic static'. With the discovery of extraterrestrial radio emission, a new window was added to the electromagnetic spectrum (see Sullivan, 1983; 2009), and although little interest was shown by most optical astronomers at the time, this new approach to astronomy was followed up during the 1930s and early 1940s by an American radio 'ham', Grote Reber (1911–2002), who also built the world's first dedicated radio telescope (Kellermann, 2005; Reber, 1984; Sullivan, 1984b; 2009).

During WWII, scientists and radar operators from several different nations independently discovered that the Sun was a strong radio emitter from metre to centimetre wavelengths (see Alexander, 1946; Hey, 1946; Reber, 1944; Schott, 1947; Southworth, 1945; cf. Orchiston, 2005a; Orchiston and Slee, 2002a; Sullivan, 2009: 79-99).

In the years immediately following WWII radio astronomy flourished as it built on these—for the most part—secret wartime solar detections and exploited WWII developments in radar antenna and receiver technology. A number of nations made important contributions to radio astronomy at this time, but undoubtedly the two leading ones were Australia and England. It is notable that both countries boasted long traditions in ionospheric research and intensive wartime research on radar (Hey, 1973; Sullivan, 2009).

In Australia, for a short time there were small solar radio astronomy research groups based at Mt Stromlo Observatory and the University of Western Australia in Perth (for Australian localities mentioned in the text see Figure 1) (Orchiston et al., 2005), but most of the post-war effort in this new research field was mounted by the CSIR's (later CSIRO) Division of Radiophysics (henceforth RP), which from 1946 through into the early 1960s maintained a large number of field stations and remote sites, mainly in and around Sydney (see Orchiston and Slee, 2005a; Robertson, 1992). Their distribution is shown in Figure 2. Two of these field stations, Hornsby Valley and Fleurs, were involved in low frequency radio astronomy—that is, research conducted at frequencies below 30 MHz. Key individuals involved in the RP low frequency research were Alex Shain, Charlie Higgins and one of the authors of this paper, Bruce Slee.

During the 1950s and early 1960s a second centre of Australian low frequency radio astronomy emerged in Tasmania to the south of the Australian mainland (see Figure 1). Because of its privileged position with respect to the South Magnetic Pole, Tasmania was one of the very few locations on the Earth where extraterrestrial radio emission down to 1 MHz or even lower could sometimes successfully reach the Earth's surface during sunspot minima. Tasmanian research primarily was in the care of two individuals, that aforementioned U.S. pioneer of radio astronomy from the 1930s, Grote Reber, and Graeme Ellis (1921–2011) from the Physics Department at the University of Tasmania.

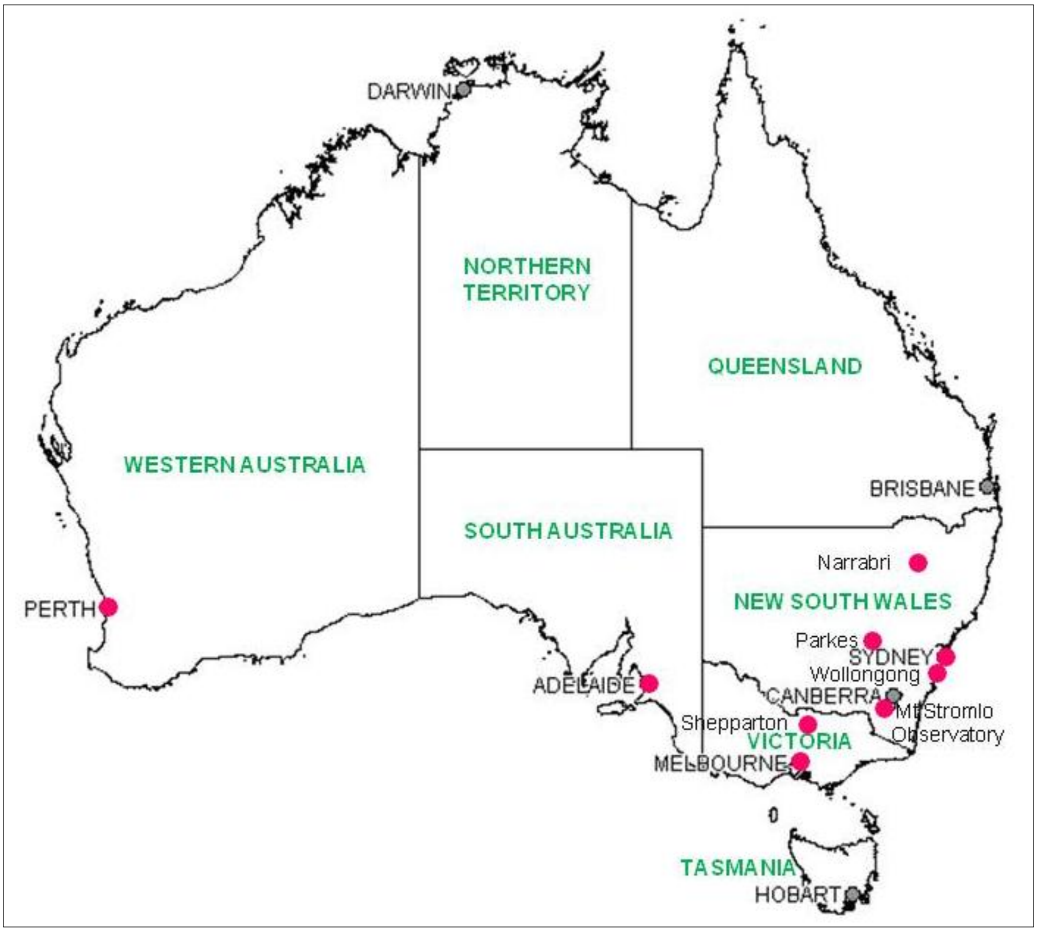

Figure 1: A map of Australia showing States and Territories and their capitals, with mainland localities mentioned in the text shown in red.

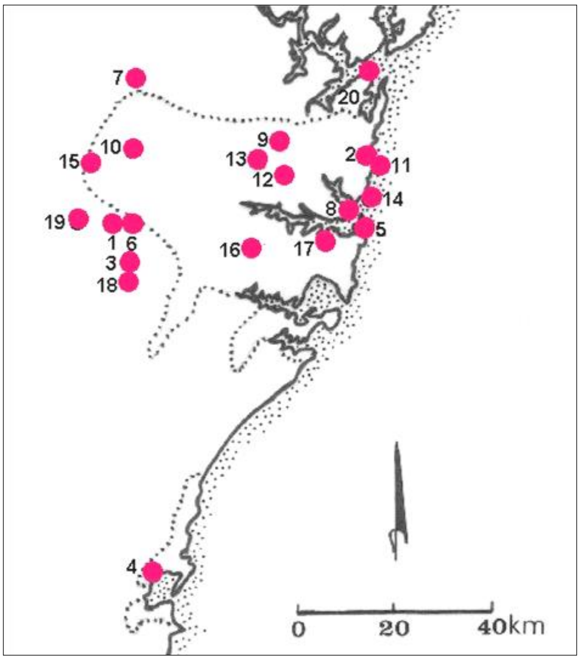

Figure 2: This map shows field stations and remote sites in the Sydney and Wollongong areas used by the CSIRO's Division of Radiophysics at one time or another between 1945 and 1965. The Hornsby Valley and Fleurs field stations where low frequency research was carried out are indicated by sites 9 and 6, respectively. The upper dotted boundary shows the approximate present-day extent of suburban Sydney and the lower dotted boundary of 'greater Wollongong'.

While the RP low frequency research was merely part of a wide-ranging campaign that extended in frequency from about 9 MHz to 24 GHz (see Orchiston and Slee, 2005a), the choice by Reber and Ellis to focus exclusively on low frequency radio astronomy was intentional, and was motivated by Tasmania's special geographical location.

The aim of this paper is to provide readers with an overview of the low frequency radio astronomy that was carried out at Hornsby Valley and Fleurs between 1949 and the mid-1960s. Details of the research conducted at these two field stations will be published in later papers in this series.

Meanwhile, collectively this paper and the next paper in this issue of *JAHH* (George et al, 2015) will provide a useful national overview of developments in early low frequency radio astronomy in Australia (cf. Orchiston et al., 2015).

2 THE DIVISION OF RADIOPHYSICS

2.1 Hornsby Valley Field Station

The Hornsby Valley field station (Orchiston and Slee, 2005b) was established in 1946 on farmland in a picturesque valley surrounded by low tree-covered hills (see Figure 3). At the time, this radio-quiet site lay just beyond Sydney's most northerly suburbs.

The first scientists to carry out research at this new field station were Frank John Kerr (1918–2000) and Charles Alexander ('Alex') Shain (1922–1960), but their interest was in radar astronomy, not radio astronomy, and in the Earth's upper atmosphere, not in extraterrestrial emission. During 1947–1948 they used a rhombic aerial to receive 17.84 and 21.54 MHz signals broadcast from Shepparton in Victoria by Radio Australia that were bounced off the Moon. These experiments provided information about the ionosphere, but what interests us is their astronomical conclusion: the nature of the echoes showed that the Moon's surface was 'rough' rather than smooth. This project was Kerr's sole exploration at low frequencies, and he then moved to the Potts Hill field station (Site 16 in Figure 2) where he concentrated on H-line work (Kerr, 1984; Wendt et al., 2011) before accepting a Chair in Astronomy at the University of Maryland.

The departure of Kerr left Hornsby Valley in the capable hands of Alex Shain and Charlie Higgins (Figure 4). Charles Alexander Shain was born in Melbourne on 6 February 1922, and after completing a B.Sc. degree at the University of Melbourne he served briefly in the military before joining the Division of Radiophysics in November 1943 (Orchiston and Slee, 2005b). During WWII he worked on the Division's radar program and immediately after the war he championed low frequency radio astronomy in Australia. When Shain died prematurely on 11 February 1960 Australia lost one of its radio astronomy pioneers. Deputy Chief of the Division of Radiophysics, Dr Joe Lade Pawsey (1908–1962), described Shain as "... a wonderful colleague in the laboratory, imaginative, well balanced, exceedingly unselfish, and a real friend to all." (Pawsey, 1960: 245). Assisting Shain was Technical Assistant Charles ('Charlie') S. Higgins (Figure 4), who came to Radiophysics with a background in radio engineering.

During 1949 and the early 1950s Shain and Higgins plotted a new course for the Division of Radiophysics by developing Hornsby Valley into the Division's forefront low frequency radio astronomy field station (Higgins and Shain, 1954; Shain, 1951; Shain and Higgins, 1954).

Figure 3: This panoramic view of the Hornsby Valley field station shows low frequency aerials, instrument huts and (far left) a farm house (courtesy: CASS RAIA: B2802-10).

Figure 4: Alex Shain (left) and Charlie Higgins (right) (both images are cropped close-ups that were taken from CASS RAIA: B2842-133).

They

> ... built 9.15 and 18.3 MHz horizontal arrays that were distinguished by their simplicity: ordinary posts were used to support the dipoles, with the ground serving as a reflector [see Figure 5] ... The most ambitious of these radio telescopes was an array of 30 horizontal half-wave dipoles, and by moving the beam electronically a strip of sky extending from declination –12° to –50° could be surveyed. These Hornsby Valley antennas were used to produce the first [contour] maps of Galactic emission at low frequencies [e.g. see Figure 6]. (Orchiston and Slee, 2005a: 132).

After completing the 9.15 MHz sky survey, Shain and Higgins planned to embark on a major new low frequency radio astronomy project, but Shain (1952) concluded that the Hornsby Valley site was unsuitable for larger arrays, and he favoured moving to the Division of Radiophysics field station at Badgerys Creek (Site 1 in Figure 2) on the western outskirts of suburban Sydney. For various reasons this did not happen, and instead it was the nearby Fleurs field station (Site 6 in Figure 2) that benefited from the eventual close down of the Hornsby Valley field station in 1955.

Before examining low frequency radio astronomy at the Fleurs field station, there is one final twist to the saga of the Hornsby Valley research that deserves to be told. Terrestrial interference was a common problem encountered by all low frequency radio astronomers because of the frequencies at which they worked, and Shain and Higgins tended to regard it as rather a nuisance and a distraction during their galactic observations at 9.15 and 18.3 MHz. However, when the U.S. radio astronomers Bernard Flood Burke (b. 1928) and Kenneth Linn Franklin (1923–2007) reported the discovery of decametric burst emission from Jupiter in 1955 Shain and Higgins were forced to reflect on this. Shain (1955; 1956) then examined some of those periods of 'intense static' that he and Higgins remembered recording at 18.3 MHz in 1950 and 1951 (e.g. see Figure 7), and he found that these were indeed Jovian bursts.[1] With the benefit of hindsight, this serendipitous 'pre-discovery' proved to be one of the Division of Radiophysics' most notable 'missed opportunities'.

Figure 5: The low frequency radio telescopes at Hornsby Valley consisted of posts that were used to support the dipoles, with the ground serving as a reflector (courtesy CASS RAIA: B2802-5).

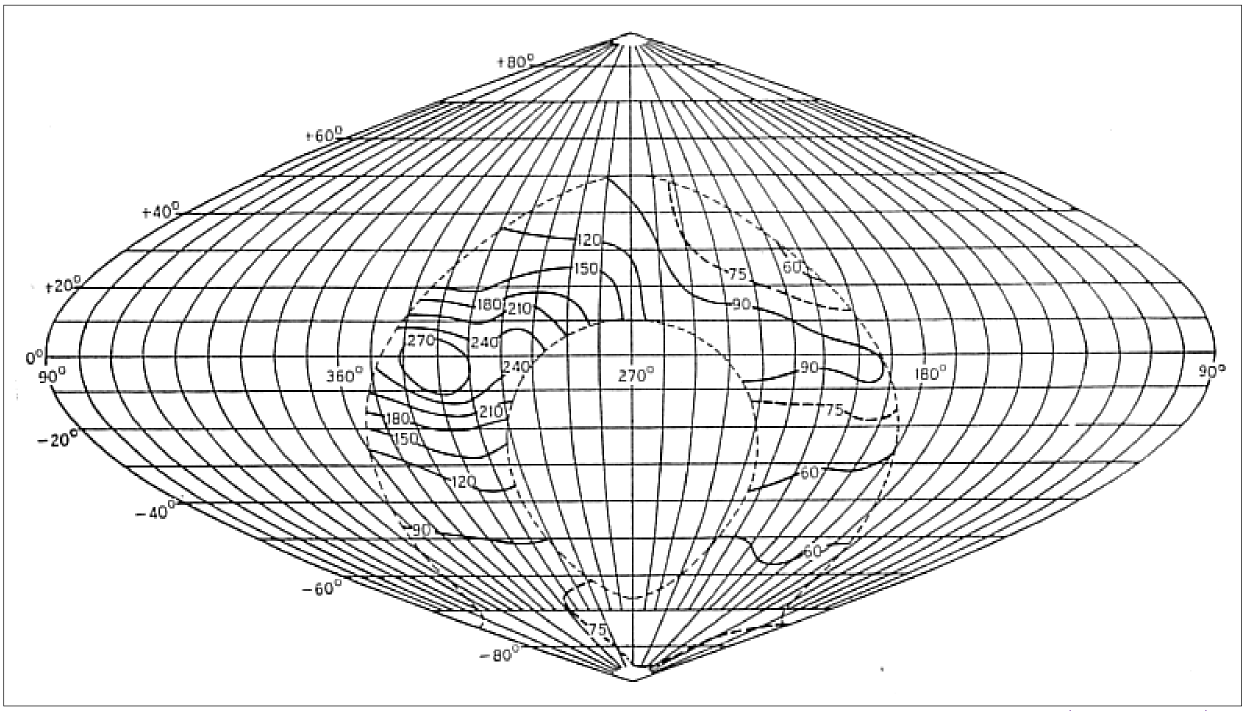

Figure 6: A galactic coordinate isophote plot of continuum emission at 18.3 MHz. The conspicuous source near l^{I} = 330° and b^{I} = –2° is Sagittarius A (after Shain 1954: 152).

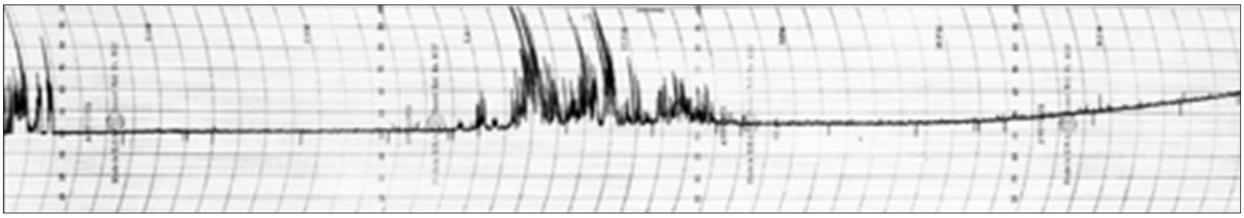

Figure 7: An example of 18.3 MHz Jovian bursts noted on the 1950–1951 Hornsby Valley chart records (CASS RAIA: B3719-13).

2.2 Fleurs Field Station

One of the last field stations to be set up by the Division of Radiophysics prior to the erection of the 64-m Parkes Radio Telescope was Fleurs, about 40 km west-south-west of central Sydney. This occupied an area of flat land between South Creek and Kemps Creek near an old WWII air strip (Orchiston and Slee, 2002b). Between 1954 and 1963, Fleurs was one of the Division's leading field stations and would become home to three innovative cross-type radio telescopes: the Mills Cross, the Shain Cross and the Chris Cross (Figure 8). All of these were to play important roles in furthering international radio astronomy (Orchiston and Mathewson, 2009; Orchiston and Slee, 2005a; Robertson, 1992).

However, when Shain arrived at Fleurs in 1955, he was not interested in using the existing radio telescope there, the Mills Cross, which operated at 85.5 MHz. Instead, he wanted to follow up his investigation of the 18.3 MHz Jovian bursts recorded at Hornsby Valley back in 1950. To do this he arranged the construction of three new small-scale low-frequency radio telescopes: a 19.6 MHz two-element E-W interferometer and 14 MHz and 27 MHz single in-line arrays of four and eight half-wave dipoles respectively. During 1955 and 1956 he and Frank Frederick Gardner (1924–2002; see Milne and Whiteoak, 2005) used these antennas to explore the rotation period of the source of the Jovian decametric emission. As a result of their study they concluded that the bursts resulted from plasma oscillations in an ionized region of the Jovian atmosphere (Gardner and Shain, 1958).

While this Jupiter research was in progress, Shain also was busy overseeing the construction of the field station's second large cross-type radio telescope. Appropriately named the 'Shain Cross', this had N-S and E-W arms of 1105 m and 1036 m, operated at 19.7 MHz, and had a beamwidth of 1.4° (Shain, 1958b). Although this new radio telescope evolved out of the Hornsby Valley arrays, it also drew on the innovative cross-type radio telescope concept invented by Shain's Radiophysics colleague Bernard Yarton Mills (1920-2011; see Mills, 1963). As at Hornsby Valley, the design was simple: a series of dipoles was strung between what looked like telegraph poles, again with the ground serving as a reflector (Figure 9).

Initially Shain used the Shain Cross to survey emission along the Galactic Plane, in the process discovering a conspicuous dip in the chart records (Figure 10), which indicated that "… absorption of 19.7 Mc/s radiation is occurring in a

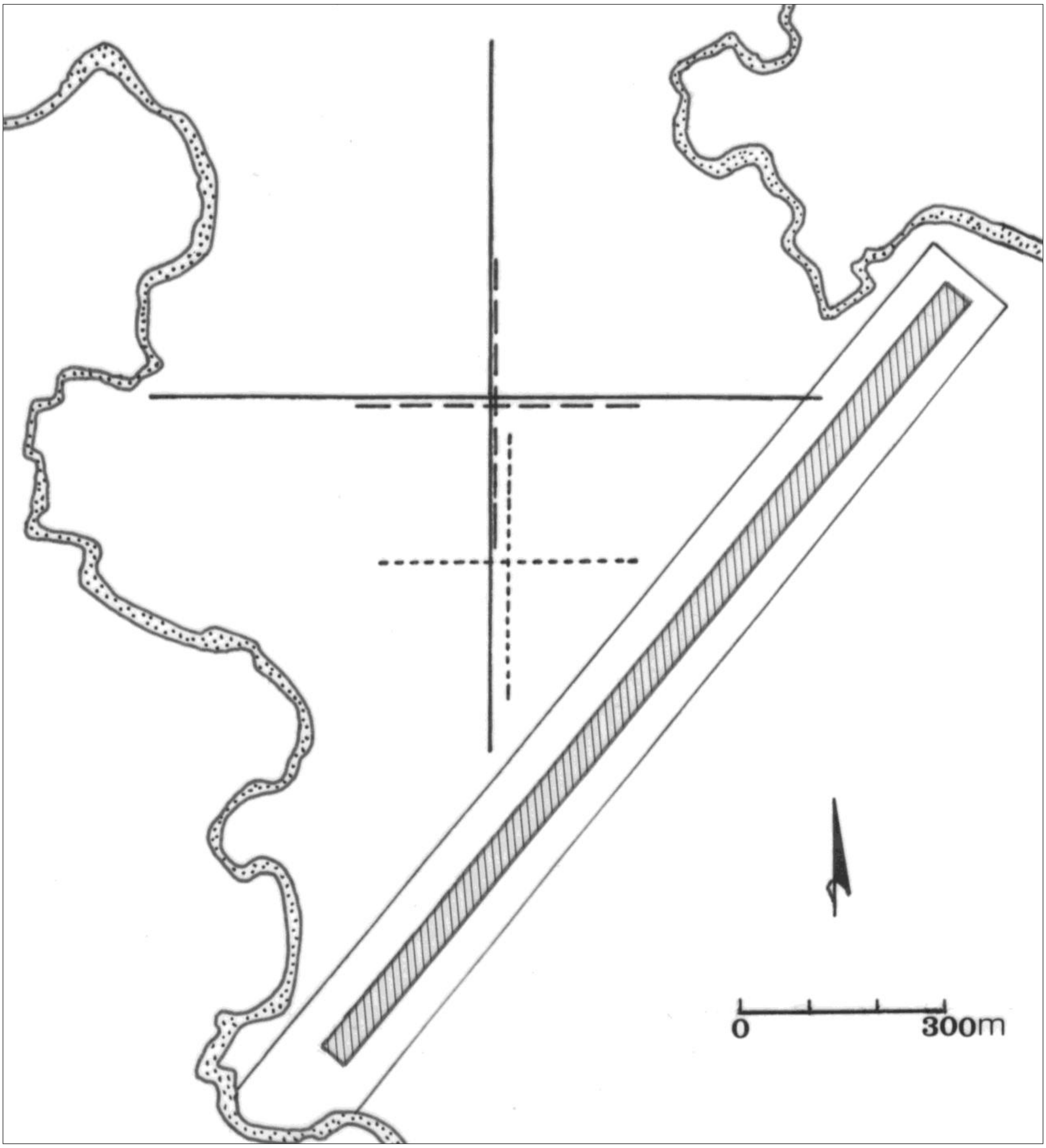

Figure 8: Plan of the Fleurs field station showing the WWII airstrip, South Creek and Kemps Creek and the three cross-shaped radio telescopes, the largest of which was the Shain Cross (map: Wayne Orchiston).

band of HII regions near the galactic plane." (Shain, 1957: 198). Meanwhile, the resulting isophote map of the region showed that some of the emission from the Galactic Centre source, Sagittarius A, also was absorbed by these HII regions. In contrast, Shain (1958a) found that the discrete sources Centaurus A and Fornax A were in emission. This promising line of research came to an unexpected end in 1960 when Alex Shain succumbed to terminal cancer, and it was left to Shain's Radiophysics colleagues Max M. Komesaroff and Charlie Higgins to publish a more detailed analysis of the 19.7 MHz Galactic Plane survey (see Shain et al., 1961).

Had he not died, Shain's plan was to also use the Shain Cross to carry out simultaneous 19.7 MHz and optical observations of Jupiter. Instead, it was Bruce Slee and Charlie Higgins who would take up the Jovian challenge.

Owen Bruce Slee (Figure 11) was born in Adelaide on 12 August 1924, and was one of those who independently detected solar radio emission during WWII while serving as a radar operator. After the war he joined the Division of Radiophysics as a Technical Assistant, and worked with John Bolton (1922–1993) and Gordon Stanley (1921–2001) on 'radio stars' at the Dover Heights field station (Site 5 in Figure 2), before transferring to Fleurs field station and

Figure 9: A view looking south along the N-S arm of the Shain Cross. To the left is part of the south arm of the Mills Cross and a broadside array that was used to investigate the angular sizes of discrete sources (courtesy: CASS RAIA: B3868-19).

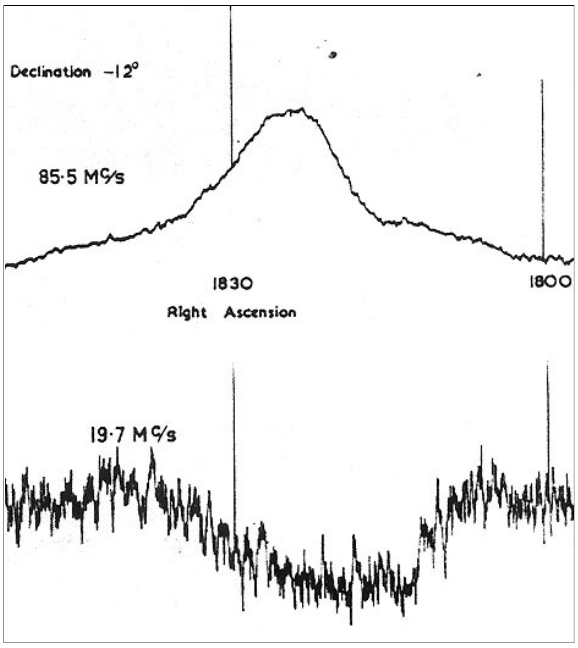

Figure 10: The Galactic Plane shown in emission at 85.5 MHz (Mills Cross) and absorption at 19.7 MHZ (Shain Cross) (after Shain, 195x: xxx).

Figure 11: Bruce Slee in the Control Room at the Parkes Radio Telescope in the 1960s (courtesy: CASS RAIA).

working with Bernie Mills on the Mills Cross. After studying evenings and obtaining a B.Sc. Honours degree he joined the Division's research staff and ultimately was awarded a D.Sc. for his international contributions to radio astronomy. Over the years, Slee made extensive use of the 64-m Parkes Radio Telescope, the Culgoora Radioheliograph (in its guise as the 'Culgoora Circular Array') and the Australia Telescope Compact Array near Narrabri—amongst other instruments—to investigate a wide range of astronomical objects and phenomena (see Orchiston, 2004; 2005c). He is a co-author of this paper, and as a CSIRO Astronomy and Space Sciences Research Associate continues to carry out research in astrophysics and on the history of Australian radio astronomy.

During the early 1960s Slee and Higgins erected small arrays of 19.7 MHz dipoles at Fleurs, and three remote sites at various distances to the north and south of Fleurs in order to carry out long-baseline interferometry of Jupiter. Their objective was to expand on the research done earlier by Shain and Gardner on the size of the source of the Jovian decametric emission (Slee and Higgins, 1963). Initially they found the source of the emission to be 10–20″ in diameter (Slee and Higgins, 1966), but later realised that the source was very much smaller (Slee and Higgins, 1968), and was

> ... due to an interplanetary diffraction pattern scattering by solar wind turbulence, which drifted across our baseline at the speed of the outward flowing solar plasma of a few hundred km/sec. (Slee, 2005: 105).[2]

It was also at this time that Slee and Higgins used the Shain Cross for one final research project: between September and December 1961 they used the N-S arm in a search for 19.7 MHz radio emission from selected flare stars (Slee, Solomon, and Patston, 1963). They were successful as Figure 12 illustrates, and along with Jodrell Bank's Sir Bernard Lovell (1913–2012), they pioneered the detection of radio emission from stars other than the Sun.

3 CONCLUDING REMARKS

The years following WWII saw Australia emerge as one of the international leaders in the new field of radio astronomy. Low frequency investigations were carried out in two quite separate geographical regions: the Sydney region, through the CSIRO's Division of Radiophysics, and far to the south in the island state of Tasmania, by staff from the University of Tasmania and the U.S. radio astronomy pioneer, Grote Reber (who conducted independent research).

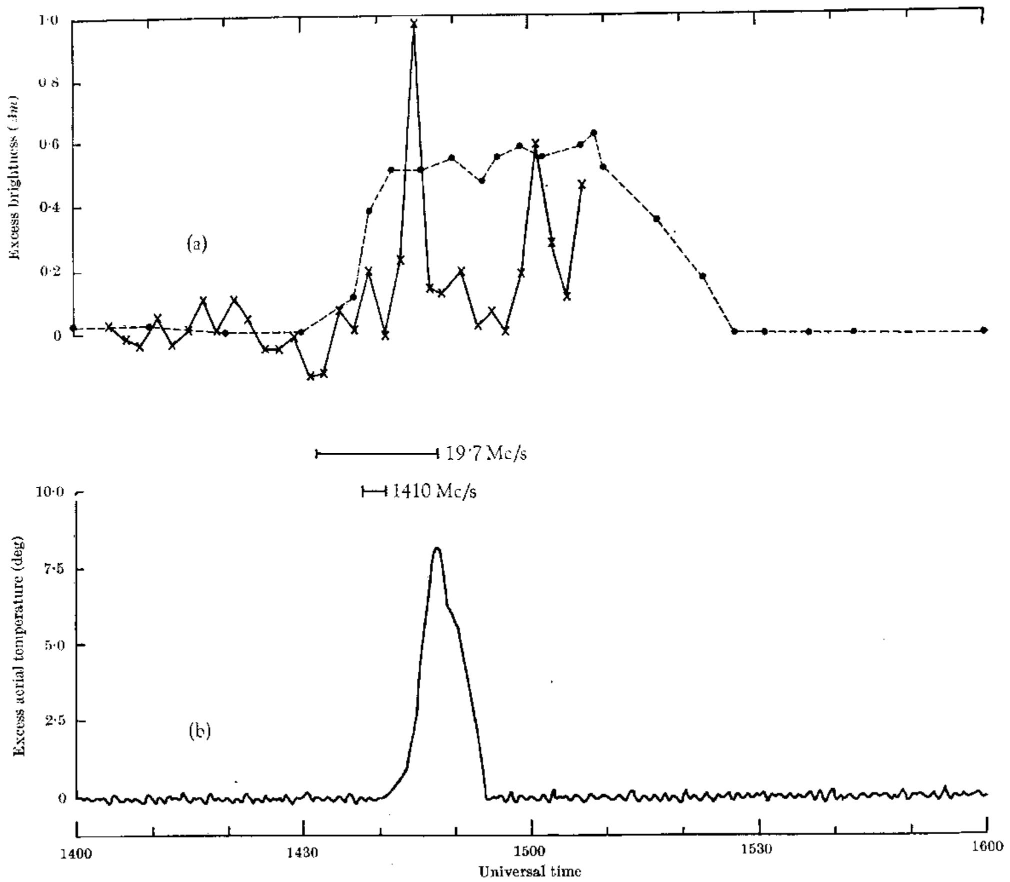

Figure 12: Optical (a) and radio (b) flaring of V371 Orionis on 30 November 1962. In (a) the solid line shows the optical light curve derived from Baker-Nunn photographs while the dashed line indicates the magnitude variation based upon visual observations by amateur astronomers. In (b) the smoothed line is the emission recorded at 410 MHz using the 64-m Parkes Radio Telescope, and directly above are the time intervals when radio emission also was recorded at 19.7 MHz and 1410 MHz using the Shain Cross at Fleurs and the Parkes Radio Telescope respectively (after Slee, Solomon, and Patston, 1963: 993).

The investigation of Jovian decametric burst emission at Hornsby Valley and later at Fleurs and three remote sites to the north and south of Sydney was a major research investigation of the Division of Radiophysics, whereas the galactic research conducted at these two field stations was merely part of a much larger program that involved other field stations and remote sites in and near Sydney and extended in frequency from 9 MHz to 1,200 MHz.

Details of the low frequency research conducted at Hornsby Valley and Fleurs will be presented in later papers in this series.

4 NOTES

1. In fact, at first Burke and Franklin also thought that their Jovian bursts were some form of interference (see Franklin, 1983).
2. We now know that the Jovian bursts originate in Jupiter's magnetosphere and are broadened by scattering caused by irregularities in the solar wind.

5 ACKNOWLEDGEMENTS

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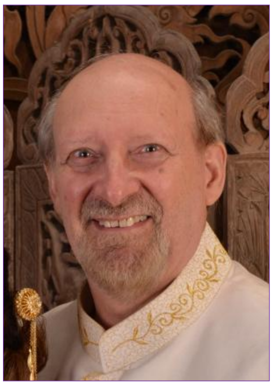
Professor Wayne Orchiston was born in New Zealand

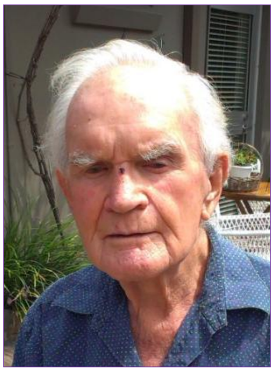


in 1943 and works as a Senior Researcher at the National Astronomical Research Institute of Thailand and is an Adjunct Professor of Astronomy at the University of Southern Queensland in Toowooma, Australia. In the 1960s Wayne worked as a Technical Assistant in the CSIRO's Division of Radiophysics in Sydney, and forty years later joined its successor, the Australia Telescope National Facility, as its Archivist and Historian. He has a special interest in the history of radio astronomy, and in 2003 he was founding Chairman of the IAU Working Group on Historic Radio Astronomy. He has supervised six Ph.D. or Masters theses on historic radio astronomy, and has published papers on early radio astronomy in Australia, England, France, Japan, New Zealand and the USA. He also has published extensively on the history of meteoritics, historic transits of Venus and solar eclipses, historic telescopes and observatories, and the history of cometary and asteroid astronomy. He is a co-founder and the current Editor of the *Journal of Astronomical History and Heritage*, and in 2013 the IAU named minor planet 48471 Orchiston.

Martin George is the Collections and Research Manager

at the Queen Victoria Museum and Art Gallery in Launceston, Tasmania, and also is responsible for the Museum's planetarium and astronomy collections. He is a former President of the International Planetarium Society. Martin has a special research interest in the history of radio astronomy, and is completing a part-time Ph.D. on the development of low frequency radio astronomy in Tasmania through the University of Southern Queensland, supervised by Professors Wayne Orchiston and Richard Wielebinski (and originally also by Professor Bruce Slee). Martin is the Administrator of the Grote Reber Medal for Radio Astronomy, and is a member of the IAU Working Group on Historic Radio Astronomy.

Dr Bruce Slee was born in Adelaide, Australia, in



1924 and is one of the pioneers of Australian radio astronomy. Since he independently detected solar radio emission during WWII he has carried out wide-ranging research, first as a member of the CSIRO's Division of Radiophysics, and then through its successor, the Australia Telescope National Facility. After working with Bolton and Stanley on discrete sources at Dover Heights, he moved to the Fleurs field station and researched discrete sources with Mills using the Mills Cross, and radio emission from flare stars with the Shain Cross and the 64-m Parkes Radio Telescope. He also used the Shain Cross and a number of antennas at remote sites to investigate Jovian decametric emission. With the commissioning of the Parkes Radio Telescope he began a wide-ranging program that focussed on discrete sources, and radio emission from various types of active stars. He also used the Culgoora Circular Array (*aka* Culgoora Radioheliograph) for non-solar research, with emphasis on pulsars, source surveys and clusters of galaxies, and continued some of these projects using the Australia Telescope Compact Array. Over the past two decades, he also has written many papers on the history of Australian radio astronomy, and has supervised a number of

Ph.D. students who were researching the history of radio astronomy.

Professor Richard Wielebinski was born in Poland in 1936, and moved with his parents to Hobart, Tasmania, while still a teenager. Richard completed B.E (Hons.) and M.Eng.Sc. degrees at the University of Tasmania. In his student days he met Grote Reber and was involved in the construction of a low frequency array at Kempton. After working for the Postmaster General's Department in Hobart he joined Ryle's radio astronomy group at the Cavendish Laboratory, Cambridge, and completed a Ph.D. in 1963 on polarised galactic radio emission. From 1963 to 1969 Richard worked with Professor W.N. (Chris) Christiansen in the Department of Electrical Engineering at the University of Sydney, studying galactic emission with the Fleurs Synthesis Telescope and the 64-m Parkes Radio Telescope. He also was involved in early Australian pulsar research using the Molonglo Cross. In 1970 Richard was appointed Director of the Max-Planck-Institute für Radioastronomie in Bonn, where he was responsible for the instrumentation of the 100-m radio telescope at Effelsberg. In addition, he built up a research group that became involved in mapping the sky in the radio continuum, studying the magnetic fields of galaxies, and pulsar research. Further developments were the French-German-Spanish institute for mm-wave astronomy (IRAM), and co-operation with the Steward Observatory, University of Arizona, on the Heinrich-Hertz Telescope Project. Richard holds Honorary Professorships in Bonn, Beijing and at the University of Southern Queensland. He is a member of several academies, and has been awarded honorary doctorates by three universities. After retiring in 2004 he became involved in history of radio astronomy research, and is currently the Vice-Chairman of the IAU Working Group on Historic Radio Astronomy.

THE HISTORY OF EARLY LOW FREQUENCY RADIO ASTRONOMY IN AUSTRALIA. 2: TASMANIA

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Abstract: Significant contributions to low frequency radio astronomy were made in the Australian state of Tasmania after the arrival of Grote Reber in 1954. Initially, Reber teamed with Graeme Ellis, who was then working with the Ionospheric Prediction Service, and they carried out observations as low as 0.52 MHz during the 1955 period of exceptionally low sunspot activity. In the early 1960s, Reber established a 2.085 MHz array in the southern central region of the State and used this to make the first map of the southern sky at this frequency. In addition, in the 1960s the University of Tasmania constructed several low frequency arrays near Hobart, including a 609m × 609m array designed for operation between about 2 MHz and 20 MHz. In this paper we present an overview of the history of low frequency radio astronomy in Tasmania.

Keywords: Australian low frequency radio astronomy, Tasmania, Grote Reber, Graeme Ellis, CSIRO Division of Radiophysics.

1 INTRODUCTION

In the 1940s and 1950s, Australia was a major contributor in the emerging field of radio astronomy (see Robertson, 1994; Sullivan, 2009). Apart from small short-lived solar research groups based at Mt Stromlo Observatory, near the nation's capital, Canberra, and at the University of Western Australia in Perth (Orchiston et al., 2005) the major role was played by the CSIRO's Division of Radiophysics, which was based in Sydney. Between 1946 and the early 1960s the Division operated a number of field stations and remote sites in the Sydney area (see Orchiston and Slee, 2005), two of which, Hornsby Valley and Fleurs, made major contributions to low frequency radio astronomy (see Orchiston et al., 2015b).

In the early 1950s the American radio engineer Grote Reber, who had constructed the world's first purpose-built radio telescope in Wheaton (Illinois) in 1937, was working with a sea interferometer atop Mt. Haleakala on the island of Maui in Hawaii (see Reber, 1955) when he developed an interest in carrying out radio astronomical research at low frequencies and making observations in the southern hemisphere (Reber, 1949). He had gathered ionospheric data from many places around the world in order to find locations that offered the best prospects.

For low frequency work, consideration of ionospheric conditions is very important. There is a frequency limit below which celestial radio waves cannot penetrate the ionosphere: upon moving downwards from 10 MHz to lower and lower frequencies, transmission becomes steadily poorer until a limit is reached at around 1–2 MHz under the best conditions. The lower limit is dependent on several factors, the most important of which is the observer's location. The lower the atmospheric ionisation, the greater the transmission. It is now well known that there is a mid-latitude ionospheric 'trough' of least ionisation—sufficiently far from the geographic and geomagnetic poles—that offers the lowest usable frequencies for radio astronomy. However, other important factors combine to produce low ionisation: low solar activity, time of day, and the season of the year. The ideal conditions under which to observe are at or near solar minimum, during winter, and at night.

During the early 1950s, Graeme Ellis, who was then working for the Commonwealth Observatory Ionospheric Prediction Service, performed ionospheric research near Hobart (see Ellis, 1954). Reber (1954) was prompted to contact Ellis after reading a paper by Ellis (1953). As a result of their correspondence, Reber (1977; 1982) decided to carry out low frequency radio astronomy in Tasmania, as it was clear from

Ellis' paper and other ionospheric data from around the world that Tasmania offered excellent conditions for the observation of cosmic radiation at low frequencies.

Reber then moved to Tasmania, and between 1955 and 1967 he carried out low frequency observations at Cambridge, Kempton and Bothwell, initially in collaboration with Ellis (for Tasmanian localities mentioned in this paper see Figure 1).

After working in Queensland and New South Wales, Ellis returned to Hobart in 1960 to take up the Chair of Physics at the University of Tasmania, thus beginning two and a half decades of low frequency radio astronomical research at the University. Observations by Professor Ellis (Figure 2) and a succession of Honours and Ph.D. students were carried out at Hobart Airport (Llanherne), Penna and Richmond to the east and north-east of Hobart (Figure 3), and they made good use of the mid-1960s minimum in solar activity (as indeed did Reber).

The aim of this paper is to provide readers with an overview of the low frequency radio astronomy that was carried out in Tasmania by Grote Reber and by Graeme Ellis and his associates from 1955. Details of the research conducted at Bothwell, Cambridge, Kempton, Llanherne, Penna and Richmond will be published in later papers in this series.

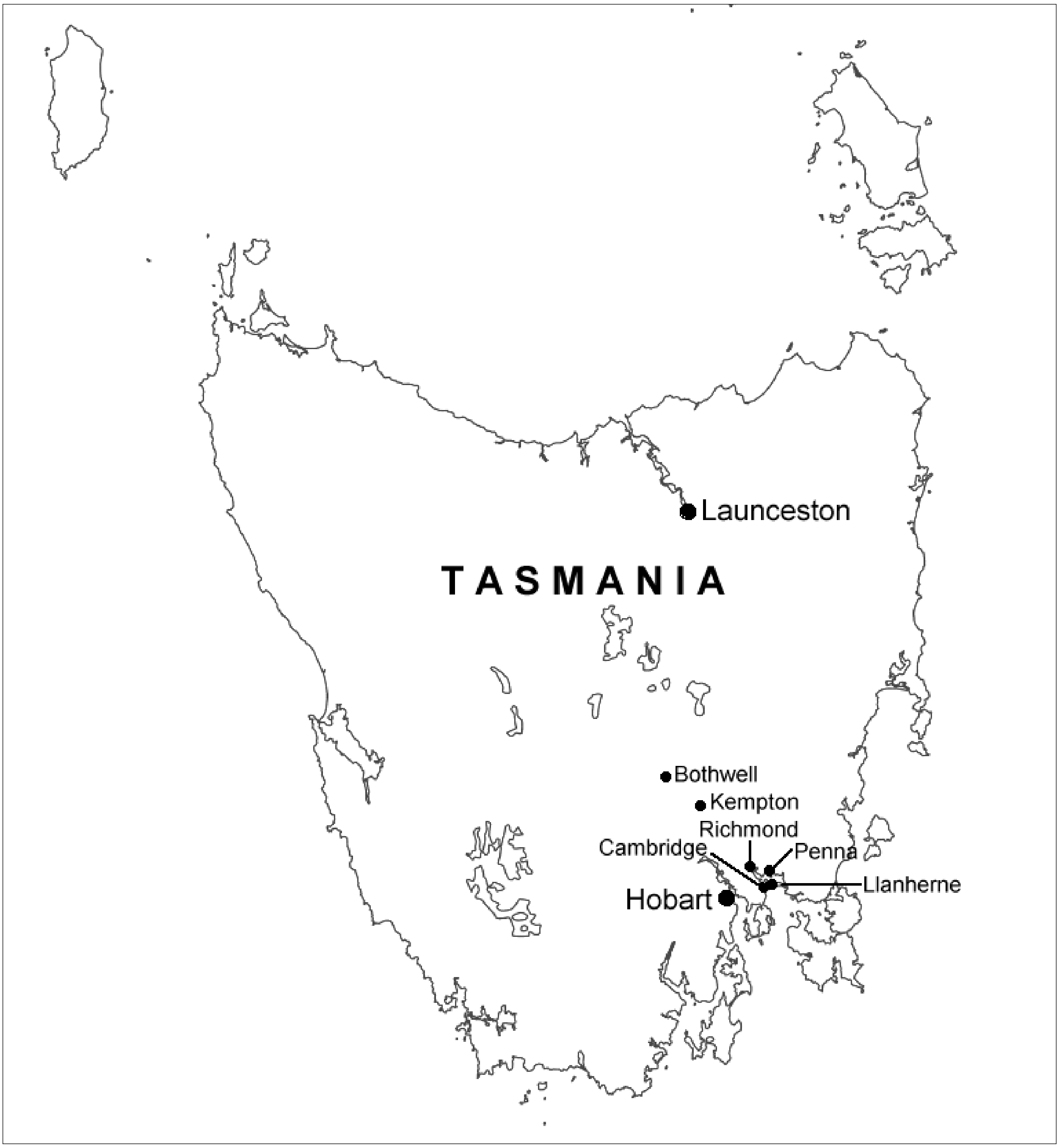

Figure 1: The island of Tasmania, showing the low frequency radio astronomy locations mentioned in the text.

Figure 2: Graeme ('Bill') Ellis in about 1970 (photograph: University of Tasmania).

Meanwhile, collectively this paper and the preceding paper in this issue of *JAHH* (Orchiston et al, 2015b) will provide a useful national overview of developments in early low frequency radio astronomy in Australia (cf. Orchiston et al., 2015a).

2 SITES AND OBSERVATIONS

2.1 The Llanherne Area

The majority of the low frequency research performed by the University of Tasmania radio astronomers took place in the vicinity of Hobart Airport, which is also called Llanherne Airport (see Figure 3).

In the early 1950s, Graeme Ellis was performing ionospheric work near Cambridge Airport, a few kilometres to the west of Llanherne Airport (which began operations in 1956). Shortly before Grote Reber arrived, the ionospheric station was moved to Mount Nelson, south of Hobart, but some equipment remained at the Cambridge site (Reber, 1982). In 1955, this and other equipment was used for observations at a number of frequencies between 0.52 MHz and 2.1 MHz (Reber and Ellis, 1956), with the higher frequencies revealing a clear celestial component. Previously, the lowest frequency at which galactic emission had been detected was 9.15 MHz by Higgins and Shain (1954) near Sydney. Subsequently, Ellis and Newstead (1957) used interferometers operating at 10.05 and 18.3 MHz to detect a number of discrete sources, probably from the same location.

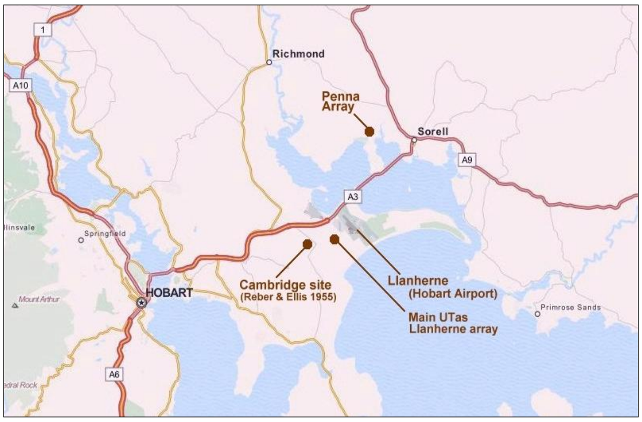

Figure 3: A map showing the locations of the Penna and Llanherne arrays. As this map shows, Reber and Ellis' earlier Cambridge array was located close to the site of the Llanherne array, near Hobart Airport.

However, the University's most significant radio telescope, termed the Llanherne Low-Frequency Array, was closer to Llanherne Airport. It covered an area 609m × 609m, and was composed of 64 east-west rows of broadband dipoles (see Figure 4). Construction commenced in 1967 and it was in full operation by 1972 (Ellis, 1972). It was used during the mid-1970s to map the radio sky at a range of frequencies between 3.7 MHz and 16.5 MHz (e.g. see Cane, 1975; Cane and Whitham, 1977; Ellis, 1982). The array was visible from the road to Llanherne Airport, and a popular misconception was that it was a field of poles for growing hops!

As the work of mapping the sky progressed, it became increasingly clear that the plane of the Milky Way was exhibiting an absorption feature due to an ionised layer (Figure 5), and an important early paper by Hoyle and Ellis (1963) supported this view.

From the early 1960s, Llanherne also was the site for several other low frequency installations, including a small array erected for galactic observations at 4.85 and 9.7 MHz (Waterworth, 1962); an array of crossed dipoles for polarisation studies of Jovian decametric emission (Dowden, 1963); a 39m × 39m array constructed for further work in this field (see Whitham, 1976) and also used for solar work (Klekociuk, 1982); two log-periodic antennas that were designed for solar observations at minimum frequencies of 8 MHz and 24 MHz, respectively, with which they noted frequency splitting using a 24–28 MHz spectrograph (Ellis and McCulloch, 1966); and an array of eight 180-m dipoles constructed for a 1.6-MHz survey of the Galaxy (Ellis and Mendillo, 1987; see Figure 6).

Another major area of low frequency research by the University of Tasmania radio astronomers was on Jovian decametric burst emission. These bursts were first observed by the U.S. radio astronomers Burke and Franklin in 1955, and although Tasmanian observations began in the 1960s, including early observations at Penna (see Section 2.2 below), a major series of observations was carried out between 1972 and 1979 using the Llanherne Low-Frequency Array (Ellis, 1979; 1982; Whitham, 1976). Much theoretical work was performed on the source of the emission (e.g. see Ellis and

Figure 4: The Llanherne Low-Frequency Array in the 1970s (courtesy: Hilary Cane**).**

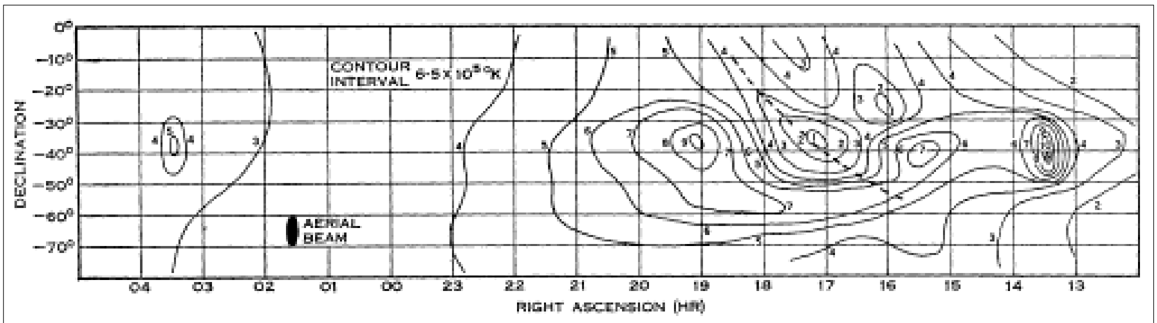

Figure 5: A contour map of 4.7 MHz emission, showing a conspicuous absorption trough, indicated by the dashed line (after Ellis, Green and Hamilton, 1963: 549).

McCulloch, 1963; Ellis, 1974; 1980; Whitham, 1978).

A significant observation made at Llanherne during the later years of low frequency work took place using a newly-constructed antenna to observe through an artificial 'hole' in the ionosphere created by the space shuttle *Challenger* on 5 August 1985. At this time, successful observations of the Galaxy were made at 1.7 MHz (Ellis et al., 1986).

2.2 Penna

Nearby Penna (see Figure 3) was the site of an important early array, used mainly for mapping the sky at frequencies of 4.7 MHz and 10.02 MHz (Ellis and Hamilton, 1966; Ellis and McCulloch, 1966; Hamilton and Haynes, 1968). The Penna installation was a 1200m × 300m array

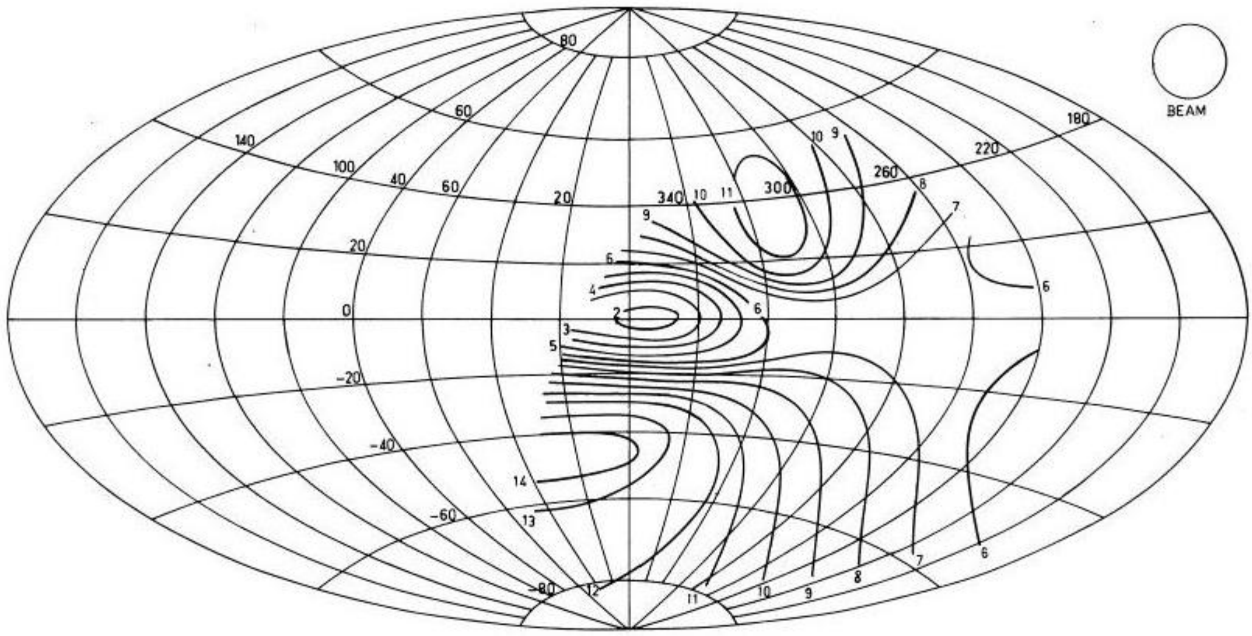

Figure 6: A 1.6 MHz isophote map of the sky (after Ellis and Mendillo, 1987).

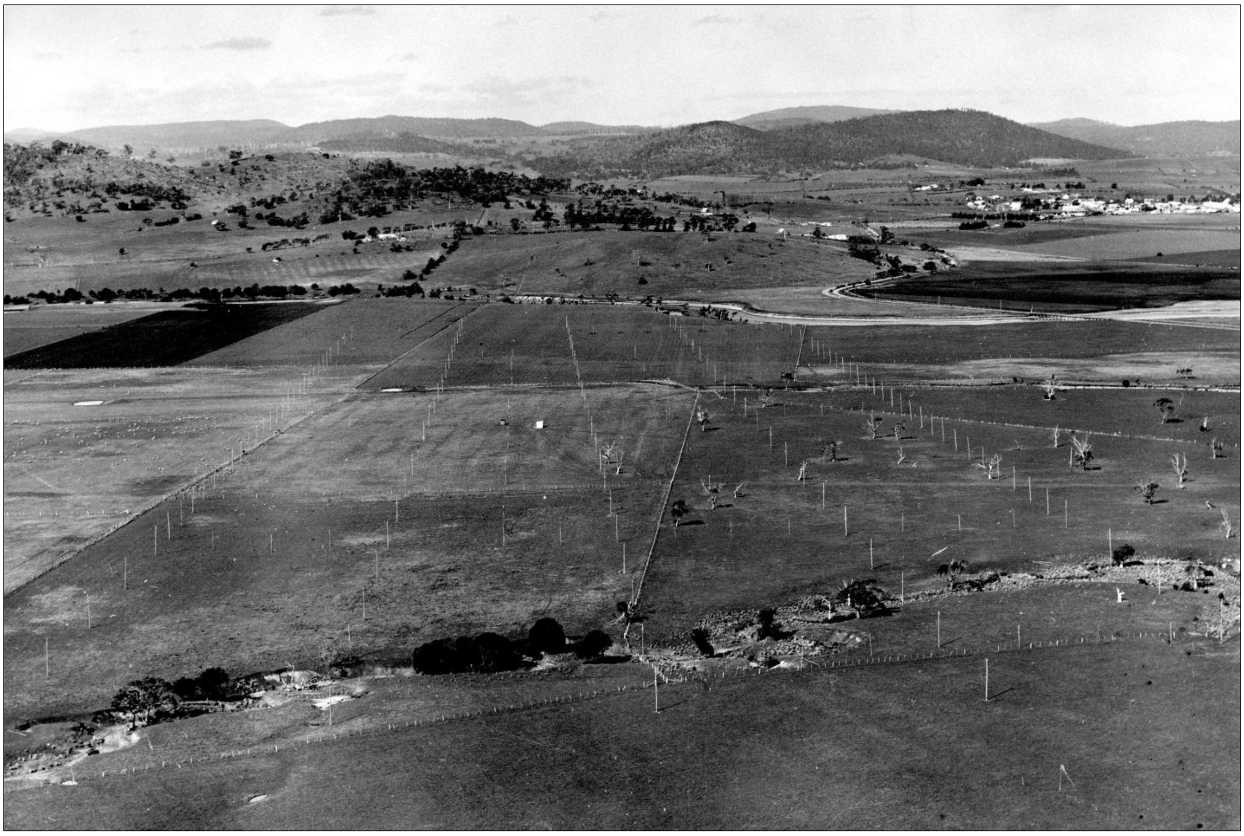

Figure 7: The Penna array in the 1960s (courtesy: University of Tasmania).

consisting of half-wave dipoles initially designed to operate at 4.85 MHz (see Figure 7). During early testing at the site, before the main construction period, Ellis succeeded in observing Jupiter at 4.7 MHz (Ellis, 1962). The full array began operation in June 1962 (Green, 1963) and was destroyed in the tragic bushfires of 7 February 1967, which cost more than 60 lives and caused major destruction in the southern half of the State.

2.3 Richmond

Contemporary with construction at Penna was the erection of arrays just north of the nearby town of Richmond (see Figure 3). Observations were carried out using full-wave dipoles at 2.35 MHz, 1.5 MHz and 1 MHz (see Figure 8), and as would be expected the 1 MHz attempts failed to produce much useable information (Bessell, 1963).

Figure 8: The Richmond Array in 1962 or 1963 (courtesy: University of Tasmania).

2.4 Kempton and Bothwell

The two sites used by Reber (Figure 9) after his collaboration with Ellis were three kilometres west of the town of Kempton (about 50 kilometres north of Hobart), and a site farther north called Dennistoun, six kilometres north-east of the town of Bothwell (see Figure 1).

Following his early observations with Ellis close to Hobart in 1955, Reber (1982) returned to Tasmania in early 1956 and erected four low frequency dipoles at the Kempton site over a valley between two hills. The main frequency at which Reber made observations was 0.52 MHz, and he obtained "... nearly continuous records ..." between August 1956 and May 1957 (Reber, 1957). Although atmospherics tended to dominate the reception Reber deduced that there was celestial emission, but later he had his doubts.

Reber then constructed a 2.085 MHz radio telescope at Bothwell (Figure 10), the largest filled-aperture array ever built, a record that still stands. It was constructed in 1961–1962, contained 192 dipoles, and covered one square kilometer—leading to modern-day comments that it was the 'first square-kilometre array'.

Observations were made between 1963 and 1967, straddling the period of the 1960s solar minimum. This instrument was used to produce am important 2.085 MHz map of the sky (Reber, 1968), and this is shown in Figure 11.

In the mid-1970s, Reber converted this Bothwell installation into a 48-dipole array in order to attempt observations at 1.155 MHz. However, this resulted in failure, attributed by Reber as due to the shallower solar minimum during that period (Reber, 1974; 1982; Ellis and Mendillo, 1987).

3 CONCLUDING REMARKS

The three-decade period beginning in the mid-1950s saw considerable activity in the field of low frequency radio astronomy in Tasmania, with the 1960s and 1970s being unquestionably the halcyon years. There is little doubt that this pursuit was considerably influenced by the presence of Grote Reber, in combination with the interests of Graeme Ellis, whose work up to that time had focused on the properties of the ionosphere.

It was understood from an early stage that Tasmania, at a geographic latitude of 43° south and a geomagnetic latitude of 52° south, was one of the best places in the world for low frequency radio astronomy, as it lay directly under the so-called southern ionospheric 'trough' where the ionosphere is most transparent.

Since these pioneering low frequency studies, the University of Tasmania radio astronomers have focused on higher frequencies, especially after the establishment in 1986 of a new 26-m

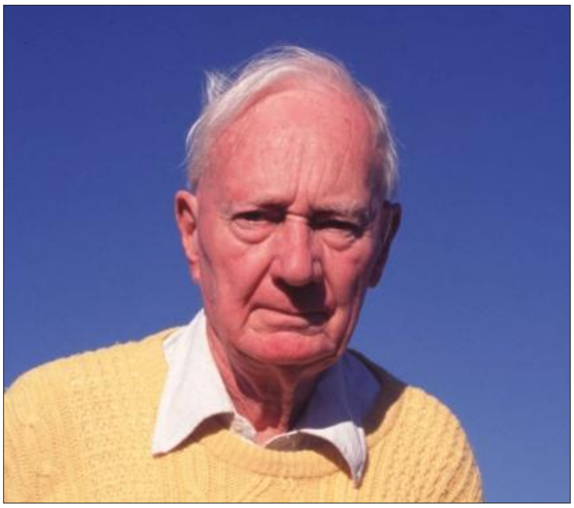

Figure 9: Grote Reber in 1995 (photograph: Martin George).

Figure 10: Reber's array, north of Bothwell, in 1975 (courtesy: Grote Reber Foundation).

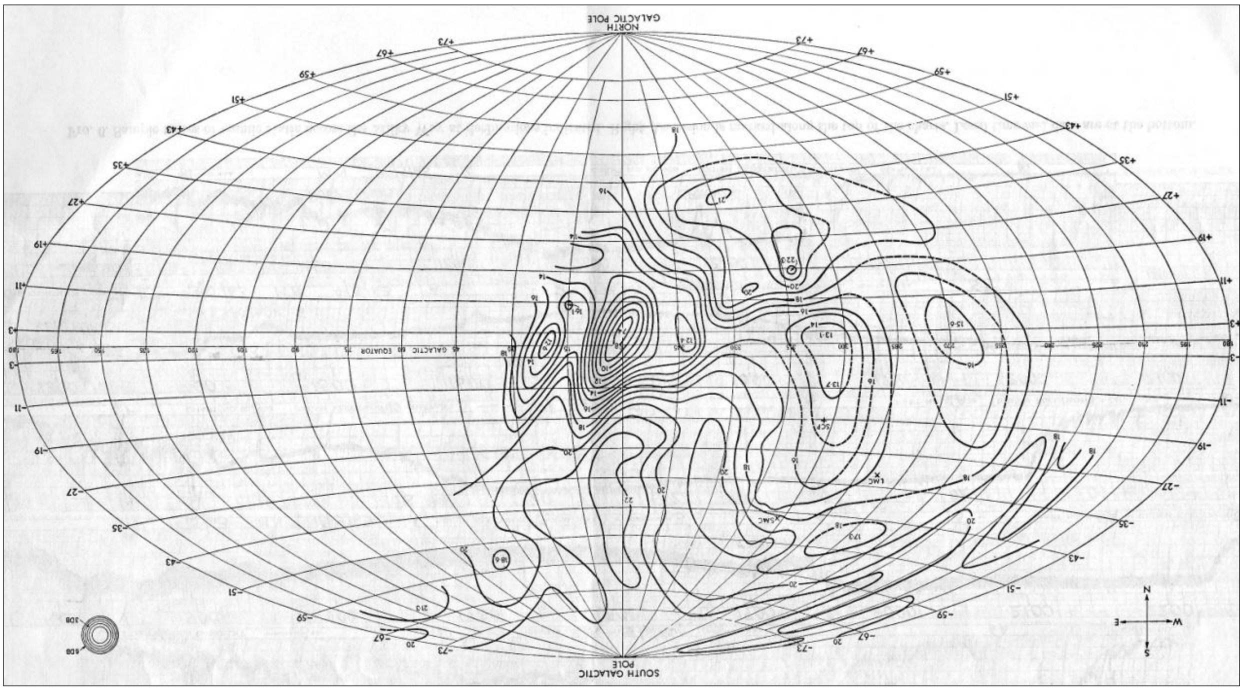

Figure 11: A 2.085 MHz contour map of galactic radio emission (after Reber, 1968: 10).

paraboloid at Mount Pleasant, near Cambridge. Today, there is almost no evidence of the low frequency radio astronomy work performed at the various sites, although some relics at Kempton offer an insight into Reber's work there, and a dilapidated shed at Llanherne brings back memories of Ellis' array.

Details of the low frequency research conducted by Reber and by Ellis and his associates will be presented in later papers in this series.

4 ACKNOWLEDGEMENTS

We are grateful to Karen Bradford and Simon Ellingsen from the University of Tasmania, who provided much assistance by supplying several references; Ellen Bouton from The National Radio Astronomy Observatory in the USA, who provided copies of Reber's Kempton notes; and to Dr Hilary Cane, from the Grote Reber Foundation and the University of Tasmania for kindly supplying Figures 2, 4, 7, 8 and 10.

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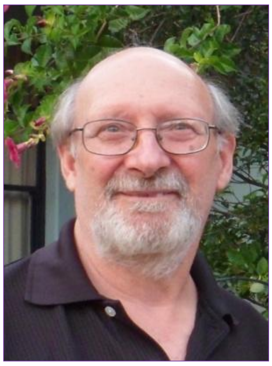
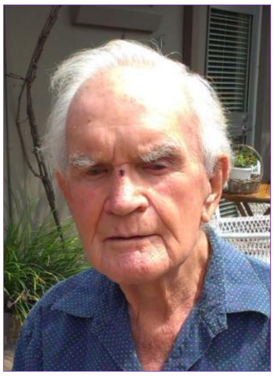
Martin George is the Collections and Research Manager at the Queen Victoria Museum and Art Gallery in Launceston, Tasmania, and also is responsible for the Museum's planetarium and astronomy collections. He is a former President of the International Planetarium Society. Martin has a special research interest in the history of radio astronomy, and is completing a part-time Ph.D. on the development of low frequency radio astronomy in Tasmania through the University of Southern Queensland, supervised by Professors Wayne Orchiston and Richard Wielebinski (and originally also by Professor Bruce Slee). Martin is the Administrator of the Grote Reber Medal for Radio Astronomy, and is a member of the IAU Working Group on Historic Radio Astronomy.



Professor Wayne Orchiston was born in New Zealand in 1943 and works as a Senior Researcher at the National Astronomical Research Institute of Thailand and is an Adjunct Professor of Astronomy at the University of Southern Queensland in Toowoomba, Australia. In the 1960s Wayne worked as a Technical Assistant in the CSIRO's Division of Radiophysics in Sydney, and forty years later joined its successor, the Australia Telescope National Facility, as its Archivist and Historian. He has a special interest in the history of radio astronomy, and in 2003 was founding Chairman of the IAU Working Group on Historic Radio Astronomy. He has supervised six Ph.D. or Masters theses on historic radio astronomy, and has published papers on early radio astronomy in Australia, England, France, Japan, New Zealand and the USA. He also has published extensively on the history of meteoritics, historic transits of Venus and solar eclipses, historic telescopes and observatories, and the history of cometary and asteroidal astronomy. He is a co-founder and the current Editor of the *Journal of Astronomical History and Heritage*, and in 2013 the IAU named minor planet 48471 Orchiston after him.

Dr Bruce Slee was born in Adelaide, Australia, in 1924 and is one of the pioneers of Australian radio astronomy. Since he independently detected solar radio emission during WWII he has carried out wide-ranging research, first as a member of the CSIRO's Division of Radiophysics, and then through its successor, the Australia Telescope National Facility. After working with Bolton and Stanley on the first discrete sources at Dover Heights, he moved to the Fleurs field station and researched discrete sources with Mills using the Mills Cross, and radio emission from flare stars with the Shain Cross and the 64-m Parkes Radio Telescope.



He also used the Shain Cross and a number of antennas at remote sites to investigate Jovian decametric emission. With the commissioning of the Parkes Radio Telescope he began a wide-ranging program that focussed on discrete sources, and radio emission from various types of active stars. He also used the Culgoora Circular Array (*aka* Culgoora Radioheliograph) for non-solar research, with emphasis on pulsars, source surveys and clusters of galaxies, and continued some of these projects using the Australia Telescope Compact Array. Over the past two decades, he also has written many papers on the history of Australian radio astronomy, and has supervised a number of Ph.D. students who were researching the history of radio astronomy. .

Professor Richard Wielebinski was born in Poland in 1936, and moved with his parents to Hobart, Tasmania, while still a teenager. Richard completed B.E. (Hons.) and M.Eng.Sc. degrees at the University of Tasmania. In his student days he met Grote Reber and was involved in the construction of a low frequency array at Kempton. After working for the Postmaster General's Department in Hobart he joined Ryle's radio astronomy group at the Cavendish Laboratory, Cambridge, and completed a Ph.D. in 1963 on polarised galactic radio emission. From 1963 to 1969 Richard worked with Professor W.N. (Chris) Christiansen in the Department of Electrical Engineering at the University of Sydney, studying galactic emission with the Fleurs Synthesis Telescope and the 64-m Parkes Radio Telescope. He also was involved in early Australian pulsar research using the Molonglo Cross. In 1970 Richard was appointed Director of the Max-Planck-Institute für Radioastronomie in Bonn, where he was responsible for the instrumentation of the 100m radio telescope at Effelsberg. In addition, he built up a research group that became involved in mapping the sky in the radio continuum, studying the magnetic fields of galaxies, and pulsar research. Further developments were the French-German-Spanish institute for mm-wave astronomy (IRAM), and co-operation with the Steward Observatory, University of Arizona, on the Heinrich-Hertz Telescope Project. Richard holds Honorary Professorships in Bonn, Beijing and at the University of Southern Queensland. He is a member of several academies, and has been awarded honorary doctorates by three universities. After retiring in 2004 he became involved in history of radio astronomy research, and is currently the Vice-Chairman of the IAU Working Group on Historic Radio Astronomy.

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THE ABORIGINAL AUSTRALIAN COSMIC LANDSCAPE. PART 2: PLANT CONNECTIONS WITH THE SKYWORLD

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Abstract: In the recorded mythology of Aboriginal Australia there is frequent mention of the Skyworld as the upper part of a total landscape that possessed topography linked with that of Earth and the Underworld. The heavens were perceived as a country with the same species of plants and animals that existed below. In Aboriginal tradition, large trees were seen as connecting terrestrial space with the sky above, while the movements of celestial bodies were linked to seasonal changes observed with plants on Earth. This paper describes the links between the floras of Earth and the Skyworld.

Keywords: ethnoastronomy, cultural astronomy, ethnobotany, seasonal calendars, Aboriginal Australians

1 INTRODUCTION

In the Australian ethnographic literature, the 'Skyworld' refers to an Aboriginal concept of the heavens as having an existence as a country, upon which human spirits and ancestors exist along with the plants and animals familiar on Earth (Clarke, 1997; 2008b; 2009a; 2014b; Fredrick, 2008; Hamacher, 2012; Haynes, 1992; 2009; Isaacs, 1980; Johnson, 1998; 2005; Norris, 2007; Norris and Hamacher, 2009; 2014; Tindale, 2005). While the mythological details pertaining to the Skyworld vary widely across Aboriginal Australia, there is much consistency with the main elements of the Skyworld, in particular its physical structure and its acknowledged influence over Earth. Aboriginal hunter-gatherers were keen observers of change within their environment, with the passage of seasons signaled by such things as the movement of celestial bodies, weather shifts and the flowering of calendar plants (Clarke, 2009b; Davis, 1989; 1997).

This paper is the second installment of a study that aims to draw out major ethnobotanical themes from the corpus of ethnoastronomical records garnered from a diverse range of Australian Aboriginal cultures. While the first paper (Clarke, 2014a) focused on the aesthetics behind the Indigenous perception of the heavens, this paper investigates the connectedness of the Skyworld with Earth. Australian localities mentioned in the text are shown in Figure 1.

1.1 Data Sources

A description of the sources of ethnographic data utilised in the current paper is given in the previous part of the study, as is an account of the Aboriginal aesthetic that determines what is seen in the sky (ibid.). While there is a wealth of ethnoastronomical and ethnobotanical data available in Australia, there are major biases. For many areas scholars must chiefly rely upon anecdotal accounts from settlers and colonial officials of the late eighteenth and early nineteenth centuries who were able to compile information from Aboriginal people who were the survivors of the first wave of European settlement.

Early missionaries, who generally arrived some years behind the first colonists in most areas, were more thorough with their recordings of Indigenous culture, although they were working before academic anthropology had begun in Australia. A generation of scholars who had developed close relationships to Aboriginal communities emerged in the late nineteenth century, although they were restricted to working with the few elderly informants who could remember when they had lived as hunter-gatherers.

By the early twentieth century, scholars realised that Aboriginal people possessed a wealth of knowledge and experience about Australian environments. In 1904 a newspaper writer observed in an article on weather forecasting that:

> It is astonishing, however, how much weather wisdom has been developed in the world merely as the result of long-continued observations by unscientific people. The man whose life has been passed in certain localities has by reason of long intimate personal communion with nature become endowed with a "gift" that is not to be despised. There are some who would even prefer to trust the instinct of the brute creation or the intuitive perception of aboriginals, whose traditions of the sky are not the least remarkable features of their native knowledge of the ways of nature. All this is only another way of emphasising the value of observation and deduction as the stepping-stones to knowledge. (Anon., 1904b).

Alfred William Howitt (1830–1908; Figure 2; Stanner, 1972) was born in Nottingham, England, and in 1852 emigrated to Australia, settling in Melbourne. He was briefly the manager of a sheep station and a prospector, prior to becoming an explorer. In later life, Howitt became a natural

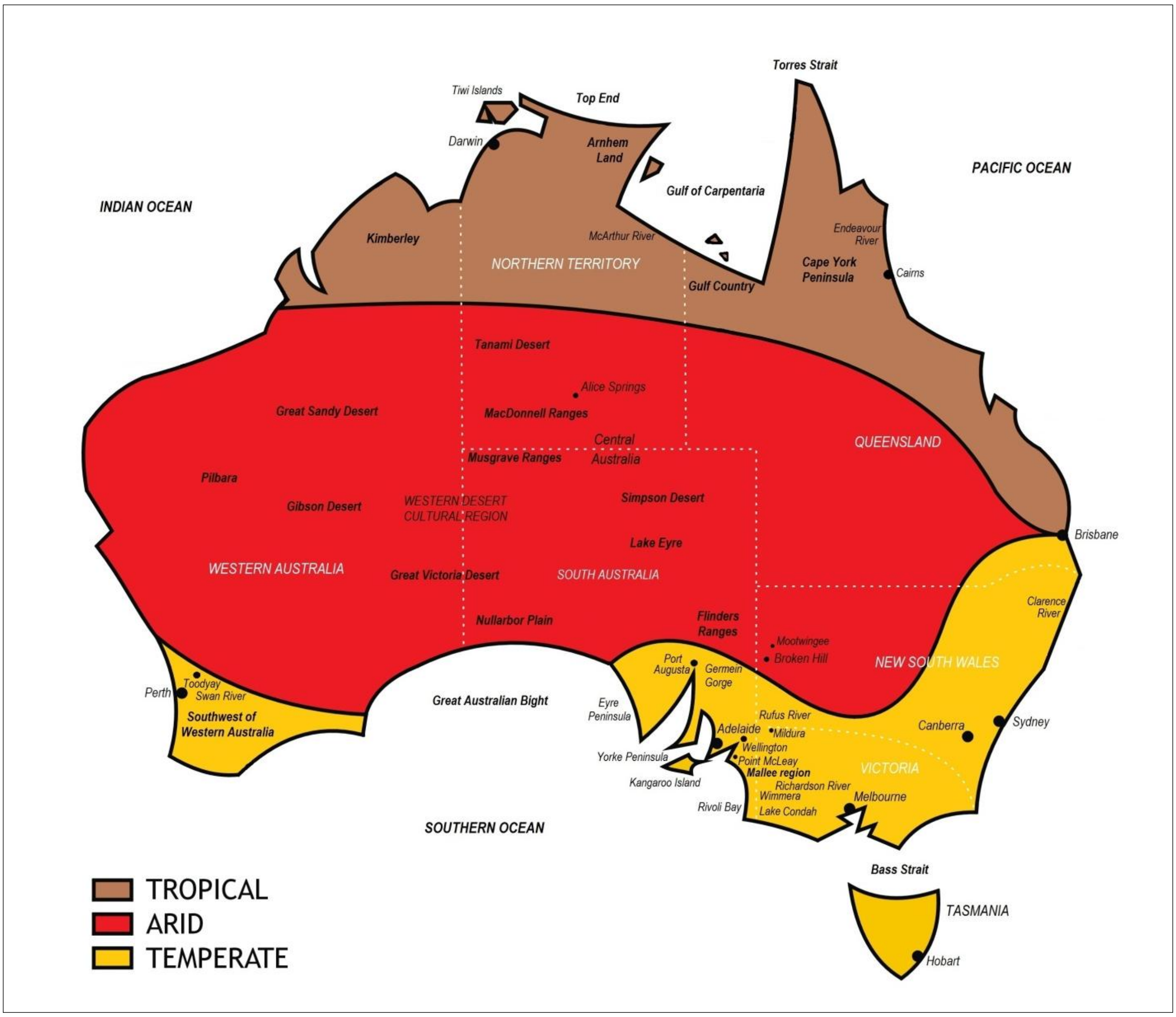

Figure 1: Australian localities or regions mentioned in the text.

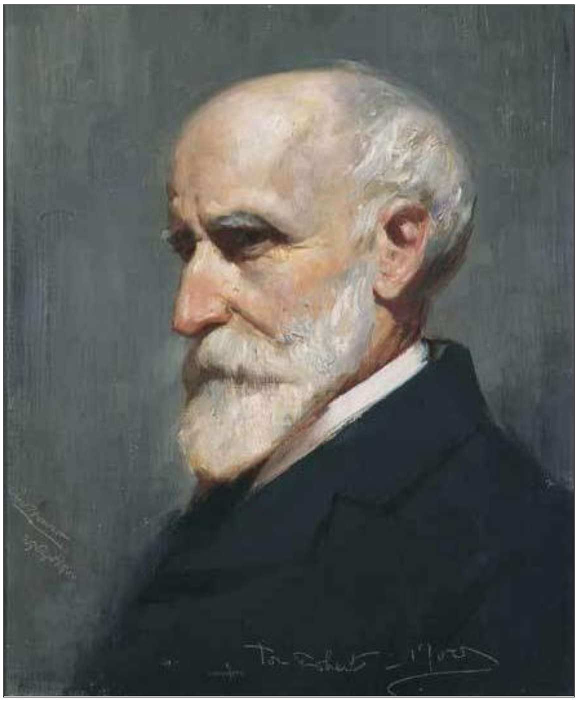

Figure 2: An oil painting of A.W. Howitt by Tom Roberts in 1900 (courtesy: Monash University Collection).

scientist and an authority on the Aboriginal people of southeastern Australia. Howitt (1904: 434) believed that the structure of many Aboriginal astronomical beliefs resonated with that from Western Europe of which he claimed "It seems that such pseudo-beliefs are an inheritance to us from our savage ancestors, and from which we are not able to free ourselves." In the case of Aboriginal traditions, he went on to remark that

> The beliefs as to the stars, which I have noted, and the manner in which they are named, seem to throw some light on the origin of the names, and even of the legends of the constellations of the northern hemisphere. (Howitt, 1904: 434).

During the twentieth century, anthropologists, astronomers, linguists and museum-based scholars recorded Aboriginal ethnoastronomical data.

2 TREES THAT CONNECTED THE EARTH WITH THE SKY

For geographers, the cultural landscape is a concept that encompasses both the physical and cultural aspects of the human construction and perception of space (Baker, 1999; Clarke, 1994). The heavens are part of the space that people experience. In Aboriginal Australia, interpretations of the sky must be understood in terms of the cosmological traditions that explain the making of the world. Fundamental to Aboriginal religious beliefs is the concept that there had been a Creation period when totemic spiritual ancestors performed heroic deeds, moulded and imparted spiritual power to the land, and formulated customs for their descendants to follow (Clarke, 2003; Hiatt, 1975; Sutton, 1988). These ancestors often took the form of animals and birds, but many were also plants, atmospheric and cosmological phenomena or even human diseases. The paths the ancestors made across the land during the Creation became ancestral tracks, or song lines, which connect mythological sites where according to Aboriginal tradition certain events had taken place. When the Creation period drew to a close, it was Aboriginal belief that many of these spiritual ancestors travelled up into the heavens, and for this reason anthropologists have referred to them as 'Sky-heroes' (e.g. Elkin, 1964: 252–254). As ancestors, they were believed to continue influencing life on Earth and for this reason Aboriginal people on Earth looked for omens in the heavens (Clarke, 1997; 2009a; Hamacher and Norris, 2010; 2011a; 2011b; Johnson, 1998).

During the Creation, the regions of the Earth, Skyworld and Underworld were connected to the extent that travel between them all was easily achieved. Ancestors were able to reach the heavens by climbing to the top of large trees or even by walking to the summits of high hills. The stated means for ascent to the Skyworld sometimes involved being helped up by whirlwinds, ropes and fast-growing trees. For instance, in the central northern region of New South Wales, the Kamilaroi people believed that female ancestors became a cluster of stars (the Pleiades) when the two pine (*Callitris* species) trees they were cutting bark from started growing higher and higher, pushing them into the sky (Greenway, 1901). An Aboriginal tradition in this region was that a star cluster they called *Mundewur*, being an S-shaped line of stars in Ophiuchus (formerly Serpentarius) between the Northern Crown and Scorpius, represented "... the notches cut into the bark of a tree to enable a blackfellow to climb it." (Ridley, 1875: 142). In the Creation mythology of the Alawa people who live in southeast Arnhem Land of the Northern Territory, two of their ancestors reached the Skyworld, where they are seen as part of the Pleiades, by climbing a large northern stringybark tree (*Eucalyptus tetrodonta*) growing on Earth (Berndt and Berndt, 1989).

On some occasions, the Skyworld was where ancestors escape to after their creative feats on Earth, while in other cases the ancestors were tricked into entering the Skyworld and were there stranded. The British-born missionary, John Bulmer (1833–1913), came to Australia in 1852 and helped establish a mission station at Yalta, west of Mildura, three years later. Soon after, he recorded a detailed version of a myth from the Wimmera district of central western Victoria that explains the connection between terrestrial space and the sky (Bulmer, 1855 –1908 [1999]). In his account, people on Earth during the Creation period were able to reach the Skyworld to collect the abundant lerp (sometimes called *manna*) found on trees. This was achieved by climbing the winding steps on a very tall pine tree (*Callitris* species) that grew on the banks of the Richardson River. An elderly man named Jeeon controlled access to the tree, and he had a pack of dogs that he would lend to foragers. On one occasion the men who were gathering lerp in the sky were unsuccessful, and so they secretly killed one of the dogs, which happened to be Jeeon's favourite. Jeeon was not fooled and wanted to punish the guilty party. So, prior to the men venturing again into the Skyworld, Jeeon made an instrument that allowed him to bore into the tap root of the pine tree and there conceal a fire. When these foragers were about to return to Earth, they heard the tree cracking. After two unsuccessful attempts to descend to Earth, they returned to the top of the pine tree just in time to see the main section of it fall. According to Bulmer's informants, the top of the tree can still be seen in the Milky Way towards the south, while the adjacent stars near a dark spot are the men who had to remain in the Skyworld.

Other ethnographers from western Victoria recorded accounts of tree connections between Earth and the Skyworld. Robert Hamilton Mathews (1841–1918; McBryde, 1974) was born at Narellan, near Sydney, in New South Wales, and during his working life as a surveyor he travelled widely and studied Aboriginal culture. He recorded that in the Kara Kara district it was an Aboriginal tradition that there was once "... a regular highway between the earth and the upper regions ..." that was formed by a large pine tree growing on Earth whose branches crossed into the sky (Mathews, 1904: 281–282). Similarly, Howitt (1904: 433) stated that in the Wimmera district of the same region:

> The Wotjobaluk had a legend of a pine-tree, which extended up through the sky (*Wurra-wurra*) to the place beyond which is the abode of Mamen-gorak ['father', 'ours']. The people of that time ascended by this tree to gather manna, which implies that trees grew there like the Eucalypt [such as *Eucalyptus viminalis*].

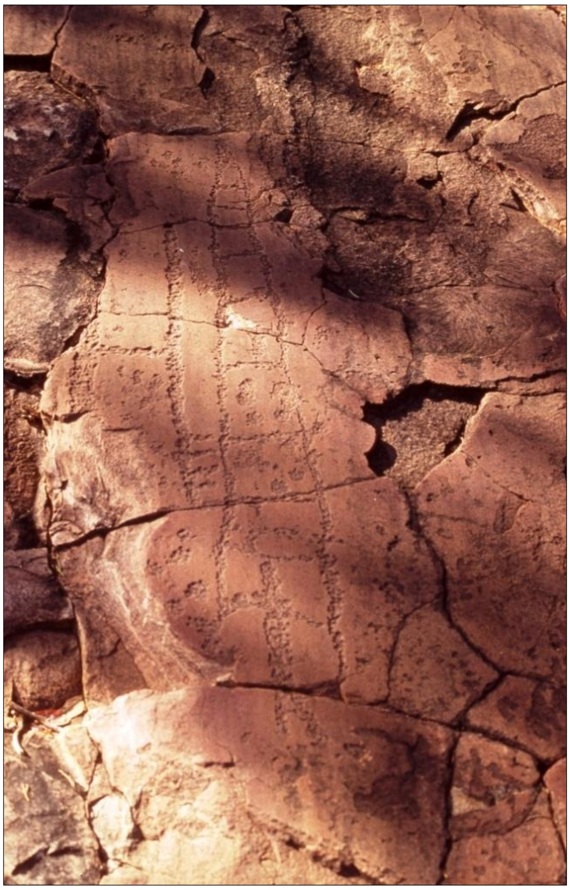

Figure 3 (left): Ancient rock engraving showing what appears to be a man with a ladder-like structure above his head, photographed at Mutawintji (Mootwingee), western New South Wales, 2004 (photograph: P.A. Clarke private collection).
Figure 4 (right): Australian pine (*Callitris glaucophylla*), a species often seen as 'ladders' to the Skyworld, growing at Germein Gorge, southern Flinders Ranges, South Australia, 2008 (photograph: P.A. Clarke private collection).

> which in the Wotjobaluk country shed the so-called manna.

The theme of large trees as 'ladders' between Earth and the Skyworld is widespread in Aboriginal Australia (see Figures 3 and 4). From south-eastern Central Australia, Howitt (1904: 433)[1] recorded that:

> Another legend of the Dieri [Diyari] and Tirari [Thirrari] accounts for the fossil remains found at Lake Eyre, and called by them Kadimarkara, as having been creatures which, in the old times of the Mura-muras [Creation ancestors], climbed down from the sky to the earth by the huge Eucalyptus trees on which it rested, and which grew on the western side of Lake Eyre.

Palaeontologists have classified some of the fossil remains, for which the region is well known, as species of Pleistocene megafauna like the *Diprotodon* (Pledge and Tedford, 1990).

In the recorded mythology of Aboriginal Australia there are variations with the mechanism that stranded the ancestors in the Skyworld. In some myth narratives they were prevented from returning to Earth at the end of the Creation because a tree being used as a 'ladder' had been either burnt or cut down, sometimes by force or trickery. For example, Mathews (1904: 280) claimed that among the Clarence River people of coastal New South Wales there was a tradition that:

> Alpha Tauri [Aldebaran] was a young man named Karam-bal, of the Womboang division, who absconded with another man's wife. He was pursued by the injured husband, and took refuge in a tall tree. His pursuer piled wood around the bole of the tree, which he then set on fire, and Karambal was carried up by the fierce flames into the sky, where he still retains the colour of fire.

On some occasions the tree 'ladder' was a means of escape from Earth. It is a Kamilaroi tradition that during the Creation two girls caught by a man called Wurunna were forced to cut bark for him (Sveiby and Skuthorpe, 2006). The first blow of the stone axe caused the pine tree they had climbed to grow rapidly upwards away from Wurunna, and the girls were saved when their five sisters pulled them up into the Skyworld where together they became the *Mirrai Mirrai* (Pleiades).

The Moon ancestor in some myths had also suffered the fate of being stranded in the Skyworld. According to Charles Pearcy Mountford (1890–1976; Figure 5; Jones, 2000), the South Australian mechanic turned anthropologist/filmmaker, in Nukunu mythology from the southern Flinders Ranges of South Australia, the Moon was tricked into entering the Skyworld:

> The Moon [Pira] was greedy with meat and would not share it with others, crowd decided to get rid of him, coaxed him to climb a tree and get [edible] grubs, coaxed him up higher and higher until they could hardly see him. They cut the tree down, and the Moon hung up in the sky. Moon said 'I'll give the light for people who walk at night. I'll die then come to life again.' (C.P. Mountford, cited Hercus, 1992: 16–17).

In a similar account from the Adnyamathanha people of the northern Flinders Ranges, *Vira Wurlka* the Moon man climbed a river red gum to gather witchetty grubs for two nephews (sister's sons), who made the tree grow higher until it touched the sky (Tunbridge, 1988). When the nephews shrank the tree, *Vira Wurlka* was stranded in the Skyworld. The lunar phases are produced when he gradually dies and becomes smaller. In a myth from the Endeavour River area in northern Queensland, *Warigan* the Moon scaled a tree using a climbing cane, only to be burnt when *Ngalan,* the Sun, set the bark ablaze (Tindale, 1938 ms). The Moon received its ashen face in this way.

For Aboriginal people, large trees are topographic features that represent tangible evidence of the actions of their spirit ancestors during the Creation. Prominent trees were often seen as creations of the ancestors. For example, the sheoak (*Casuarina stricta*) tree is significant in Lower Murray mythology, being the tree that supreme male ancestor *Ngurunderi* created and then sat under before ascending to the Skyworld (Berndt et al., 1993). In temperate regions, the 'ladders' leading to the Skyworld are often specified as tall pine trees (*Callitris* species) (e.g. Bulmer, 1855–1908 [1999]; Greenway, 1901; Howitt, 1904; Mathews, 1904; Sveiby and Skuthorpe, 2006), possibly because of their characteristic of having multiple branch levels from the ground to the crown and due to the fact that they often grow on hilltops.

In arid areas, long-living trees like river red gums growing along creek beds or at waterholes are prominent features of the landscape and therefore attracted significance in the local mythologies (Clarke, 2014c). The Nukunu people of the southern Flinders Ranges in South Australia had a tradition of *Atyilpa* the Western Quoll ancestor carrying an immense tree across their country (Hercus, 1992). The tree, which is symbolic of a giant ceremonial pole, was carried about in a bag before being placed in the land. Hercus (1992: 13) recorded that:

> Nukunu country contained the sites which marked the beginning of the longest known continuous song-line, the *Urumbula* which goes from Pt. Augusta to the Gulf of Carpentaria. The main feature was a huge tree, so high that it was like a great ceremonial pole which in turn represented the Milky Way. This giant tree was located close to the present-day Port Augusta Hospital. According to the oldest singers of the *Urumbula* this tree was destroyed long before their time, in the very early days of European settlement.

In traditions of southeast Arnhem Land in the Northern Territory, it was a large northern stringybark tree connected with the Skyworld (Berndt and Berndt, 1989). At the close of the Creation period, most people were forced to remain on Earth while they were alive, with the Skyworld and Underworld being beyond their reach.

Since the end of the Creation, the order of life on Earth required the maintenance of this gap

Figure 5: C.P. Mountford in 1947 (courtesy: National Archives of Australia, A1200/1).

between the terrestrial and sky regions. In the Lower Murray region, particular large trees and big sand dunes were avoided as malevolent places because they attracted lightning strikes due to their proximity to the clouds (Clarke, 1997; J.C. Harwood, cited N.B. Tindale, 1930–1952). Irish-born self-taught anthropologist Daisy May Bates (1859–1951; Figure 6; De Vries, 2008; Reece, 2007), lived in small settlements in Western Australia and South Australia from 1899 and tirelessly studied Indigenous culture for the next 40 years. Inland from the Great Australian Bight she recorded that the vault of the heavens was supported by a large tree, called *Warda*, that had to be protected at all times (D.M. Bates, cited Isaacs, 1980).[2] In the Ngaanyatjarra and Ngaatjatjarra languages of the Western Desert, *yilkari warta* (idiom for 'very distant') literally means "...sky tree ..."(Glass and Hackett, 2003: 570). Spirit beings, many of them taking the form of birds with the power of flight, had retained the ability to move freely across all parts of the total landscape (Clarke, 1999; 2007b).

In Aboriginal tradition, 'doctors' and 'sorcerers' who travelled to the Skyworld variously used a 'magic rope', a tree as a 'ladder', or ritual power to pass through space itself (Elkin, 1977). Scottish-born Duncan Stewart (1834–1913) was an early South Australian colonist. When still a child, he emigrated to Victoria with his widowed mother in 1839, and in 1845, after she had remarried, the family moved to Rivoli Bay in the southeast of South Australia where they were supportive of the local Aboriginal population (MacGillivray, 2005). In 1850 Duncan Stewart observed a 'séance' conducted by Bunganditj man Kootwor, who:

Figure 6: Daisy Bates (en.wikipedia.org).

> … was supposed to go up into the clouds at night, to induce "those above" to go down and show themselves to the credulous blacks. … Kootwor – the doctor or medium – obtained from "those above" not only dances to amuse, but food, good damper, tobacco, etc., the latter often being dropped into their camp during the night, or found close by in the morning. (Stewart, c.1870–c.1883 [1977: 67]).

Stewart had to be well hidden among the Aboriginal observers, as it was said he might be struck by lightning from above. To achieve his ascent the 'doctor' climbed a tree and then "... the sky people lowered a rope for him to be hauled up by." (Stewart, c.1870–c.1883 [1977: 90]). In this region, a healer reportedly gained knowledge through crossing into the Heavens by climbing a tree (Smith, 1880). There are similar accounts from southwestern Victoria of Aboriginal 'doctors' and 'sorcerers' having claimed to be regular visitors to the Skyworld (Dawson, 1881).

3 THE FLORA AND CELESTIAL INFLUENCES OVER THE EARTH

European recorders acknowledged the role that heavenly bodies in classical Aboriginal tradition had in the making of the Earth as a terrestrial landscape. For instance, in a Creation account that is not localised in the record but probably relates to the east coast of Australia, an anonymous writer in a newspaper stated that:

> In the beginning, black men wore wings and chased winged game; they were prosperous, but grew weary for a place to rest their feet, so they begged help of the stars and other heavenly bodies. Each sent a contribution towards a settlement [Earth]. The stars sent rocks and sand, the moon sent water for sea, rivers, and springs, the evening star [possibly Venus] sent rich soil for growing things, the sun sent animals and plants, and the wings were dropped at once for the 'sole of a foot' to rest on. (Anon., 1904a).

The Skyworld was the acknowledged source of fire. In the Lake Condah area of western Victoria it was recorded that

> A blackfellow threw a spear towards the clouds; to the spear a string was attached. The man climbed up with the aid of the string and brought fire to the earth from the sun. (Anon., 1888: 2).

In Tasmania, Aboriginal people believed that "... fire was thrown down from heaven like stars by two blackfellows who were now stars, the twin Stars, Castor and Pollux." (Mercer, 1912).

Aboriginal people cited cosmological events in order to account for environmental rhythms of their country (see Appendix 1). For instance, the Northern Territory missionary Wilbur Selwyn Chaseling (1910–1989) recorded from northeast Arnhem Land the Yolngu tradition that during the Creation period the ancestor Jurrpan left his sons and their wives on Earth so that he could live in the Heavens as the 'evening star' (Arcturus).[3] From the Skyworld Jurrpan ordered his family to stay below near his former camp and to transform themselves into swamp food. Chaseling (1957: 150–151) stated that:

> They did as they were told and changed themselves into the well-known 'rarkai', or swamp rush-corm [*rakay*, *rakai*, *Eleocharis dulcis*]. Rarkai is a favourite food and spreads over great areas of swamp in the wet season, ripening after the water evaporates. Late in the year women gather the corms, and at sunset they can see Jurrpan in the western sky shining down on his ripening swamp-children.

There is a tradition recorded from a Kumbainggiri person in northern coastal New South Wales that incorporates the theme of rejuvenation, both in terms of lunar phases and the regrowth of the vegetation (McDougall, 1901).[4] In this myth the Moon ancestor once lived on the Earth, where as a man he was speared and his bowels spilt out onto the land. Two plant men, Wintarn (blady grass, *Imperata cylindrica*) and Cummin-Guroon (ferns), took pity on the Moon man and carried him home. Due to their kindness, the two plant men never completely die and are always, as plants, the first to regenerate after a fire or drought.

In Aboriginal Australia it was widely believed that certain species of fungi retained power from their connection with the heavens. For instance, in the Adnyamathanha language of the Flinders Ranges in northern South Australia, puffballs (*Podaxon* species) are known as *vudlivuta*, literally 'star-dust'.[5] When a young man deliberately kicks one of these fungi the yellow spores fill the air and people say that he is "... pulling down stars." (McEntee et al., 1986: 13). Here, to 'break the *vudli*' means that he is "... falling in love." In Central Australia, Spencer and Gillen (1904: 627)[6] recorded that:

> Falling stars appear to be associated with the idea of evil magic in many tribes. The Arunta [Arrernte] believe that mushrooms and toadstools are fallen stars, and look upon them as being endowed with arungquiltha (evil magic) and therefore will not eat them.

Species of fungi have been linked to spirits in other parts of Aboriginal Australia. Scottish-born naturalist and plant collector James Drummond (ca. 1787–1863; Figure 7; Erickson, 1966) emigrated to the Swan River colony in 1829 and subsequently set up a farm at Toodyay. In 1841 Drummond stated that in the southwest of Western Australia he had been shown a glowing fungus; "... to the natives when giving out light … They called it a *chinga*, their name for spirit, and they were much afraid of it." (J. Drummond, 1841 [cited Clarke, 2008a: 84]).[7] The species involved was a large luminous mushroom (most likely *Omphalotus nidiformis*) that glows naturally for four or five days after it is cut.[8] An association of fallen stars with mushrooms occurs in other cultures outside of Australia (e.g. Beech, 1986; Hamacher and Norris, 2010).

3.1 The Seasonal Calendar

Culture shapes the ways people divide the year and how they relate to seasonal changes within the landscape (Clarke, 2009b). The annual cycles recognised by Aboriginal hunter-gatherers varied widely across the continent, ranging anywhere between four and nine distinct seasons (Clarke, 2003; Reid, 1995; Thomson, 1939). Movements of stars and animals, weather changes and the flowering of certain plants together indicate the onset of each season, during which specific foraging strategies would be employed. Sutton (1998: 371) remarked that while Aboriginal religion is primarily structured around

> ... places where ancestral events occurred, and their relative locations … time in the sense of seasons of the year or phases of the day and night carries much symbolic power in Aboriginal classical thought.

With the seasonal calendar in mind, Aboriginal people aimed to hold their ceremonies in honour of the ancestors at specific mythological places

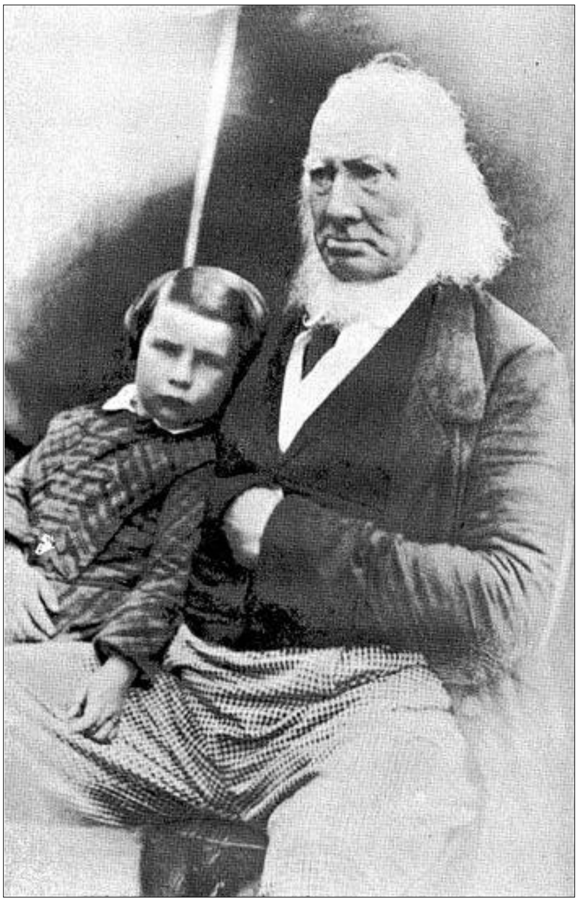

Figure 7: James Drummond with one of his grandchildren (courtesy: en.wikipedia.org).

over many days during a period when there is plenty of food to nourish participants, and to have it end with a Full Moon (Morphy, 1999).

The links Aboriginal people perceived between the movements of heavenly bodies and the onset of seasons was widespread across the Australian continent (e.g. Neidjie et al., 1985; Stanbridge, 1857). Mathews (1904: 279) noted that it was generally recognised that:

> … the stars which occupy the northern sky in the cold winter evenings travel on, and are succeeded by others in the following season; and that these are again displaced by different constellations during the warm evenings of summer.

In Tasmania, London-born Aboriginal Protector George Augustus Robinson (1791–1866, Figure 8; Robinson ..., 1967), who arrived in Hobart in 1824 and spent the next 15 years studying the Island's Indigenous people, claimed that:

> The Aborigines have considerable knowledge of the signs of the weather … Indeed they have numerous signs by which they judge and I have seldom found them to err. Thus they are enabled to know when to build their huts, to go to the coast for fish, travel &c. They also judge by the stars and have names by which they distinguish them. (G.A. Robinson, 1830 [Plomley, 1966: 300]).[9]

Figure 8: G.A. Robinson (courtesy: en.wikipedia.org).

Australian-born Brian Gilmore Maegraith (1907–1989; Figure 9; Radford, 2012) carried out anthropological research during university vacations while studying to be a doctor, before leaving Adelaide in 1931 and pursuing post-graduate studies at Oxford. In Central Australia he observed that:

> The aborigine has differentiated between the two apparent motions of the stars through the year, namely, the nightly movement from east to west (similar to that of the sun in the day), and the gradual annual shift of the constellations in the same direction. (Maegraith, 1932: 24).

Immediately outside of Aboriginal Australia, Johnson (1998) and Sharp (1993) have outlined the calendars of the horticultural peoples of the Torres Strait, which involve the movements of stars timed to a range of environmental phenolmena, such as the fruiting of native apples (*Eugenia* species) and the rampant growth of yams (*Dioscorea* species) that require planting in the gardens.

For the Tiwi in tropical northern Australia, the Upperworld of the sky is similar to Earth with respect to land and the seasons; each having a Dry and a Wet (Sims, 1978). During the Dry, the Upperworld was the home of Pakataringa (Thunderstorm Man), Tomituka (Monsoonal Rains Woman) and Pumaralli (Lightning Woman). At the end of the Dry, these ancestors move further up and into the Skyworld, and when doing so they cause rain to fall upon all the lower levels. Upperworld trees and plants use the rain drops passing through as carriers for spirits that will grow into plants when they hit the parched Earth below. The Skyworld is the abode of the stars and of the Moon and Sun ancestors. In Tiwi cosmology, plants are created by the movement of ancestors who control the weather. Elsewhere in northern Australia, the Rainbow Serpent was perceived as the spirit being in the sky who generated the annual monsoonal weather (Clarke, 2009b).

Hot seasons were in a generalized way associated with the ripening of fruit. For instance, Arrernte people of the Macdonnell Ranges in arid Central Australia linked their hot and wet season, *uterne*, with the availability of edible fruit from the wild passion fruit (*Capparis spinosa* var. *nummularia*), wild oranges (*Capparis mitchellii*), wild bananas (*Marsdenia australis*) and wild tomatoes (*Solanum ellipticum*), because the Sun has "… cooked them ripe." (Henderson and Dobson, 1994: 613–614). It was also a good time here for drying wild tobacco (*Nicotiana* species) leaf. In the Eastern Arrernte language of Central Australia, the term, *ampeme*, has the meanings of "... to burn something ...", "... to experience hot weather ..." and "... to ripen fruit." (Henderson and Dobson, 1994: 121). Similarly, the Kukatja people of the southeast Kimberley in Western Australia recognise that the heat of the Sun is important for ripening edible fruit. Peile (1997: 24) remarked that for Kukatja, "The sun (*tjirntu*) is considered to be close to the earth at dawn and further away at sunset."

In the semi-arid country of central New South Wales, the Wiradjuri people considered that there were six winds controlled by ancestors in the Skyworld (McKeown, 1938).[10] They were said to be divided equally between males and females, with those winds controlled by the former being responsible for changing the season, which brought on plant responses such as flowering and fruiting of the bumble tree (native orange, *Capparis mitchellii*).

In temperate Australia, Aboriginal people also recognised the Sun as having a strong influence upon themselves and over the plants and animals of their country. For example, in western Victoria, Nyaui the Sun clan had both the Moon and the planet Venus among its set of subordinate totems,[11] which were mainly plants and animals (Mathews, 1904). The Narangga people on Yorke Peninsula in South Australia had a song to ripen the quandongs (wild peaches, *Santalum acuminatum*), which translated meant "Wild peaches hanging in the trees, the sun will burn you (to the colour of fire), we will gather you (for food)." (Tindale, 1936: 58). Aboriginal people used songs and other rituals to help hasten the production of favoured foods.

The association between specific plant phenomena within a local area and the observed changes in the Skyworld produced a diversity of Aboriginal calendars. In northeast Arnhem Land, Yolngu people began to harvest the corms of the spike-rush (water chestnut, *Eleocharis dulcis*) when Arcturus appeared in the dawn sky of late November during the *Rarrandharr Dhuludur* season, which is the build-up to the Wet (Hamacher, 2012; Mountford, 1956).[12] In this region, the season for gathering spike-rush corms was also signalled by the 'lily star' (probably Spica), in reference to the lotus (red lily, *Nelumbo nucifera*), when it appeared in the western horizon soon after sunset (Wells, 1973).[13] The spike-rush, which was called *rakia* (*rakay*) in the Yolngu-matha language, is a large fleshy-leaved sedge which is prominent in northern wetlands. It has edible squashed marble-shaped tubers, which were gathered either directly from the swamp beds or opportunistically from the crops of magpie geese killed when hunted (Clarke, 2007a; 2012). The tubers are generally harvested during the monsoonal wet season, when rains have stimulated growth. Spike-rush stems were placed in earth ovens to generate steam for cooking (Clarke, 2012). In northeast Arnhem Land, stars also signal the start of the Dry season, when *Djulpun* (Orion's Belt) is visible on the western horizon during the early night sky. This is the *Dharratharramirri* season when the tall grasses from the Wet are knocked over by southeast storms (Davis, 1989; 1997).

While Aboriginal hunter-gatherers across arid inland regions connected star movements with the seasons for hunting animals and birds and collecting lizard eggs, in southwest Queensland they also signalled the time for gathering the aged sporocarps of nardoo (*Marsilea drummondii*), which were embedded in the dry mud (E.K.V., 1884). In southern parts of the Western Desert, the rising of the *Kungkarungkara*, the Pleiades, marks the *nyinnga* season from May to September, which is cold and dry (Clarke, 2003; Mutitjulu Community and Baker, 1996). At this time of the year, women previously collected vegetable foods, such as grass seed, to sustain their band. In the Western Desert, the seasonal variation in the warmth of sunlight was explained as the Sun ancestor having different roads to travel along through the Skyworld (Mountford, 1976).

The timing of gathering activities for invertebrate foods was also dictated by the calendar. For instance, in the Mallee region of western Victoria the beginning of the *Gnallew* ('spring') season for gathering the larva of *bittur*, the 'wood ant' (termite), was signalled by *Marpeankurrk* (Arcturus) being in the north during the evening (Johnson, 1998; Stanbridge, 1857). Here, it was recorded that the constellation of 'Tourtchinboiong-gherra (Coma Berenices, Berenice's Hair)' was "A flock of small birds drinking rainwater, which has lodged in a fork of a tree." (Stanbridge, 1861: 302).[14] A qualification of this stated that Coma Berenices represented a tree with three main branches, and at the junction with the trunk there was a hollow where birds were drinking (MacPherson, 1881; Johnson, 1998; Massola, 1968). The appearance of this constellation was symbolic of the dry summer weather, when such sources of drinking water

Figure 9: Queen Elizabeth II meeting Professor Brian Maegraith in 1954 (www.lstmliverpool.ac.uk/about-lstm/history-of-lstm/lstm-archives/maegraith-archive/).

Figure 10: Earthstar (*Geastrum* species), a fungus species that might be the identity of *parnappi* ('mushroom') at Aldgate, Adelaide Hills, South Australia, 1983 (photograph: P.A. Clarke private collection).

were crucial for human survival. For the foraging bands, the seasons dictated the choice of subsistence strategies and influenced movement patterns.

The sudden surface appearance of fungi may have been important in signifying the change in season across the Adelaide Plains region. Ellis (1976: 120)[15] suggested that here the recorded term for 'mushroom', *parnappi*, was linguistically related to *parna*, "... a star indicating autumn ...", and to *parnatti*, "... the Australian autumn, when

Figure 11: Yam daisy (*Microseris lanceolata*), a staple food in southeastern Australia and possibly a 'calendar plant', at Mount George, Adelaide Hills, South Australia, 2009 (photograph: P.A. Clarke private collection).

the star *Parna* is seen." *Parna* has been identified as Fomalhaut, based upon its heliacal rising in mid-March during a time of increased rainfall on the Adelaide Plains (Hamacher, 2012; 2015). To the Adelaide people, the arrival of *Parna* in early autumn indicated the change of season and was a sign that large and waterproof huts needed to be built in the Adelaide foothills (J.P. Gell, 1842 [cited Clarke, 1990]). The Aboriginal place name for a hilltop campsite at Morphett Vale, south of Adelaide, was Parnangga, which reportedly was a reference to the appearance of *Parna* (Tindale, c.1931–c.1991; see also Hamacher, 2015). To the east, the Murray River people living between Wellington and Rufus River may also have made this seasonal association, with *pidli* recorded as the Ngaiawung term for "... mushroom, a star." (Moorhouse, 1846 [1935]; see Figure 10).

When conducting fieldwork in the Lower Murray during the 1980s, the present author noted that Ngarrindjeri residents of Raukkan (Point McLeay) believed that it was not safe to swim in the nearby lake if what is locally called the 'dandelion' (*Arctotheca calendula*) was still in flower. Those who did so risked contracting 'dandelion-fever', particularly if they were children (Clarke, 1994; 2014c). Ngarrindjeri people were generally unaware that this plant was introduced by Europeans from South Africa, probably in the early nineteenth century. This tradition had some depth, as in the 1960s there was an account recorded from a Ngarrindjeri woman, Annie Rankine, which illustrated a link between the flowering season of this species and the celestial movements of the Seven Sisters (Pleaides) star cluster. She said:

> My father [Clarence Long, Milerum] used to tell us children of a special group of stars which is called the Seven Sisters, and before they were moving we weren't allowed to swim because the dandelions were in bloom then, and it was said that when the dandelions are out the water is still chill, and this is why our people are very strict and don't allow us to swim. When the flowers all died off and the stars moved over a bit further, this is when we were allowed to swim because in that time the dandelion flower which would cause a fever to anyone would not be out to make us sick. (A. Rankine, 1969 [cited Clarke 1994: 123]).

It is likely that the 'dandelion' mentioned was originally the yam-daisy (native dandelion, *Microseris lanceolata*), which has become locally scarce since the country was cleared of scrub for farming (Clarke, 2014c; see Figure 11).

While regular patterns of celestial movement were linked to the known behaviour of ancestors, less predictable events in the night sky were seen as malevolent omens. For instance, Bella Charlie of the Yanyuwa people in the McArthur

River area at the Gulf of Carpentaria gave a description of the night sky, and said that:

> There is a lot of story here, *wunhaka*. Then there is that dangerous star, shooting star, we call him *Baribari* – he can make you sick, make you die. Dinny and Isaac can block him, have songs to stop him. (B. Charlie, quoted Bradley and Yanyuwa Families, 2010: 161).

Apart from the use of ritual to prevent bad things occurring, there were rituals that were believed to have positive influences, such as affecting short-term changes to the weather generated in the Skyworld. It was Aboriginal tradition that certain individuals were 'rain-makers', and had the ritual power to alter the weather and bring rains to their country (Berndt, 1947; Clarke, 2009b; Elkin, 1977; McCarthy, 1953). In central New South Wales the Wiradjuri 'medicine men' were believed to have had the ability to climb into the Skyworld to obtain rain (Berndt, 1947).[16]

4 DISCUSSION AND CONCLUDING REMARKS

Across Aboriginal Australia, there were topographical features that were believed to be portals linking the Earth with the Skyworld and Underworld. From Earth, the entry into the Skyworld during the Creation period was often perceived as being via the eastern horizon, although the ancestors generally first travelled to the western horizon and then through the Underworld. In some cases, ancestors made their ascent by climbing tall trees that connected the Earth with the Skyworld. When the existing landscape was set at the close of the Creation period, certain tall trees remained as 'ladders' that allowed a variety of spirits and specially-trained humans to travel both ways between these sections of the landscape. Plants can therefore be seen as having physical properties that can be utilised within the psychic realm.

In Aboriginal Australia, celestial changes observed in the Skyworld were an analogue for seasons occurring on Earth. Through the use of calendars that linked together such phenomena as star movements, plant flowering and weather changes, hunter-gatherers were able to position themselves in the landscape to maximize subsistence foraging and comfort. Calendars were also relevant to ceremonial life, within which ancestors responsible for the reproduction of the environment on Earth were honoured.

5 NOTES

1. The names of the 'Dieri' and 'Tirari' people are today generally written as Diyari and Thirrari respectively (Sutton, 1995).
2. In the Wirangu language of the region, *warda* means "... tree, stick, also object of any kind, thing." (Miller et al., 2010: 81).
3. While both the 'Evening Star' and 'Morning Star' are often said to be Venus, a planet cannot be an annual seasonal marker because its position constantly changes (D. Hamacher, pers. comm., September 2014). Hamacher (2012) has shown that in north-east Arnhem Land it was the acronycal rising of Arcturus that signalled the commencement of the spike-rush collecting season.
4. McDougall (1901) referred to the 'Kumbaing-giri', which is the form favoured by Tindale (1974), as 'Coombangree'.
5. McEntee et al. (1986) use the spelling of 'Adna-mat-na' for the people of the northern Flinders Ranges, although generally today this is written as 'Adnyamathanha' (Sutton, 1995).
6. For similar accounts, refer to Spencer and Gillen (1899: 566; 1927(2): 500). These authors use the spelling of 'Arunta' when referring to the Arrernte people of Central Australia (Sutton, 1995).
7. The term, 'chinga', may be a rendering of *djanga* (or *janga*), meaning "... spirits of the dead." (Bates, 1912 [1992: 16]).
8. The identification of the fungi species is tentative, see https://www.anbg.gov.au/fungi/aboriginal.html.
9. See also G.A. Robinson (1834 [Plomley, 1966: 892–893]).
10. McKeown (1938) spelled 'Wiradjuri', which is the form favoured by Tindale (1974), as 'Wiradjurie'.
11. A 'totem' is a spirit being, sacred object, a plant, animal or celestial object that serves as the emblem of a group. In Aboriginal Australian culture most clan members in a tribe have a hierarchy of different totems.
12. For an account of Yolngu resource use during this pre-Wet season refer to Davis (1989).
13. Johnson (1998:24) considered the 'lily star' to be Venus, but Hamacher (pers. comm., September 2014) thinks that Spica is more likely.
14. See also Stanbridge (1857: 139).
15. Words recorded by Teichelmann and Schürmann (1840(2): 37).
16. Berndt (1947) spelled 'Wiradjuri', which is the form favoured by Tindale (1974), as 'Wuradjeri'.

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APPENDIX 1: SOME EXAMPLES OF PLANT–ASTRONOMICAL ASSOCIATIONS IN AUSTRALIAN ABORIGINAL CALENDARS

Botanical Event	Astronomical Phenomena	Seasonal Association	People/Area	Major References
Mushroom (species?)	Heliacal rising of *Parna* (Fomalhaut: Alpha Piscis Austrini)	Autumn (*Parnatti*)	Kaurna/Adelaide Plains, South Australia	Ellis, 1976: 120; Gell, 1842 [1988: 7, 9]; Hamacher, 2015; Teichelmann and Schürmann, 1840: 2:37
Yam daisy (*Microseris lanceolata*) flowering	The Pleiades at highest altitude in the sky during early morning (meridion-al crossing)	Late winter/early spring – too cold to swim	Ngarrindjeri/Lower Murray, South Australia	Clarke, 1994: 407; 2014: 32.
Hardest time to obtain food, therefore relying on vegetables	The Southern Cross is high in the sky	Winter (*Babang*)	Wiradjuri/central New South Wales	Crackerjack Education (2012)
Time to eat vegetable roots as main food	*Dhinawan* (emu in the Milky Way, from Crux to Scorpius) rising at sunset	Autumn (*Bangalang*)	Wiradjuri/central New South Wales	Crackerjack Education (2012)
Bulrush (*Typha* species) rhizomes and wattle (*Acacia* species) seeds ready to eat	The Southern Cross is low in the sky after sunset (SE in late October, SW in late December)	Summer (*Yiraybang*)	Wiradjuri/central New South Wales	Crackerjack Education (2012)
Wattle (*Acacia* species) blooming	Heliacal rising of the Pleiades	Beginning of winter and start of Orca migrating north	Dharawal/southern Sydney area, New South Wales	L. Bursill, 2014
Waratah (*Telopea speciosissima*) blooming	Appearance of meteors	Formation of waratah	Great Dividing Range, New South Wales	Peck, 1925: 1–5.
Vegetable foods, such as grass seed, mainly collected	Heliacal rising of the Pleiades (*Kungkarungkara*)	Cold and dry season (*Nyinnga*)	Southern parts of the Western Desert	Clarke , 2003: 153; Mutitjulu Community and Baker, 1996: 1.
Wild passion fruit (*Capparis spinosa* var. *nummularia*), wild oranges (*Capparis mitchellii*), wild bananas (*Marsdenia australis*) and wild tomatoes (*Solanum ellipticum*) fruit ripens	The Sun is dominant	Hot and wet season (*Uterne*)	Arrernte/ Macdonnell Ranges, Northern Territory	Henderson and Dobson, 1994: 613–614.
Spike-rush (*Eleocharis* species) corms ready for collecting	Acronychal rising of Arcturus	Pre-Wet (*Rarrandharr Dhuludur*)	Yolngu/northeast Arnhem Land, Northern Territory	Hamacher, 2012: 76–77; Mountford, 1956: 495.
Spike-rush (*Eleocharis* species) corms ready for collecting	Heliacal setting of unidentified ‘lily-star’ (incorrectly attributed to Venus in publications); almost certainly Spica	Pre-Wet (*Rarrandharr Dhuludur*)	Yolngu/northeast Arnhem Land, Northern Territory	Wells, 1973: 21–30; D.W. Hamacher (pers. comm., 2014)
Tall grasses (such as spear grass, *Sorghum* species) from the Wet knocked over by southeast storms	Heliacal setting of Orion’s Belt (*Djulpun*)	Beginning of the Dry (*Dharratharramirri*)	Yolngu/northeast Arnhem Land, Northern Territory	Davis, 1989: 53–67; 1997: 32.

RADIO ASTRONOMY AND THE *JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE*

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IDENTIFYING SEASONAL STARS IN KAURNA ASTRONOMICAL TRADITIONS

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Abstract: Early ethnographers and missionaries recorded Aboriginal languages and oral traditions across Australia. Their general lack of astronomical training resulted in misidentifications, transcription errors and omissions in these records. In western Victoria and southeast South Australia many astronomical traditions were recorded but, curiously, some of the brightest stars in the sky were omitted. Scholars claimed these stars did not feature in Aboriginal traditions. This continues to be repeated in the literature, but current research shows that these stars may in fact feature in Aboriginal traditions and could be seasonal calendar markers. This paper uses established techniques to identify seasonal stars in the traditions of the Kaurna Aboriginal people of the Adelaide Plains, South Australia.

Keywords: Australian Aboriginal astronomy; cultural astronomy; ethnoastronomy; Indigenous knowledge

1 INTRODUCTION

In the astronomical traditions of Aboriginal Australians, the rising and setting of particular stars at dusk and dawn are used as calendrical markers, noting the changing of seasons, the availability of food sources and the breeding cycles of animals (Clarke, 2007; Hamacher, 2012; Johnson, 1998; Tindale, 1983). Some stars are described in Aboriginal traditions but their identities are unclear, in part because of misidentifications (e.g. Howitt, 1884a).

The Adelaide Plains of South Australia are the traditional lands of the Kaurna people (Figure 1).[1] Much of their culture was damaged by colonisation, particularly from 1836 onwards (Manning, 2002). Kaurna astronomical traditions are not well recorded, as the Kaurna "… carefully conceal them [astronomical traditions] from Euro-

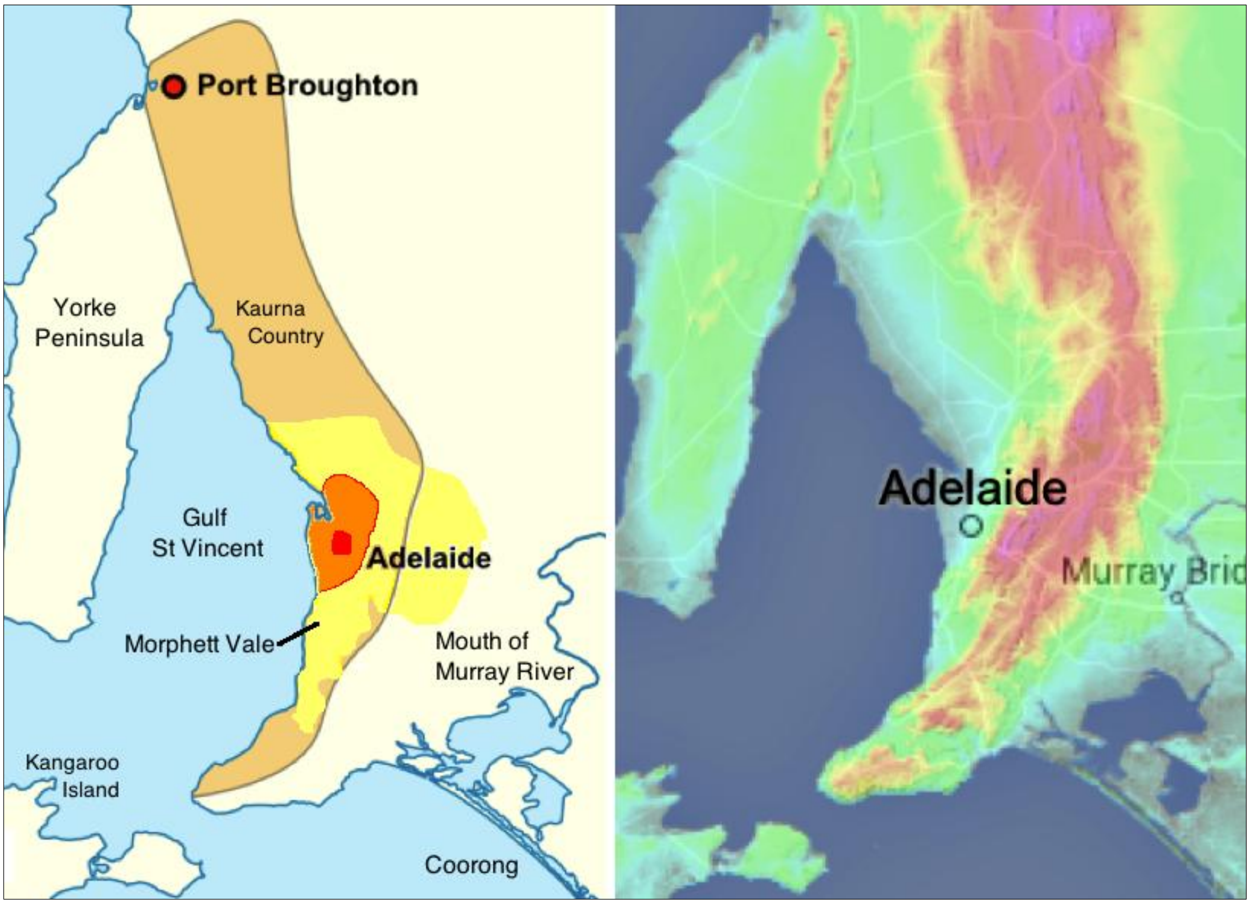

Figure 1, Left: The traditional lands of the Kaurna people, South Australia, stretching from Adelaide in the south to Port Broughton in the north (image: Wikipedia Commons license). Right: Topographic map showing the extent of the Adelaide Plains, following the Kaurna lands closely (green indicates low elevation areas while red/pink indicate higher elevation). (Image: topographic-map.com). The right image indicates the Mount Lofty Ranges (red/pink). Left image shows Adelaide Central Business District (red), Adelaide city (orange), and the greater metropolitan area (yellow), based on Google Maps.

peans, and even their own males are only at a certain age initiated into the knowledge of them." (Teichelmann, 1841).

What we do know about Kaurna language comes predominantly from the records of the German Lutheran missionaries Christian Gottlieb Teichelmann (1807–1888) and Clamor Wilhelm Schürmann (1815–1893), who came to Adelaide in October 1838. In 1840, they published a dictionary of 2,000 Kaurna words (Teichelmann and Schürmann, 1840). Much of the Kaurna language was provided by local Aboriginal men, including Mullawirraburka (*aka* King John) and Kadlitpinna (*aka* Captain Jack) (Amery, 2000).

Teichelmann continued working on the Kaurna language, compiling a manuscript of Kaurna vocabulary and grammatical notes (Teichelmann, 1857). Clarke (1990; 1997) published research on Kaurna astronomical traditions, but the identity of many of the stars remains a mystery.

We do know that in Kaurna traditions, particular stars govern seasons. For example, autumn (*Parnatti*) is signaled by the morning appearance of the star *Parna*. This warns the Kaurna that the annual autumn rains will soon arrive and that they need to build large, waterproof huts (Teichelmann and Schürmann, 1840). Summer (*Woltatti*), the hot season, is governed by *Wolta*, the wild turkey 'constellation',[2] and Spring (*Willutti*) is under the influence of *Wilto*, the eagle star. Winter (*Kudlilla*), the rainy season, was not associated with any particular star in the record (Clarke, 1997; Teichelmann and Schürmann, 1840).

2 KAURNA ASTRONOMICAL TRADITIONS

Astronomical traditions of the Adelaide region were first recorded by Teichelmann and Schürmann as part of their linguistic study of the Kaurna language. Since then, a number of publications have explored the local language and astronomy (e.g. Black, 1920; Clarke, 1997; 2007; Gell, 1842; Hartland, 1898; Teichelmann and Schürmann, 1840; Tindale, 1937; 1974; 1983). However, surprisingly little detail about Kaurna astronomy was recorded. The records provide some details (Table 1), but most star names are given with no reference to their Western counterpart, and only fragmentary details are given about the stories of the stars themselves.

We know the Kaurna have rich astronomical knowledge. Gell (1842: 116–117) says that "… most of the stars have some legend attached to them …", and Teichelmann (1841: 9) wrote that:

> … the exaltation of almost every constellation they give the history of the attending circumstances, which the reasons of their present movements explain.

The sky was seen as a component of the land, a reflection, and

> … all the celestial bodies were formerly living upon Earth, partly as animals, partly as men, and that they left this lower region to exchange for the higher one. Therefore all the names they apply to the beings on Earth, they apply to the celestial bodies … (Teichelmann, 1841: 4).

But we also know that the Kaurna were very secretive about their astronomy, only providing fragments of information to the white colonists. For example, Schürmann's Aboriginal informants closely guarded their secrets, and when an Aboriginal man told Schürmann about his cosmology, he did so under the condition that Schürmann (1840) would not tell another Aboriginal person.

In Kaurna traditions (Gell, 1842; Teichelmann and Schürmann, 1840), *Tinniinyaranna* are the stars of Orion (most likely the Belt and scabbard, as with many Aboriginal cultures),[3] representing a group of boys who hunt kangaroo and emu on the celestial plain, while the *Mangkamangkaranna* (the Pleiades star cluster) represents a group of girls digging roots. The red star *Madletaltarni*, probably Betelgeuse (Alpha Orionis) or Aldebaran (Alpha Taurii), is the mother of the *Tinniinyaranna*, and *Parnakkoyerli* is the father, described as 'a seasonal star', possibly Rigel. Betelgeuse and Rigel flank the boys on either side (see Figure 2).

Linguistically, *Parnakkoyerli* could mean two things: 1) 'their father' (*yerli* = 'father' and 'their' refers to *Tinniinyaranna*), and 2) 'father of *Parna*'. In Teichelmann and Schürmann (1840), *Parnakkoyerli* is mentioned directly after *Tinniinyaranna*, which suggests that the Aboriginal informant pointed out the stars of *Tinniinyaranna*, then probably moved to Rigel and said it was 'their father'. In this case, *Parnakkoyerli* is a descripttion rather than a proper name.

3 SEASONS ON THE ADELAIDE PLAINS

The fertile Adelaide Plains of South Australia (SA) are flanked by the Mount Lofty Ranges to the east and Gulf St Vincent to the west. The lower section of the Plains is taken up by the city of Adelaide. Rain is not evenly distributed throughout the year (Figure 3).[4] Long-term data show that February, the driest and hottest month of the year, only sees an average of 3.6 days and 15.8 mm of rain. June, the wettest month of the year, experiences 14.8 days and 80.6 mm of rain. The rainfall increases in autumn, and decreases in spring.

Ethnographic records indicate four distinct seasons in Kaurna traditions, similar to those of

Table 1: Celestial objects in the Kaurna sky (after Teichelmann and Schürmann, 1840 and Clarke, 1990; 1997).

Kaurna Name	Western Name	Description
Kakirra	Moon	Called *Piki* in eastern communities. The husband of *Tindo* (the Sun), first to ascend into the sky. Encouraged others to follow him to keep him company.
Kumomari	Constellation, *Unidentified*	
Kurkukurkurra	Orion	Same as *Tinniinyaranna*, the constellation Orion (probable reference to the Belt and scabbard stars).
Madletaltarni	Red Star, *Unidentified*	Mother of the *Tinniinyaranna*. Probably Betelgeuse.
Mankamankarranna	Pleiades	Girls who dig for roots.
Mattinyi	Constellation, *Unidentified*	
Monana	*Unidentified*	Man who threw spears into the sky.
Ngaiera	Sky	
Ngakallamurro	Magellanic Cloud (one of)	Ashes of parakeets (Adelaide Crimson Rosella?), from '*murro'* meaning 'ashes'. The birds are gathered there by another constellation, and then roasted. The constellation is not identified. Teichelmann (1841: 2) suggests both Magellanic Clouds are the lorikeets' ashes.
Njengari	*Unidentified*	A man who created the landscape, and then was transformed into a star.
Parna	Star, *Unidentified*	A star indicating autumn.
Parnakkoyerli	Star, *Unidentified*	Father of the *Tinniinyaranna*. This name translates as 'their father', probably Rigel.
Purle	Star, *Unidentified*	A generic term for a star?
Tindo	Sun	The wife of the Moon. She beats him to death every month but he comes back to life. This describes the lunar cycle.
Tinniinyaranna	Orion (Belt/Scabbard?)	A group of young boys who hunt kangaroos, emus and other game on the great celestial plain, probably represented by the Belt and maybe the scabbard of Orion.
Wayakka	Star or Constellation, *Unidentified*	
Willo	Star, *Unidentified*	One whose older brother (*Yunga*) has died.
Wilto	Star, *Unidentified*	Summer season, Eaglehawk (Wedge Tailed Eagle). Possibly the Southern Cross (Crux).
Wodliparri	Milky Way	A river (*parri*) with huts (*woldi*).
Wolta	Star? *Unidentified*	The wild turkey (Australian Bustard).
Womma	Space/Sky	The celestial plain, where the *Tinniinyaranna* hunted emu and kangaroo.
Yurakauwe	Absorption nebulae	Dark spots in the Milky Way, thought to be large ponds in the *Wodliparri*, and the residence of the aquatic monster *Yura. Yura* who punishes those who break sacred law.
Makko	Cloud	
Unnamed	Planets (generic)	The wives of the Sun-father?
Unnamed	Comets	Evil sisters of the Sun?
Unnamed	Meteors	Orphans.

other Aboriginal groups in southeastern Australia (Clarke, 1997; Stanbridge, 1861; Teichelmann and Schürmann, 1840). There is ongoing debate as to the reliability of this interpretation, as the traditions and language were recorded by German missionaries and contain their biases and interpretations. For example, Heyes (1999) suggests there were more than four seasons, but due to the backgrounds and research methods of Teichelmann and Schürmann, the Kaurna and European seasons were conflated. This may also be the case with other Aboriginal seasons recorded in southeast Australia that seem to correspond to the four European seasons.

Heyes (1999: 16) suggests that the missionaries melded multiple seasons into a single cycle to more closely match the four-season framework familiar to Europeans (Figure 4):

- *Woltatti* (hot season) or *Bokarra* (hot north winds that blow in summer)
- *Wadlworngatti* (time of building huts against fallen trees) or *Parnatti* (Autumn—when the *Parna* star appears)
- *Kudlilla* (winter—icy cold south west winds)
- *Wullutti* (spring—*Wilto*/*Willo* star appears).

Teichelmann and Schürmann attribute summer to *Woltatti*, autumn to *Parnatti*, winter to *Kudlilla*, and spring to *Willutti*.

The stars or constellations associated with *Parna* (autumn star), *Wolta* (wild turkey), and *Wilto* (eagle) are not identified in the literature by

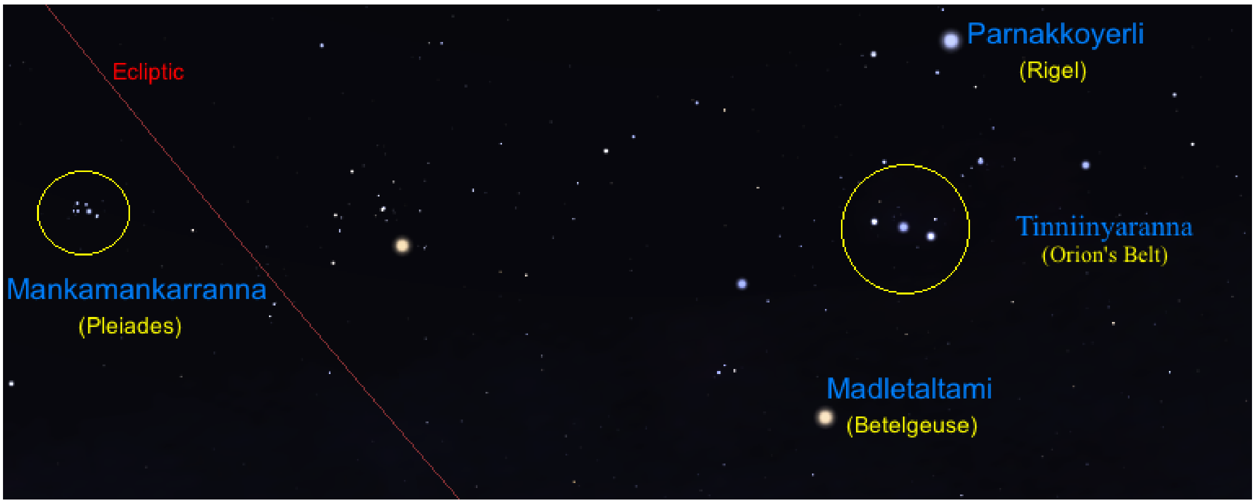

Figure 2: Stars identified by name in Kaurna astronomical traditions (or inferred by Teichelmann and Schürmann). In Western terminology, Orion is to the right, the Pleiades to the left, and Aldebaran and the Hyades in between. The ecliptic is noted in red (image: Stellarium, altered by the author).

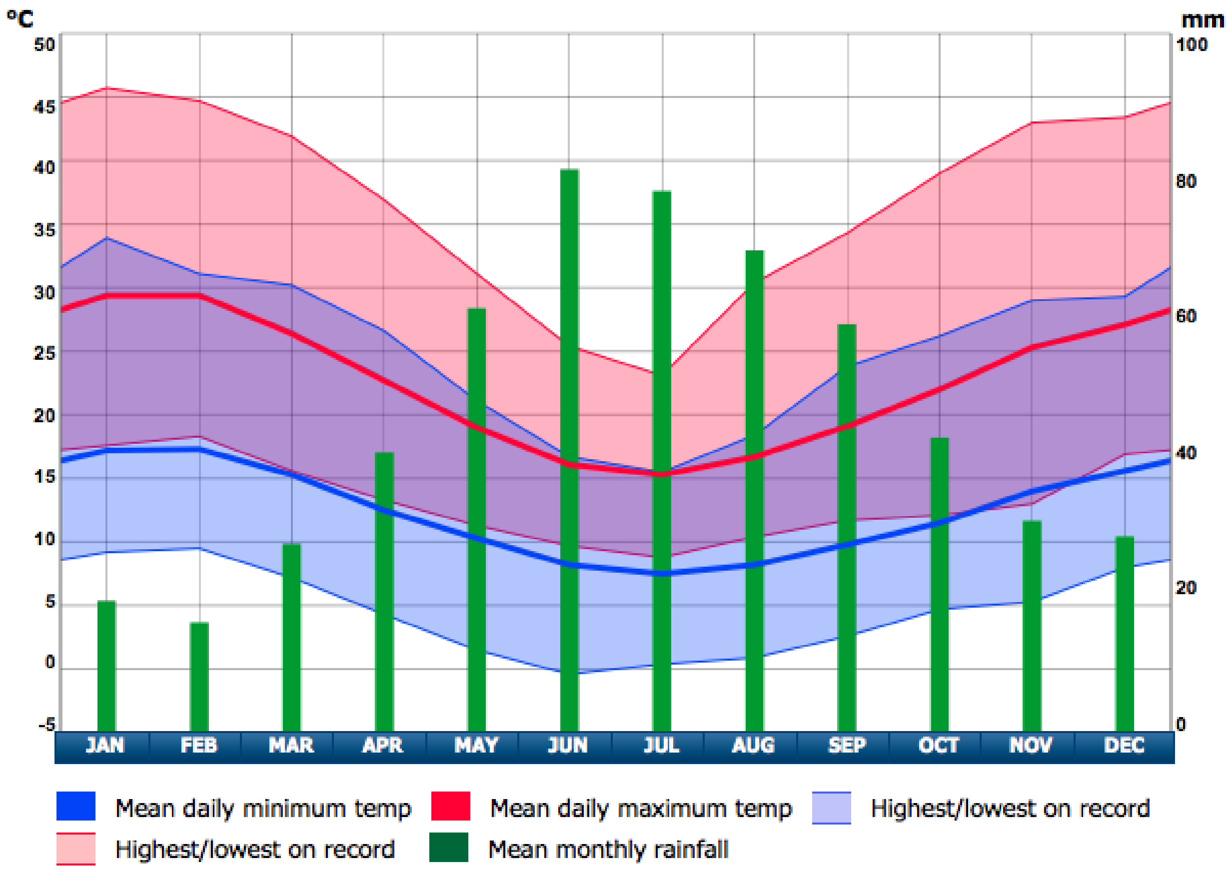

Figure 3: Long-term average seasonal data from Kent Town, Adelaide, recorded between 1977 and 2014, including information on temperature and rainfall. From Weatherzone and based upon data provided by the Bureau of Meteorology (www.weatherzone.com.au/climate/station.jsp?lt=site&lc=23090).

their Western counterparts. Clarke (1997) suggests that *Kudlilla* (winter) is associated with a star, but the original records do not state this.

We are given no information about the rising or setting of the other seasonal stars, so we apply the same criteria to them as we do to *Parna*: we assume they rise at dawn or dusk at the start of their associated seasons.

In this paper, we apply methods for identifying these stars by examining their heliacal and acronycal rise times and corresponding seasonal change, and by exploring their presence and/or associations in Kaurna astronomical traditions. The process of identifying previously-unnamed celestial objects in Indigenous astronomical traditions can be difficult, so developing and demonstrating rigorous methods for accomplishing this is useful for future work in cultural astronomy.

The published records of Kaurna astronomical

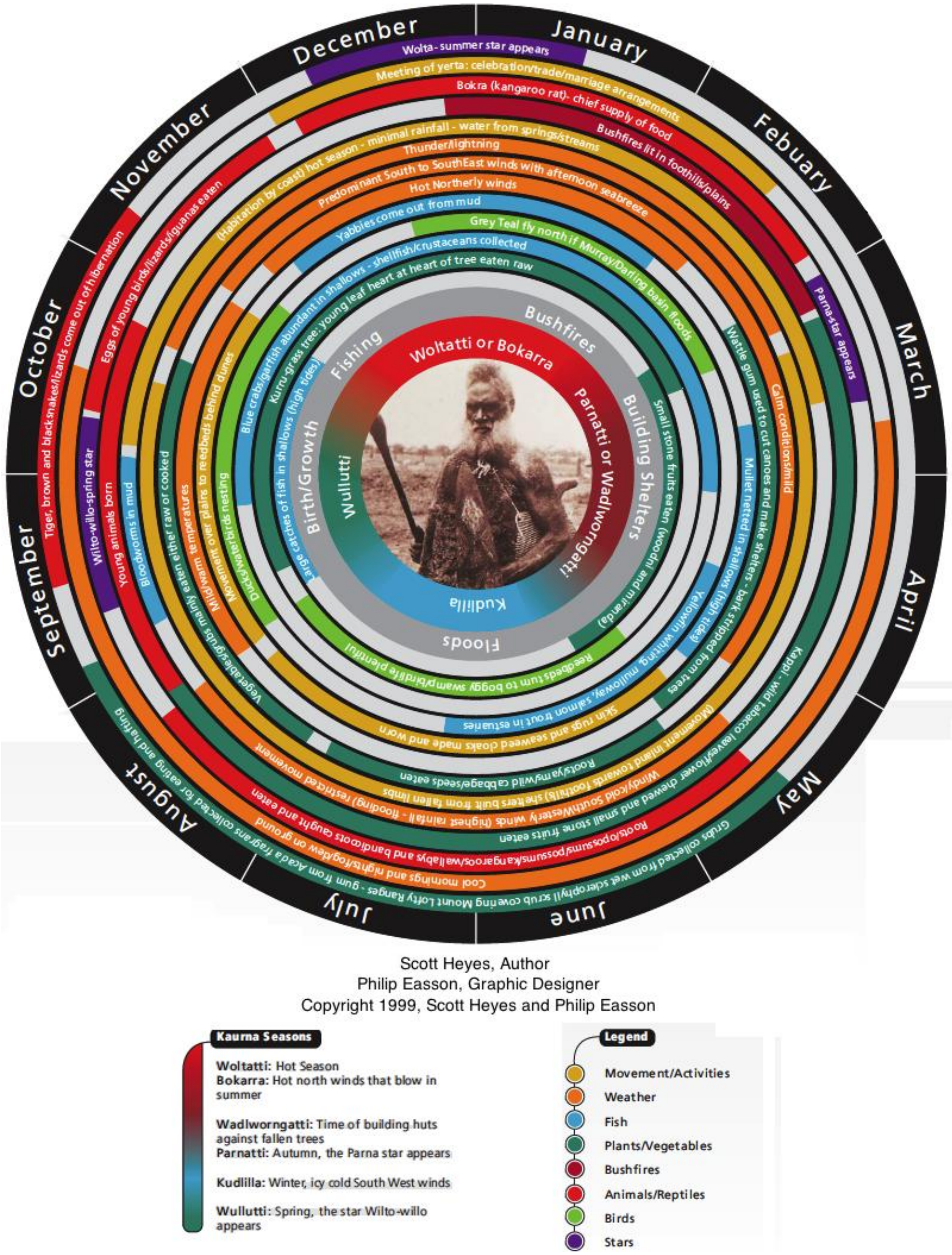

Figure 4: A seasonal Kaurna calendar, based on the Honours research of Scott Heyes (1999). Seasonal stars and the times of their appearance are noted in purple (image: Scott Heyes and Philip Easson).

traditions are incomplete and may contain errors. Only *Parna* is clearly denoted as appearing to signal coming winter rains. Neither *Wolta* nor *Wilto* is said to rise at dawn or dusk to signal seasonal change, and *Kudlilla* is never specifically associated with a star.

No further information is given so it is assumed, for the purposes of this study, that they rise heliacally. By extrapolating the relationship between *Parna* and seasonal change, we apply criteria to search for candidate stars for *Wolta*, *Wilto* and *Kudlilla*, as an associated star may exist but simply not have been recorded.

4 METHODOLOGY

For this study, two important factors are necessary to determine the identity of Kaurna seasonal stars:

1) The heliacal and acronycal rise times and locations of stars, and;
2) The time of seasonal change on the Adelaide Plains.

The former can be calculated very precisely (to the day), while the latter cannot (it ranges from weeks to months). Therefore, a suitable methodology must be developed to identify the best candidates for Kaurna calendar stars.

4.1 Calculating Heliacal/Acronycal Rising

When a star first appears on the eastern horizon just before sunrise (before its light is drowned out by the Sun), it is referred to as *heliacal rising*. For millennia, cultures across the globe, including those in Australia (Johnson, 1998), have used the heliacal rising of particular stars for hunting and gathering, agriculture and as seasonal markers (see Aveni, 2003; Kelley and Milone, 2011). *Acronycal rising* (meaning opposite the Sun) is when a star rises in the east at sunset. This is also significant for denoting calendar changes in Aboriginal astronomical traditions (e.g. see Hamacher, 2012).

Table 2: First magnitude stars, their Bayer designations and their apparent magnitudes (V_{mag}). The V_{mag} for each star is its average apparent magnitude in the absence of an atmosphere (not its apparent magnitude when at an altitude of 5°), taken from the SIMBAD catalogue (simbad.u-strasbg.fr/simbad/).

Name	Bayer Designation	V_{mag}
Sirius	Alpha Canis Majoris	−1.46
Canopus	Alpha Carinae	−0.72
Rigil Kent	Alpha Centauri	−0.29
Arcturus	Alpha Boötis	−0.04
Vega	Alpha Lyrae	0.03
Capella	Alpha Auriga	0.08
Rigel	Beta Orionis	0.12
Procyon	Alpha Canis Minoris	0.34
Achernar	Alpha Eridani	0.46
Betelgeuse	Alpha Orionis	0.45
Hadar	Beta Centauri	0.61
Altair	Alpha Aquilae	0.77
Acrux	Alpha Crucis	0.77
Aldebaran	Alpha Taurii	0.85
Spica	Alpha Virginis	0.98
Antares	Alpha Scorpii	1.06
Pollux	Beta Geminorum	1.14
Fomalhaut	Alpha Piscis Austrini	1.16
Mimosa	Beta Crucis	1.25
Deneb	Alpha Cygni	1.25
Regulus	Alpha Leonis	1.36

The heliacal or acronycal rising of a star is dependent on a number of factors, including the azimuth and altitude of a star, the altitude and azimuth of the Sun relative to the star's position in the sky, the location and elevation of the observer, atmospheric conditions and the star's brightness and colour.

4.1.1 Star Brightness

First magnitude stars are the 22 brightest stars in the sky, ranging from the brightest, Sirius (Alpha Canis Majoris, V_{mag} = −1.46), to the dimmest, Regulus (Alpha Leo, V_{mag} = 1.35, see Table 2). Many single stars used for calendrical purposes in Aboriginal astronomical traditions are first magnitude (Clarke, 2007; Hamacher and Norris, 2011; Johnson, 1998).[5] Named celestial objects that are dimmer than this magnitude limit tend to be star clusters (e.g. the Pleiades), the Milky Way (including the dark spaces within it), close pairs of stars (e.g. Shaula and Lesath in Scorpius) or stars that form an asterism (e.g. Crux, and the Belt and scabbard of Orion). Therefore, we assume Kaurna seasonal stars are all first magnitude.

4.1.2 Stellar and Solar Position

The minimum altitude of a star when it is first visible to the naked eye depends on the brightness of the star, the colour of the star, the elevation of the observer, the atmospheric conditions between the star and the observer and the presence and phase of the Moon. Under good seeing conditions, a human observer with very good visual acuity can detect stars as faint as magnitude 8 (Kelley and Milone, 2011; Schaefer, 2000).

Assuming the observer is at sea-level, looking towards an unobstructed horizon in very good seeing conditions, a first magnitude star needs to have a minimum altitude of 5° to be visible (ibid.). Otherwise, extinction of the star's light is too great. The Sun needs to have a maximum altitude of −10° for a first magnitude star to be visible when it rises (Aveni, 2001). If the Sun's altitude is greater than this limit, its light will drown out the light of the star.

Heliacal and acronycal rising only applies to objects with an azimuth between 0° (due north) and 180° (due south). The appearance of stars nearer to the Sun will be more greatly reduced by the Sun's light than stars with an azimuth further from the Sun, such as those rising acronycally.

Stars that are circumpolar as seen from Adelaide ($\delta \leq -54.5°$) are always visible above the horizon and therefore do not 'rise'.

4.2 Selection Criteria

Seasonal change occurs on a timescale of weeks to months. Therefore, minor factors affecting the calculation of heliacal and acronycal rise times by a few days can be ignored for this study. The interested reader is referred to Purrington

(1988) and Schaefer (2000) for detailed analyses of heliacal rising calculations.

Using the major factors for calculating heliacal and acronycal rise times, calendar stars must meet the following four criteria:

1. The star must be first magnitude.
2. The star must not be circumpolar as seen from Adelaide (δ ≤ −54.5°)
3. The star must have an azimuth between 0° and 180° at the time of heliacal or acronycal rising.
4. The star must have a minimum altitude of 5° when the Sun has a maximum altitude of −10°.

Because early ethnographers sometimes conflated 'star', 'planet' and 'constellation', we are unsure if some seasonal stars are in fact a star or an asterism/constellation. We consider the latter case, provided that at least one star in the asterism is first magnitude. It should be noted that connect-the-dots constellations in Aboriginal astronomical traditions are rare. Clarke (2014) suggests that Aboriginal observers focused on individual elements, such as stars, rather than drawing lines between them to make shapes.

4.3 Estimating Seasonal Markers

The Kaurna traditions do not claim that seasonal change occurs exactly when the star is first visible. In the case of *Parna*, it serves as a warning of the coming wet season, allowing the people a 'grace period' during which they need to prepare.

The association between stars and seasons is less clear with *Wolta* and *Wilto*, and non-existent for *Kudlilla*. We use the description given in Kaurna traditions (if any) and combine that with temperature and rainfall data from the region to approximate the time of year we expect to see the calendar star rise.

When estimating the time of month we search for heliacally- and acronycally-rising seasonal stars, and the following definitions are used:

- Early = 1st to 10th of the month
- Mid = 11th to 20th of the month.
- Late = 21st to 30th/31st of the month.

4.4 Comparative Studies

Another line of evidence for identifying celestial objects in Kaurna traditions is to compare the roles of these stars and their terrestrial counterparts in nearby Aboriginal astronomical traditions. Although Aboriginal languages and cultures are distinct, many have similar linguistic themes and related astronomical associations, particularly in southeastern Australia (Clarke, 2007; Fredrick, 2008; Hamacher, 2012; Johnson, 1998; Tindale, 1983).[6]

5 KAURNA SEASONAL STARS

5.1 *Parna*: The Autumn Star

In the Kaurna language recorded by Teichelmann and Schürmann (1840: 37), *Parna* has three different meanings. It can signify (1) the personal pronoun 'they'; (2) one of the two men

Figure 5: Aboriginal huts, or 'wurlies', constructed by the Kaurna as shelter during the rainy winter season (image: Alexander Schramm, South Australian Museum).

placed at either side of a line the people form when about to perform a circumcision as part of a male ceremony (the other man, *Tappo*, is a fly); or (3) the 'autumn star', which is derived from *Parnatti*, meaning "… autumn, when the star Parna is seen."

Autumn on the Adelaide Plain is denoted by increased rainfall, which peaks during the winter months. Building waterproof homes (colloquially called 'wurlies', Figure 5) was essential for the Kaurna to survive the cold, wet winter months (Taplin, 1879). This is due, in part, to water run-off from the Mount Lofty Ranges to the east, flooding the relatively flat plains that drain into Gulf St Vincent to the west (Figure 1).

The most significant rise in rainfall in terms of the percentage difference between any particular month and the previous month occurs in March (Table 3). Rain increases by an average of 20 mm each month until it peaks in June. The

Table 3: The mean and median rainfall (in millimeters) in the Adelaide Plain, taken from the data in Figure 3. The percentage change in rainfall from the previous month to the current month is given in columns 2 and 4.

Month	Mean Rainfall	% Change	Median Rainfall	% Change
January	18.9	−32.7*	20.1	−15.5
February	15.8	−16.4	06.8	−66.2
March	27.0	70.9	19.0	179.4
April	40.1	48.5	33.6	76.8
May	60.7	51.4	56.8	69.0
June	80.6	32.8	76.8	35.2
July	77.5	−03.8	68.8	−10.4
August	69.0	−11.0	69.2	00.6
September	58.4	−15.4	58.0	−16.2
October	42.2	−27.7	37.0	−36.2
November	30.3	−28.2	30.3	−18.1
December	28.1	−07.3	23.8	−21.5

* Note that a negative value indicates a decrease in rainfall.

records indicate that the appearance of the star *Parna* provides enough time for the Kaurna to build their huts before the heavy rains arrive. This suggests that *Parna* appears at the start of March, in agreement with Heyes (1999).

Teichelmann and Schürmann (1840: 50) say people begin building huts during *Wadlaworngatti*, "… the beginning of April (autumn season)." Heyes suggests that the confusion may be due to Teichelmann and Schürmann conflating *Parnatti* and *Wadlaworngatti* into a single 'autumn' season that stretched from late February to early June. Teichelmann and Schürmann do not clarify the time of day the star *Parna* is seen; only that it signals the start of autumn.

In the nearby Yaraldi dialect of the Ngarrindjeri language, the term for autumn is *marangalkadi*, which means "… autumn, time of the crow …" (raven)—from February to April—and *parnar* means 'rain'. The raven is a prominent figure in Ngarrindjeri Dreamings (Berndt et al., 1993). In Ngarrindjeri culture, the 'autumn stars' are low in the southeastern sky because the crow-spirit entered the Skyworld to the southeast of the Lower Murray, towards Mount Gambier in the far southeast corner of South Australia (Clarke, 1997).

Although the Ngarrindjeri language is very different from the Kaurna language, there are cultural relationships between the groups. It is unknown if this plays a significant part in the identity of *Parna*, but the link is plausible.

Given the information above, we search for stars that meet the criteria in both early March and early April. Ngarrindjeri traditions indicate that *Parna* may have a southeasterly azimuth (between 90° and 180°). Heyes (1999) identifies early-March as the time *Parna* appears in the sky.

5.1.1 Place Names Indicating *Parna*

Place names incorporate *Parna* and its stellar significance. *Parnangga*, a hilltop campsite at Morphett Vale, in the southern suburbs of Adelaide, allegedly means "… place of the autumn star." The suffix *–ngga* is locative (Amery, 2002: 167). *Parnangga* may refer to the appearance of *Parna* and/or "… place of the procession leader." (Schultz, 2013a). The latter probably relates to male circumcision, a common component of manhood rites and male initiation. In the nearby Nukunu culture, *partnapa* was the "… first stage of initiation; young initiate who has gone through this." (Hercus, 1992: 26).

Amery (2002) suggests that *Parnangga* may be a 'stepping-off' place (typically mountains or hills) where an ancestor ascended into the sky. The campsite is believed to be near the primary school at Morphett Vale East, although this is uncertain (Schultz, 2013a). Considering the topography of the area, such as the elevation of *Parnangga* and the maximum elevation of the nearby Lofty Ranges, a star with a minimum altitude of 5° will be visible above the Ranges as seen from *Parnangga*. Tindale (c.1931) relates *Parna* to *Parnangga*, which he claims means "… autumn rains …" or "… place of autumn rains." This is probably based on the mistaken equivalence of the Ngarrindjeri word *Parnar* (rain) for the Kaurna words for rain (*kuntoro* and *manya*; Teichelmann and Schürmann, 1840). The Ngarrindjeri are south of Adelaide, along the Coorong, and speak a very different language to the Kaurna.

According to Tindale (c.1931), a stream near Second Valley on the Fleurieu Peninsula south of Adelaide named *Parananacooka* translates to "… excreta and urine of the Autumn Star women, so called because of the intense brackishness of the river at the end of summer." Schultz (2013b) and Clarke (1997) both claim Tindale's derivation is speculative. The interested reader is directed to Schultz (2013a; 2013b) for a detailed etymology of the place names *Parnangga* and *Parananacooka*.

5.2 *Kudlilla*: The Winter Star?

Kudlilla is "… winter … the rainy season …" (Teichelmann and Schürmann, 1840: 12). It is not associated with a star in the recorded literature. For this study, we propose it *could* be, and we predict it will rise at the beginning of winter. The mean monthly rainfall is highest from June to August, which corresponds to the three coldest months of the year (in terms of mean daily temperature).

For this reason, we search for stars that meet the criteria in late May or early June.

5.3 *Wilto*: The Spring Star

Teichelmann and Schürmann (1840) record *Wilto* as a species of eagle (most likely the wedge-tailed eagle, *Aquila audax*).

As with *Wolta*, little information is provided in the literature about the appearance of either the star or its relationship to the season (or the eagle). In the Turra (Narangga) traditions of Yorke Peninsula (bordering Kaurna country to the west), *Wiltu* is the eaglehawk (wedge-tailed eagle) (Fison and Howitt, 1880; Tindale, 1936).

Teichelmann and Schürmann (1840) refer to *Wilto* as a star or constellation. Teichelmann (1857: 41) clarifies that Wilto is an eagle and a "… constellation governing the spring." Clarke (1990) suggests that *Wilto* refers to the brightest stars in the Southern Cross (Crux), as it shares linguistic similarities with Ngadjuri traditions in north-central South Australia where the eagle, *Wildu*, is associated with Crux (regarded as the footprint of the eagle). Crux is also related to the wedge-tailed eagle in other Aboriginal traditions, such as the Adnyamathanha of South Australia (Hamacher et al., 2015; Johnson, 1998). Crux is at its highest altitude (crossing the meridian) at dawn in mid-January and its lowest altitude at dawn in early July. Crux is circumpolar as seen from Kaurna country (the minimum altitude of Gamma Crucis in 1840 as seen from Adelaide was ~1.5°), and was thus rejected from the criteria.

Across Aboriginal Australia, stars are connected to birds or animals because the rising and setting times of stars at dusk and dawn respectively correlate with some aspect of that bird's or that animal's behaviour. This might include migration patterns, nest building, breeding, whelping and brooding. Therefore, we examine eagle behaviour to see if any aspects correspond to the heliacal rising of first magnitude stars. This is conjecture, but may provide some insight as to why the star is associated with a particular bird. The study of the stars' rising and setting times and their avian counterparts in Indigenous traditions is the focus of ongoing research by Leaman et al. (n.d.).

The breeding cycle of the wedge-tailed eagle begins in March and April and runs to September, but the majority of eagles lay their eggs in July (Olsen, 1995; 2005). Mid-July is the middle of winter, thus making it a poor 'spring star'. Eagles incubate their eggs for 45 days and brood the chicks for an additional 30 days.

Therefore, most young eagles are leaving their nests in mid-September (between 11 and 20 September), which is also the end of the greater breeding season and the middle of spring. Heyes (1999) cites the appearance of the *Wilto* star in early to mid-September, although he does not associate this with the bird's behaviour.

Given this information, we search for a star that meets the criteria in mid-September, keeping in mind that linguistic evidence supports Crux as *Wilto*.

5.4 *Wolta*: The Summer Star

Wolta, the 'wild turkey' star, is associated with 'summer' (*Worltatti*). Little information is provided about the appearance of *Wolta* or its relationship to summer. Summer is the hottest and driest season of the year, with the highest temperatures occurring in January and February, and with nearly equal mean temperatures in December and March.

The terms 'brush turkey', 'plains turkey' and 'wild turkey' are commonly used by Aboriginal people to describe the Australian bustard (*Ardeotis australis*), which is found across the Adelaide Plains. *Walta*/*Waltja* is also the name of the bustard in the nearby Narranga language of southern Yorke Peninsula (Tindale, 1936). In the Nukunu language, *Waalha* refers to the 'plains turkey' (Hercus, 1992)

The relationship between the star and the bird is unknown, but probably relates to some aspect of the bird's behaviour, such as the breeding cycle or seasonal migrations. The Australian bustard breeds once a year. In South Australia, egg-laying occurs from July to November (Boehm, 1947), but primarily from September/October through to November/December, and the eggs incubate for 23–24 days (Beruldsen, 2003). The bustard is diurnal, being active in the early morning and late evenings.

Detailed study of bustard behaviour in Victoria (Ziembicki, 2009) shows that the bustard returns to its breeding ground in spring and summer when more food is available (following the wet winter rains). Anecdotal observations suggest that numbers peak during the summer in Victoria, implying possible movements southwards from inland regions at this time (ibid.). No similar, in-depth studies have been conducted on the Adelaide Plains, so any comparison with bustard behaviour in Victoria is conjectural.

This poses a challenge to clearly identify the time of year this star might rise heliacally or acronycally. For this study, we search for stars that rise in early to mid-December, coinciding with the end of the bustard breeding season and the start of the hot, dry summer. In agreement, Heyes (1999) cites early to mid-December as the time when *Wolta* appears.

6 RESULTS

All first magnitude stars that rise heliacally and acronycally during the year as seen from Adelaide are given in Table 4. Stars that meet the criteria for each seasonal star for both heliacal and acronycal rising are given. Those in green are the best candidates, and those in red are within two days of the time period explored for each candidate (i.e. early, mid, late month).

Table 4: Stars visible from Adelaide that meet the criteria for dates in 1840 (when Teichelmann and Schürmann published their work on the Adelaide Aboriginal language). The dates given are the first day the criteria are met (using Stellarium). The azimuth (Az in degrees) is rounded up to the nearest degree. Stars in green meet the criteria. Candidate stars (CS) in red 'marginally' meet the criteria, meaning they are within two days of the estimated start or end period.

Star	Az (°)	Heliacal Rise		Acronycal Rise	
		Date	CS	Date	CS
Arcturus	61	17 Dec	*Wolta*	18 May	*Kudlilla*
Altair	76	16 Feb		29 Jul	
Vega	35	27 Feb	*Parna*	11 Aug	
Fomahlaut	124	1 Mar	*Parna*	14 Aug	
Deneb	23	4 Apr	*Parna*	18 Sep	*Wilto*
Canopus	156	10 May		22 Oct	
Rigel	97	5 Jun	*Kudlilla*	15 Nov	
Aldebaran	66	12 Jun	*Kudlilla*	21 Nov	
Sirius	106	21 Jun		28 Nov	*Wolta*
Betelgeuse	77	24 Jun		2 Dec	*Wolta*
Procyon	79	21 Jul		22 Dec	
Capella	20	7 Aug		4 Jan	
Pollux	50	17 Aug		11 Jan	
Regulus	71	18 Sep	*Wilto*	8 Feb	
Spica	99	8 Nov		30 Mar	*Parna*
Antares	119	16 Dec	*Wolta*	17 May	

6.1 *Parna*

Three stars are possible contenders for *Parna*: Fomalhaut and Deneb, depending on whether it coincides with early March or early-April (Heyes, 1999 suggests the former—see Figure 4), and Vega, as it is within two days of early March.

The stars Fomalhaut and Vega appear in the sky at close to the same time, with Vega appearing in the northeast and Fomalhaut in the southeast. Deneb appears in early-April in the far northeastern sky. Because of the declination of Fomalhaut (−29.61°), from the latitude of Adelaide it also heliacally sets on the same days it heliacally rises. This means Fomalhaut has an altitude of 5° when the Sun has an altitude of −10° at both dusk and dawn around the first of March. This is not the case with either Vega or Deneb.

In the nearby Mallee region of southeast South Australia and western Victoria, Vega is associated with the malleefowl (*Leipoa ocellata*), a ground dwelling megapode (mound-building bird) in Wergaia traditions (Stanbridge, 1861). The acronycal rising of Vega coincides with the time of year the birds are building their nesting mounds. The star's heliacal setting coincides with the time when Aboriginal people collected the eggs.

Fomalhaut meets the description of an autumn star in Yaraldi (Ngarrindjeri) traditions, as it appears in the southeastern sky (both Deneb and Vega are northerly stars with an Az <35°). Fomalhaut also rises and sets heliacally on the same days, unlike any of the other calendar stars listed in Table 4. It is unknown if this is significant.

With this information, Fomalhaut is the most plausible candidate for *Parna*. Tindale (1934) originally identified *Parna* as the Pleiades, but the heliacal rising of that cluster occurs in June, and the Pleiades are also already identified in Kaurna astronomical traditions as the *Mankamankarranna*.

6.2 *Kudlilla*

In terms of heliacal rising, only one candidate star meets the criteria for *Kudlilla* and this is Rigel, although Aldebaran is near the boundary of the upper-limit of the time period for *Kudlilla*. In terms of its acronycal rising, Arcturus marginally qualifies. When comparing candidate stars with those identified in Kaurna traditions, we see that Rigel is already associated with *Parnakkoyerli*. Heyes does not include *Kudlilla* as a seasonal star in his analysis of the Kaurna calendar—see Figure 4.

Both *Kudlilla* and *Parna* have marginal associations with Arcturus and Spica.

6.3 *Wilto*

Regulus meets the heliacal rising criterion and Deneb meets the acronycal rising criterion. For reasons described in Section 4.3, *Wilto* is probably the Southern Cross (which includes two first magnitude stars), but this constellation is circumpolar when viewed from the Adelaide Plains and thus is rejected in this analysis.

6.4 *Wolta*

Two stars meet the criterion for heliacal rising in mid-December: Antares and Arcturus. Betelgeuse meets the criterion for acronycal rising, and Sirius marginally does. It should be noted that Arcturus, Antares and Betelgeuse are all visibly red stars, and this may somehow relate to the hot, dry season as red stars commonly relate to fire.

7 DISCUSSION AND CONCLUDING REMARKS

The identification of only one seasonal Kaurna star is supported by this study with multiple lines of evidence: *Parna*. *Parna* is identified as Fomalhaut, which meets the criteria and is at such a declination that it heliacally rises *and* sets at the same time of year—the start of the autumn season.

Additional circumstantial evidence is found by examining Ngarrindjeri traditions to the south, where the autumn stars *Marangani*/*Marangalkadi* (Western counterpart unidentified) are visible in the southeastern sky towards Mount Gambier. Autumn is the time of the crow (Australian Raven) and lasts from February to April (Berndt et al., 1993). Records of both the Kaurna and Ngarrindjeri indicate that they have four main seasons, each denoted by a star or group of stars (ibid.). This suggests that if these two groups possess some similarities in their astronomical traditions, *Parna* may also appear in the southeastern sky.

It should be emphasized that the Kaurna and Ngarrindjeri languages are very different, so traditions from both groups cannot be easily conflated. Therefore, without further supporting evidence, any connection is speculative. A more detailed study of Ngarrindjeri astronomical traditions will be the focus of future work.

Fomalhaut is found in the astronomical traditions of other Aboriginal cultures of Australia, though rarely (Clarke, 2007; Hamacher and Frew, 2010; Johnson, 1998):

- In Wotjobaluk (Wergaia) and Mara (Gunditjmara) traditions of western Victoria, Fomalhaut is the moiety eaglehawk (wedge-tailed eagle) ancestor (Massola, 1968), despite not being included in the detailed Boorong (Wergaia) study by Stanbridge (1861).
- In Wurundjeri traditions of central Victoria, Fomalhaut is *Bunjil*, the primary sky-hero and 'all father' (Dawson, 1881; Hartland, 1898; Howitt, 1884a; 1884b; Howitt, 1904), although *Bunjil* also relates to the star Altair (ibid.).
- In Bundjalung traditions of northern coastal NSW, Fomalhaut is *Bunnungar*, the 'frill-necked lizard' (Patston, 1997), a probable reference to the Eastern bearded dragon (*Pogona barbata*).
- Similarly, in Euahlayi traditions of north-central NSW, Fomalhaut is *Gani*, a 'small iguana' (Brough-Smyth, 1878; Ridley, 1875). This is probably a reference to a small species of goanna.
- In Wardaman traditions of the north-central Northern Territory, Fomalhaut is *Menggen*, the white cockatoo, whose feathers were used for ceremonial decoration (Cairns and Harney, 2003). *Menggen* watches over ceremonies and is part of a complex songline. Senior Wardaman custodian, Bill Yidumduma Harney, is from the *Menngen* (White Cockatoo) community.
- In the Torres Strait, Fomalhaut was called *Panauna graz* (Rivers, 1912), but no further details about its meaning are provided.[7]

In the records of Aboriginal astronomical traditions across Australia, some first magnitude stars are conspicuously absent. For example, the first magnitude stars omitted by Stanbridge (1861) in his study of Boorong (Wergaia) traditions of western Victoria are Procyon, Betelgeuse, Spica, Fomalhaut, Deneb and Regulus. Curiously, these are all potential seasonal stars described in this paper (see Table 4).

The Reverend Peter MacPherson (1881) provides a possible explanation for the omission of some of these first magnitude stars: Fomalhaut, Spica and Regulus (as well as Procyon) are 'isolated' stars that do not fit into any 'mechanical' grouping, an apparently common occurrence in the Aboriginal astronomical traditions of nearby western Victoria.

In this grouping process, MacPherson proposes that characters represented by stars of a particular family are either:

(1) grouped based upon their arrangement in the sky, specifically grouping three stars (or clusters) in a linear pattern;
(2) grouped into four linear arrangements that are roughly parallel to each other; or
(3) arranged roughly parallel to the horizon as they rise in the evening sky in their respecttive seasons at the latitude of the region (36° S) (after Hamacher and Frew, 2010).

Perhaps another reason these stars do not feature in Aboriginal traditions is that certain stars are considered secret and sacred. For example, an Aboriginal man was once pressed as to why Procyon was unnamed in his people's astronomical traditions, and he "… merely shook his head in a negative sort of way." (EKV, 1884).

Considering the diversity of Aboriginal cultures (over 350 distinct languages) and the length of time people have been in Australia (>50,000 years), relatively little research has been conducted on Aboriginal astronomical traditions, and much of that was recorded by amateur (and professional) ethnographers with limited astronomical training. It is possible that the omission of these stars reflects the incompleteness of recorded Aboriginal astronomical traditions. Hopefully, further research will shed light on this issue.

Using a combination of linguistic analysis, heliacal and acronycal rise-time calculations, seasonal weather data, and comparative studies of Aboriginal astronomical traditions, we attempted to identify Kaurna seasonal stars.

Only one star is supported by more than one line of evidence, and this is Fomalhaut, the autumn-star *Parna*. This star is uncommon in recorded Aboriginal astronomical traditions, which poses important considerations for future research.

8 NOTES

1. The term Kaurna was not used at the time of European colonisation to refer to the Aboriginal people of the Adelaide Plains. It was later popularized by Norman Tindale in the 1920s, resulting in its adaptation by Adelaide Plains traditional owners and its common usage today (see Amery, 2000; Clarke, 1997). A comprehensive database of information on the Kaurna language can be found at: www.mobilelanguageteam.com.au/languages/kaurna
2. Sometimes ethnographers conflate the terms ‘star’ and ‘constellation’, such as *Wayakka,* which is a Kaurna word for an unidentified star or constellation (Teichelmann and Schürmann, 1840).
3. In Aboriginal astronomical traditions across Australia, the stars of Orion’s Belt and scabbard commonly represent a group of boys or men and the Pleiades commonly represent a group of girls or women (see Clarke, 2007; Fuller, et al., 2014; Hamacher, 2012; Johnson, 1998; Leaman and Hamacher, 2014; Tindale, 1983). A detailed study of the Pleiades and Seven Sisters Dreamings in Aboriginal traditions is the focus of doctoral candidate Melissa Razuki at RMIT in Melbourne.
4. Weather data (1977–2014) for Adelaide are taken from: www.weatherzone.com.au/climate/station.jsp?lt=site&lc=23090
5. There are exceptions to this, as one would expect. But this tends to be the case overall.
6. Kaurna astronomical traditions are not well known to non-initiated Kaurna men, and only a small portion of these traditions have been recorded (Curnow, 2006).
7. *Panauna* was not defined or otherwise mentioned in any Torres Strait Islander records, but *graz* is a fishtrap or weir built of stones on a reef (Ray, 1907). This term was recorded on Mabuiag Island, suggesting it is from the Kalaw Lagaw Ya language.

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BURMESE ECLIPSE CALCULATIONS

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Abstract: Two Burmese eclipse calculations, one lunar and one solar, are analysed using examples from a Burmese manuscript. The fundamental parameters are with some important exceptions the same as in the *Suryasiddhanta*, but the handling of, for instance, parallax in the solar eclipse is different and much simplified. Specific to Burma are also the shadow calculations.

Keywords: Burmese astronomy, eclipse calculations, eclipse parallax.

1 INTRODUCTION

The traditional astronomical calculation procedures in Southeast Asia are little known in the West. Although they clearly show a great influence from traditional methods in India, their actual implementation is very different. The procedures are laid out as a kind of computer program, a set of rules without explanation that once followed, generate a set of numbers that describe the astronomical phenomenon in question. Clearly, this set of rules has been established by some competent agent who knew very well their astronomical background but who intended the rules to be used by other agents whose only function was to compute by rote. This presents some difficulties for the analysis as many of the intermediate steps in the calculation are omitted and have to be reconstructed.

There are many clever calculation shortcuts, as will be seen below. The parallax calculation procedures, for instance, are extremely simplified but still quite adequate. In an earlier paper (Gislén and Eade, 2014) we explained the Burmese shadow calculations, and they will reappear in the present paper and will vindicate the conclusions we made there.

2 THE SOURCE

The main source for this investigation is a Burmese astrology dissertation (U Thar-Tha-Na, 1937).

3 PARAMETERS

Hindu and Southeast Asian astronomers use sidereal longitudes, i.e. longitudes measured eastward along the ecliptic from a fixed origin on the ecliptic. Modern astronomy uses tropical longitudes where this origin is slowly moving westward along the ecliptic due to precession and is determined as the point on the ecliptic where the Sun crosses the celestial equator on the vernal equinox. In Hindu astronomy the fixed origin for longitude is the point where the mean Sun, the mean Moon and the mean planets were assumed to gathered together at the start of the Kaliyuga epoch, which was midnight on 18 February 3102 BCE.

The [Old] *Suryasiddhanta* has 1577917800 days in 4320000 solar revolutions, the *Kaliyuga*. As is usual in Southeast Asian astronomy these numbers are divided by 5400 to have the more handy 292207 days in 800 years. In the Burmese *Thandeikhta* scheme (Irwin, 1909), used in the calculations, this is corrected by 28 extra days (4320000/193/800) in a *Kaliyuga*, making the mean solar theory precisely that of the modern Hindu *Suryasiddhanta*.

The longitude of the solar apogee, the point on the ecliptic where the solar longitude is such that the distance between the Sun and the Earth is largest, is assumed to be 4640′. The apogee value (*mandocca*) in modern *Suryasiddhanta* is 4636′.

The Moon is assumed to make 5775336 revolutions in a *Kaliyuga* or exactly 7219167′ in 25 years. The mean daily motion of the Moon is then 790.5811288′ ≈ 790′ 35″. These are *Suryasiddhanta* values.

The lunar apogee is as in *Suryasiddhanta* (without *bija*) and makes 488203 revolutions in 4230000 solar years or precisely 488203′ in 200 years. The daily motion is then 6.682974624′ ≈ 6′ 41″.

The lunar node is as in *Suryasiddhanta* (with *bija*) and makes 232242 retrograde revolutions in a *Kaliyuga* or precisely 116121′ in 100 years or 3.179143493′ ≈ 3′ 11″ per day.

The epoch of *Thandeikhta* is BE (Burmese Era) 1100.

The calculations are made for *Amarapura* (Mandalay) with a geographical latitude given as 21° 32′.

For the Moon, the lunar apogee, and the lunar node, the epoch is *Kaliyuga* 0 (i.e. midnight on 18 February 3101 BCE). The Moon has an extra epoch correction of –12′ as compared with *Suryasiddhanta*. This could be a way to account for the difference in geographical longitude between India and Burma. The lunar apogee is assumed to have a *Kaliyuga* epoch value of 5140′ and the lunar node has an epoch value of 10945′. The *Suryasiddhanta* values are 5400′ and 10800′ respectively.

4 UNITS AND NOTATION

The time unit used in Southeast Asia is the *nadi* (Burmese *nayi*) that is 1/60 of a day and night. The *nadi* is further divided into 60 *vinadis* (Burmese *bizana*). A hexadecimal notation is used: xx:yy, meaning xx + yy/60. For longitudes the same notation means arc minutes and arc seconds. We sometimes use the notation xx:yy:zz for signs, degrees, minutes. The Burmese calculations are presented in grids that we denote by A, B, C … Within each grid we give the column number and the row number. Thus [B 2,8] denotes grid B, column 2, and row 5. The transcribed grids are given in the Appendix. The Burmese grids have labels specifying the different numbers, some of these labels can be identified as somewhat distorted Sanskrit or Pali words but most labels are obscure Burmese technical terms.

5 LUNAR ECLIPSE CALCULATION

5.1 Preliminaries

One of the model calculations made in the source is the partial lunar eclipse of 26 July 1934. The input for the calculation is the BE year (1296) and the *sutin* (102), the elapsed days of the Burmese year. The Burmese calculations are typically arranged such that all operations involve entire numbers. The Burmese division algorithm is rather involved and for this we have used Western notation instead without affecting the final result. In two cases we have used decimal notation for simplicity.

First the *thawana*, the elapsed days since the *Thandeikhta* epoch BE 1100, is calculated (Irwin, 1909: 16) by:

{(y – 1100)·292207 + 17742 + int((y – 1100)/193)}/800 = a + b/800

292207 = 1577917800/5400 is the number of uncorrected days in 4320000/5400 = 800 solar years. It is a standard number in Southeast Asian calendar computations (Eade, 1995).

int(x) means the integer part of the number x. This term gives an extra correction of 28 days in a *Kaliyuga*.

y is the Burmese year, and *a* the integer part of the division and *b* the remainder. The New Year *thawana* then is *a* + 1.

The New Year weekday is given by the remainder of (*thawana* – 2)/7 with 1 = Sunday. 800 – *b* is the *kyammat*, the mean solar longitude at the New Year midnight (24 hours) expressed in 800 parts of a mean solar day. The *Kaliyuga* year is the Burmese year + 3739.

Thus we have

[A 1,1] 1296, the Burmese year.
[A 1,2] 1296 + 3739 = 5035, the *Kaliyuga* year.
(196·292207 + 17742 + 1)/800 = 71612 + 715/800
[A 1,3] 800 – 715 = 85, the New Year *kyammat.*
thawana = 71612 + 1 = 71613
[A 1,4] (71613 – 2)/7 = 10230 + 1/7, the New Year weekday = 1, Sunday.
[A 1,5] 102, the *sutin.*

5.2 Mean Solar Longitude

The total elapsed *kyammat* at midnight on the New Year is 85. To this we add the *kyammat* resulting from the elapsed days from the New Year to the eclipse day, 102, the *sutin*. Each day corresponds to a *kyammat* of 800. Thus we have in total 85 + 102·800 = 81685. Now the mean daily motion of the Sun in arc minutes is 21600·800/292207 = 59:8′. By multiplying the *kyammat* by 21600 and dividing by 292207 we arrive at the mean solar longitude in arc minutes, skipping whole rotations (21600) if possible: 6038:10 [A 1,6].

5.3 Mean Lunar Longitude

Multiply the *Kaliyuga* year by 7219167, the motion of the mean Moon in arc minutes in 25 years and divide by 25. Skip whole rotations. The result is 1033:48. Subtract the epoch correction of 12′ to get 1021:48. This is the New Year mean position.

For the mean daily motion we use 79058′ in 100 days. The correct value is 79058.11287. This introduces an error 79058.11287 – 79058 = 0.11287 ≈ 1/9 in 100 days. The *kyammat* gives a contribution 85·79058/800/100 = 84:0. The *sutin* gives a contribution 102·79058/100 = 80639:9.6. The extra correction gives 102·(1/9)/100 = 0:6.6. In total 80723:16, with rounding. Adding the New Year longitude and skipping whole rotations we finally get 16945:4 [A 1,7].

5.4 Lunar Apogee

Multiply the *Kaliyuga* year by 488203, the motion of the lunar apogee in 200 years and divide by 200. The result is 12290510:31. Add the epoch value 5140 and skip whole rotations to get 5250:31. For the mean daily motion during 101 days we use 675. The correct value is 6.682974624·101 = 674.980437. The error is 674.980437 – 675 = –0.019563 ≈ –1/51 in 101 days. The *kyammat* gives a contribution 85·675/800/101 = 0:43. The *sutin* gives a contribution 102·675/101 = 681:41. The extra correction gives –102·(1/51)/101 = –0:1. In total 682:23. Adding the New Year longitude and skipping whole rotations we finally get 5932:54 [A 1,8]. The source has 5932:53, either a typo or the result of a different rounding.

5.5 Lunar Node

Multiply the *Kaliyuga* year by 116121, the motion of the lunar node in 100 years and divide by

100. The result is 5846692:21. Add the epoch value 10945 and skip whole rotations to get 4037:21. For the mean daily motion during 100 days we use 318. The correct value is 317.9143493. The error is 317.9143493 – 318 = –0.0857 ≈ –1/12 in 100 days. The *kyammat* gives a contribution 85·318/800/100 = 0:20. The *sutin* gives a contribution 102·318/100 = 324:22. The extra correction gives –102·(1/12)/100 = –0:5. In total 324:37. Adding the New Year longitude and skipping whole rotations we finally get 4361:58 [A 1,9].

5.6 True Longitudes

The true longitudes are calculated from

$$\lambda = \lambda_M + e\cdot\sin(\omega - \lambda_M) \qquad (1)$$

where λ is the true longitude, λ_M the mean longitude, ω the apogee longitude and e the eccentricity.

This expression uses a constant eccentricity, a difference from *Suryasiddhanta* that uses an eccentricity dimension that varies with the anomaly. For the Sun the *Suryasiddhanta* dimensions of the epicycle vary between 14° and 13:40° (Burgess, 2000: 70). The Burmese calculation uses a fixed dimension that corresponds to 13:44°. For the Moon the *Suryasiddhanta* epicycle dimension varies between 32° and 31:40° (ibid.) while the Burmese dimension is fixed at 31:44°.

The second term of the formula, the equation, is taken from Table 1 (Solar *chaya)* with argument in steps of 10°. The anomaly $\alpha = \omega - \lambda_M$ is reduced to lie in the interval [0 , 90°] using the symmetry of the sine function, i.e.

If 0′< α ≤ 5400′ do nothing Quadrant 0
If 5400′ < α ≤ 10800′ replace α with 10800′ – α. Quadrant 1
If 10800′ < α ≤ 16200′ replace α with α – 10800′ Quadrant 2
If 16200′ < α ≤ 21600′ replace α with 21600′ – α Quadrant 3

The equation is positive for anomaly in quadrants 0 and 1, otherwise negative.

For the Sun we have the fixed value of the apogee ω = 4640′ and with λ_M = 6038′ [A 6,1] and get an anomaly of 4640 – 6038 = –1398. As this is negative we add a whole turn, 21600′, to get 21600 – 1398 = 20202.

This anomaly is in quadrant 3, [A, 1,10] and the reduced value is 21600 – 20202 = 1398′. Each 10° interval corresponds to 600′ so the entry point in the table is 1398/600 = 2 + 198/600. Interpolation in the table gives the equation

45 + (66 – 45)·198/600 = 51:56 [A 2,1].

Table 1: Solar *chaya*.

Arg/10	0	1	2	3	4	5	6	7	8	9
Equation	0	23	45	66	85	101	113	123	129	131

The table difference 66 – 45 = 21 [A 1,11] is saved for the computation of the true daily motion of the Sun below. As we are in quadrant 3, the equation is subtractive and we get the true solar longitude

6038:10 – 51:56 = 5986:14 [A 2,2].

For the Moon we have ω = 5932:53 [A 1,8] and λ_M 16945:4 [A 1,7]. The Moon's mean longitude is given an extra correction of the solar equation (including sign) divided by 27, in our case –51:56/27 = –1:55. We have no explanation for this correction.

The corrected mean longitude is then 16945 – 1:55 = 16943:9 [A 2,3]. Thus the corrected anomaly is 5932:53 – 16943:9 + 21600 = 10589:44. This is in quadrant 1 [A 2,4], and the reduced anomaly is 10800 – 10589:44 = 210:16 ≈ 210.

With the same procedure as for the Sun, but with a lunar *chaya* (Table 2), we get a difference of 53 [A 2, 5], and an equation of +18:34.

The true longitude is then 16943:9 + 18:34 = 16961:43 [A 2,6].

The motion of the node is retrograde and its longitude is 21600 – 4361:58 = 17238:2 [A 2,7].

5.7 True Daily Motions

The mean daily motion of the Sun is 59:8 [A 2,8].

Using the table difference in [A 1,11] we compute the difference correction to the mean motion: 59:8·21/600 = 2:4.

The correction is positive for the anomaly in [90°, 270°], quadrants 1 and 2, otherwise negative. The true daily motion of the Sun is thus 59:8 – 2:4 = 57:4 [A 2,10].

The correctness of this procedure can be seen by taking the time derivative of the true longitude equation: $d\lambda/dt = d\lambda_M/dt + d(e\cdot\sin\alpha)/d\alpha\cdot d\alpha/dt$. Here, $d\lambda/dt$ is the true daily motion in longitude, $d\lambda_M/dt$ the mean daily motion in longitude, $d(e\cdot\sin\alpha)/d\alpha$ is the *chaya* table difference, and $d\alpha/dt$ the mean daily change in anomaly.

As the apogee of the Sun is fixed, its motion in anomaly is the same as the mean motion.

The mean daily motion of the Moon is 790:35 [A 2,9]. For the Moon we use the table difference

Table 2: Lunar *chaya*.

Arg/10	0	1	2	3	4	5	6	7	8	9
Equation	0	53	104	152	195	232	262	285	298	303

Table 3: Excess day time.

Sign				Excess
0	6		12	0
1	5	7	11	48
2	4	8	10	86
3		9		102

ence [A 2,5] and a mean motion of the anomaly that is the difference between the mean lunar motion and the motion of the apogee 790:35 – 6:41 = 783:54. The correction to the mean motion is then 783:54·53/600 = 69:15. As we are in quadrant 1 the correction is positive. True daily lunar motion 790:35 + 69:15 = 859:50 [A 2,11].

The daily motion of the node is 3:11 (retrograde) [A 3,1].

The true daily motion in elongation is 859:50 – 57:4 = 802:46 = 48166 [A 3,2]. The last number comes from multiplying 802:46 by 60.

5.8 Precession

The precession is identical with the one used in Hindu astronomy. It is a zigzag function with a period of 7200 years and an amplitude of 27° = 1620′ = 1800·9/10. The precession is positive from AD 412 to AD 2212.

Add the epoch value 88 to the *Kaliyuga* year and divide by 1800: (5035 + 88)/1800 = 2 + 1523/1800. The number 2 [A 3, 3] tells us that the precession is positive and has the value 1523·9/10 = 1370:42 [A 3,4]. The tropical true solar longitude is thus 5986:14 + 1370:42 = 122° 37′ = 4:2:37 [A 3,5]. The tropical true lunar longitude is thus 16961:43 + 1370:42 = 305° 32′ = 10:5:32 [A 3,6].

5.9 Length of Day and Night

Again a table is used for this calculation. Table 3 gives the varying excess day times in *vinadis* over the mean half day of 15 *nadis*. For zodiacal signs above 6 the excess is negative. The solar tropical longitude is 4:2:37. Interpolating in the table gives 86 – (86 – 48)·2:37/30 ≈ 82 = 1:22.

A half day is then 15 + 1:22 = 16:22 [A 3,7].
A half night is 30 – 16:22 = 13:38 [A 3,8].
A quarter day is 8:11 [A 3,9].
A quarter night is 6:49 [A 3,10].

5.10 Noon Shadow

The equinoctial shadow for a location with geographical latitude φ is given by

Table 4: Shadow table.

Sign		Excess	Sign		Excess
0	6	0	6	12	0
1	5	92	7	11	110
2	4	159	8	10	214
3		183	9		262

$$S_{eq} = G \tan\varphi \qquad (2)$$

where G is the height of the gnomon, in Burmese astronomy taken as 420 units or 7:0. The noon shadow at another date is

$$S_{noon} = G \tan(\varphi - \delta) \qquad (3)$$

where δ is the declination of the luminary. The Burmese method is to state the equinoctial shadow for the particular location, for *Amarapura* 165 (S_{eq} = 420 tan (21:32) ≈ 165), and then a table of the quantity $|G \tan(\varphi - \delta) - G \tan\varphi|$ for different zodiacal signs. For *Amarapura* we have Table 4.

Using the table with the Sun we have the tropical true longitude 4:2:37. Interpolating in the table gives 159 – (159 – 92)·2:37/30 = 153. Subtracting this from the equinoctial shadow gives 165 – 153 = 12. Thus the solar noon shadow is 0:12 [A 3,11].

The Moon has a true tropical longitude of 10:5:32. Again interpolation gives 214 – (214 – 110)·5:32/30 = 194. In this case we add the equinoctial shadow and the table number to get the Moon ‘noon’ shadow: 165 + 194 = 359 = 5:59 [A 3,11].

The reason for calculating both the solar and lunar noon shadow is, as we will see, that this eclipse starts before sunset.

5.11 Conjunction Time

The longitude of the Earth’s shadow will be exactly 180° away from the Sun. In our case we get 5986:14 + 10800 = 16786:14 [B 1,1].

The longitude of the Moon is 16961:43, thus it has moved 16961:43 – 16786:14 = 175:29 too far. This is converted into time using the daily motion in elongation, 175:29·3600/48166 = 13:7 *nadis before* midnight (24 hours) [B 1,2]. This is 30 – 13:7 = 16:53 *after* noon [B 1,3]. The Moon will move 859:50·13:7/60 = 187:58 backwards during this time and have an opposition longitude of 16961:43 – 187:58 = 16773:45 [B 1,4].

In the same way we can calculate the opposition position of the node, remembering its retrograde motion, and get 17238:44 [B 1,5]. The Moon has not yet reached the ascending node and its latitude is south. The number 0 [B 1,6] is the quadrant relative to the ascending node: (17238:44 – 16773:45)/5400 = 0: 464:59. The number 464:59 is the distance of the Moon from the ascending node.

5.12 Latitude of the Moon

The inclination of the lunar orbit in many Indian texts is taken as 4.5°. In the neighbourhood of the node we can approximate a spherical triangle by a planar one and get the lunar latitude by multiplying the distance from the node by tan(4.5°) = 0.0787 ≈ 1/12.7. Some Southeast Asian astronomical schemes use the small angle approximation of the tangent function tan(4.5) = tan(9°/2) ≈ 9/2·π/180 ≈ 9/2·3/180 = 9/2·1/60 ≈ 1/13.3 (Faraut, 1910; Gislén and Eade, 2001; Wisandarukorn, 1997). The Burmese scheme uses the factor 1/13 that may be a rounded value of either of these previous numbers. In the present case the distance from the node is 464:59, thus the latitude is 464:59/13 = 35:46 [B 1,7]. There can be an eclipse only if the distance of the Moon from the node is less than about 10°. The resulting difference in latitude between the above schemes is less than about 1 arc minute.

5.13 Diameters and Radii

As in Hindu astronomy, the diameter of the luminaries is assumed to be proportional to their true daily motions with a mean diameter of 31′. The diameter of the shadow is taken as 2.5 times the lunar diameter, a value also used in other Southeast Asian schemes (Gislen and Eade, 2001).

Diameter of the Moon 31·859:50/790:35 = 33:43 [B 1,8].
Diameter of the shadow 33:43·2:30 = 84:18 [B 2,1].
Sum of the radii (84:18 + 33:43)/2 = 59: 1 [B 2,2].
Difference of radii (84:18 – 33:43)/2 = 25:18 [B 2,3].
Eclipsed part 59:1 – 35:46 = 23:15 [B 2,4].
Crescent 33:43 [B 1,7] – 23:15 = 10:28 [B 2,5].

5.14 Eclipse Duration

$(59{:}\,1\cdot 60)^2$ = 12538681 [B 3,5].
$(35{:}46\cdot 60)^2$ = 4605316 [B 3,6].
$(25{:}18\cdot 60)^2$ = 2304324 [B 3,7].
This is smaller than the number on the row above, thus the eclipse is partial.
$\sqrt{(59.1\cdot 60)^2 - (35{:}46\cdot 60)^2}$ = 2816:37

See Figure 1 for the geometry.

We convert this value to time using the daily motion in elongation 2816·60/48166 = 3:30 [B 2,6], the preliminary half duration.

5.15 Correction for the Change in Latitude During the Eclipse

The relative daily motion of the Moon relative to the node is 859:50 + 3:11 = 863:1.
This motion during 3:30 *nadis* is 863:1·3:30/60 = 50:21.
The change in latitude is 50:21/13 = 3:52.
The Moon is approaching the ascending node. Thus its south latitude decreases during the eclipse.
The latitude at the start of the eclipse is 35:46 + 3:52 = 39:38 (south) [B 2,7].
The latitude at the end of the eclipse is 35:46 – 3:52 = 31:54 (south) [B 2,8].

The eclipsed part is 59:1 – 39:38 = 19:23 [B 3,1] and 59:1 – 31:54 = 27:7 [B 3,2] respectively.
$(39{:}38\cdot 60)^2$ = 5654884 [B 3,8].
$(31{:}54\cdot 69)^2$ = 3663396. This number is written below grid B.

The formula $R + r - \beta$, used for the 'eclipsed part' above, is only correct at the conjunction. The correct formula to use is $R + r - \sqrt{(\beta^2 + \Delta^2)}$, where Δ is the Moon's distance from the conjunction longitude. The numbers in [B 3,1] and [B 3,2] are purely nominal.

5.16 Corrected Duration Times

We repeat the duration calculations with the new set of latitudes. The duration from the start to the middle eclipse is then 3:16 [B 3,3] and from the middle eclipse to the end, 3:43 [B 3,4]. In the *Suryasiddhanta* scheme this iteration is repeated several times.

5.17 Eclipse Times

Start of the eclipse 16:53 – 3:16 = 13:37 after noon [C 1,1]. This is before sunset as the half day length is 16:22.

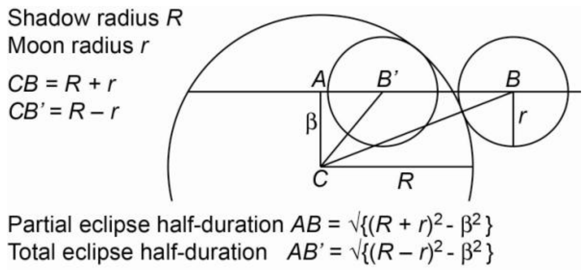

Figure 1: Eclipse geometry.

Middle eclipse 16:53 after noon [C 1,2], shortly after sunset.
End of the eclipse 16:53 + 3:43 = 20:36 after noon [C 1,3].
13:37 – 8:11 (quarter day) [A 3,9] = 5:26 [C 2,1].
The middle eclipse is 16:53 – 16:22 = 0:31 after sunset [C 2,2].
The end of the eclipse is 20:36 – 16:22 = 4:14 after sunset [C 2,3].

Column [C3] contains the times converted to Western hour:minute:second. This is done by multiplying the times in *nadis* by 2/5.

13:37·2/5 = 05:26:48 (p.m.) [C 3,1].
16:53·2/5 = 06:45:20 [C 3,2].
20:36·2/5 = 08:14:24 [C 3,3].

Modern calculations give 05:24 p.m., 06:51 p.m., and 08:6 p.m. respectively, local true solar time.

5.18 Shadow Calculations

The Burmese method of calculating shadows for times other than noon/midnight is based on the following model. At noon the deviation from the

Table 5: Multipliers.

Nadis		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Capricorn		61	124	168	216	251	280	307	325	338	345	349	350	325			
Aquarius	Sagittarius	63	133	176	220	250	280	305	321	331	335	337	337	310			
Pisces	Scorpio	79	134	187	232	267	291	309	320	324	325	320	312	301	288		
Aries	Libra	89	162	236	283	312	330	339	340	335	328	317	303	286	267	268	
Taurus	Virgo	178	304	363	395	408	415	402	391	375	313	338	318	296	309	251	
Gemini	Leo	571	599	582	563	590	509	484	456	430	409	375	349	322	301	270	229
Cancer		455	522	539	530	515	494	471	450	427	402	372	351	326	302	267	241

noon shadow has to be zero. At set/rise the deviation is infinite. A mathematical function with the required behaviour is

$(H{\cdot}M)/(D - \mathrm{H})$

or the equivalent expression

$(D{\cdot}M)/(D - H) - M$

where H is the time from noon/midnight, D is the length of a half day/night, and M is a suitably chosen multiplier. Actually this multiplier is a rather complicated function of H, the geographical latitude of the location and the tropical longitude of the luminary. Ignoring the rather weak geographical latitude dependence, we arrive at a multiplier, that depends on two arguments: H and the tropical longitude of the luminary. A table with such multipliers is given in the present and several other Burmese sources (Gislén and Eade, 2014); see Table 5 above.

When using the table, only the zodiacal sign is used and H is rounded to the nearest *nadi*; there is no interpolation involved. The total shadow, S, will then be

$$S = S_{noon} + (D{\cdot}M)/(D - H) - M \qquad (4)$$

Grid D treats the shadow calculations. Column [D 1] shows a solar shadow calculation as the Sun has not yet set at the start of the eclipse and the Moon is below the horizon. [D 2] and [D 3] are lunar shadow calculations. We have

Start eclipse:

The solar tropical longitude is 4:2:37 [A 3,5].
D = 16:22 = 982.
H =13:37 from solar noon = 817 [D 1,1], [D 1,2].
Zodiacal sign = 4 (Sun) H = 14 gives M = 301 [D 1,3].
$D{\cdot}M$ = 982 × 301 = 295582 [D 1,4].
$D - H$ = 982 – 817 = 165 [D 1,5].
S_{noon} = 0;12 = 12 from [A 3,11].

Shadow:

$S = S_{noon} + (D{\cdot}M)/(D - H) - M$ = 12 + 1791 – 301 = 1502 = 25:2 [D 1,6].

Middle eclipse:

The lunar tropical longitude is 10:5:32 [A 3,6].
The time is 0:31 from sunset [D 2,1].
The time is 16:53 from solar noon, H = 30 – 16:53 = 13:7 = 787 from midnight [D 2,2].
D = 13:38 = 818 (half night).
Zodiacal sign = 10, H = 13 gives M = 310 [D 2,3].
$D{\cdot}M$ = 818 × 310 = 253580 [D 2,4].
$D - H$ = 818 – 787 = 31 [D 2,5].
S_{noon} = 5:59 = 359 from [A 3,11].
$S = S_{noon} + (D{\cdot}M)/(D - H) - M$ = 359 + 8180 – 310 = 8229 = 137:9 [D 2,6].

End eclipse:

The time is 4:14 from sunset [D 3,1].
The time is 20:36 from solar noon, H = 30 – 20:36 = 9:24 = 564 from midnight [D 3,2].
Zodiacal sign = 10, H = 9 gives M = 331 [D 3,3].
$D{\cdot}M$ = 818 × 331 = 270758 [D 3,4].
$D - H$ = 818 – 564 = 254 [D 3,5].
S_{noon} = 5:59 = 359 from [A 3,11].
$S = S_{noon} + (D{\cdot}M)/(D - H) - M$ = 359 + 1066 – 331 = 1094 = 18:14 [D 3,6].

6 SOLAR ECLIPSE CALCULATION

The solar eclipse calculation example is for the annular eclipse on BE 1295, *sutin* 128, 21 August 1933. By coincidence this eclipse is also calculated for Calcutta (Burgess, 2000: 392g). The procedures for calculating the longitudes are the same as for a lunar eclipse but the *kyammat* is reduced by 400 in the calculations in order to get the longitudes at noon. In Burma the eclipse was partial.

For grid A, we only give the numbers without a detailed derivation.

6.1 Fundamental Data

[A 1,1] The Burmese year, 1295.
[A 1,2] The *Kaliyuga* year, 5034.
[A 1,3] The New Year *kyammat*, 292.
[A 1,4] The New Year weekday, 0, Saturday.
[A 1,5] The *sutin*, 128.

6.2 Mean Longitudes

[A 1,6] Mean solar longitude, 7561:27.
[A 1,7] Mean lunar longitude, 7742:47.
[A 1,8] Lunar apogee, 3664:2.
[A 1,9] Lunar node, 3242:38.

6.3 True Longitudes

[A 1,10] Quadrant 3 for the solar equation.
[A 1,11] Difference in solar equation table, 16.
[A 2,1] Solar equation, 98:54, negative.
[A 2,2] Solar true longitude, 7462:33.
[A 2,3] Lunar mean longitude corrected by –98:54 / 27, gives 7739:7.

[A 2,4] Quadrant 3 for the lunar equation.
[A 2,5] Difference in lunar equation table, 24.
[A 2,6] Lunar equation 280:13, negative.
[A 2,7] True lunar longitude, 7458:54.
[A 2,8] Lunar node, 21600 – 3242:38 = 18317:22.

6.4 True Daily Motions

[A 2,9] Mean solar daily motion, 59:8.
[A 2,10] Mean lunar daily motion 790:35.
[A 2,11] True solar daily motion, 57:33.
[A 3,1] True lunar daily motion, 760:32.
[A 3,2] Daily motion of the node, retrograde, 3:11.
[A 3,3] True daily motion in elongation, 42179.

6.5 Precession, Day Length and Noon Shadow

[A 3,4] Quadrant for precession, 2.
[A 3,5] Precession, positive, 1369:48.
[A 3,6] True solar tropical longitude, 147° 12′ = 4:27:12.
[A 3,7] Half day, 15:52.
[A 3,8] Half night 14:8.
[A 3,9] Quarter day, 7:56.
[A 3,10] Quarter night, 7:4.
[A 3,11] Solar noon shadow, 1:7.

6.6 Parallax of the Middle Eclipse

The difference in longitude between the Sun and the Moon at noon is 7462:33 – 7458:54 = 3:39. This is the distance the Moon still has to travel. We convert this into time using the daily motion in elongation [A 3,3]: 3:39·3600/42179 = 0:19 *nadis* [B 1,1]. This is the time of the true conjunction after noon. The time after midnight is 30 + 0:19 = 30:19 [B 1,2].

The procedure used to calculate the parallax in longitude (time) is to take the true conjunction time after noon and express it in *vinadis*, v. The parallax in *nadis*, n, is then computed from the formula

$$n = (7\cdot v)/(600 + |v|), \quad (5)$$

$|v|$ being the positive value of v.

The correct parallax is a complicated function of the latitude of the luminary, the time of day, and geographical latitude. However, the formula above gives a surprisingly good approximation to the true parallax at least for locations not too far from the equator (see below). For times before noon the parallax correction in longitude is negative. Applying the formula with 19 *vinadis* above, we arrive at the longitudinal parallax (in time measure) of 0:13 [B 1,3]. Thus the true apparent conjunction time, corrected for parallax is at 0:19 + 0:13 = 0:32 [B 1,4] after noon.

During the time from noon the Moon moves 0:32·760:32/60 = 6:46 [B 1,5]. The movement of the node is in the same way 0:2, backwards [B 1,6]. The longitude of the Moon is then

Table 6: Declination table.

λ_N	0	10	20	30	40	50	60	70	80	90
δ_N	0	4	8	12	15	18	20	22	23	24

7465:40 [B 1,7], and of the node 17317:20 [B 1,8].

The descending node is at 17317:20 – 10800 = 6517:20. The Moon has not reached the descending node; its longitude is still north. Relative to the ascending node it is in quadrant 1 [B 1,9]. The distance from the descending node is 51:40, giving a latitude of 51:40/13 = 3:58 (north) [B 1,10].

The procedure for calculating the parallax in latitude is as follows. The time in *nadis* of the apparent conjunction after noon is multiplied by 6 in order to convert it to degrees (360° = 60 *nadis*). The result is then added to the true tropical longitude of the Sun. The result is an approximation to the longitude of the *nonagesimal*, λ_N, the highest point of the ecliptic. From Table 6 we then calculate the declination of the *nonagesimal*, δ_N. The table uses the standard Southeast Asian value of 24° for the obliquity of the ecliptic. The table is based on the formula $\sin \delta_N = \sin 24° \cdot \sin \lambda_N$.

In our case we have λ_N = 147° 12′ + 6·0:32 = 150° 24′. Reducing to the first quadrant we get by interpolation δ_N = 11° 50′ [B 1,11], positive.

The parallax in latitude is then

$$\pi_\beta = 49' \sin(\delta_N - \varphi) \quad (6)$$

where φ = 21° 32′ is the actual geographical latitude. The value, 49′, is the effective horizontal parallax of the Moon and the Sun used in Southeast Asian astronomy. This is also the mean value used in *Suryasiddhanta* (Burgess, 2000(V): 11).

We have $\delta_N - \varphi$ = 11° 50′ – 21° 32′ = –9° 42′ [B 1,12]. The parallax is taken from a new table (Table 7); we get by interpolation 7:45, negative [B 1,13].

The latitude corrected for parallax is then 3:58 – 7:45 = –3:47 (south) [B 1,14].

6.7 Diameters and Radii

[B 2,1] True diameter of the Sun, 30:10.
[B 2,2] True diameter of the shadow (Moon), 29:49 .
[B 2,3] Sum of radii, 29:59.
[B 2,4] Difference of radii, 0:10.
[B 2,5] Eclipsed part, 26:12.

Table 7: Parallax table.

$\delta_N - \varphi$	0	10	20	30	40	50	60	70	80	90
π_β	0	8	17	24	31	37	42	46	48	49

6.8 Preliminary Data for the Beginning and End of the Eclipse

[E 1,1] Square of sum of radii, $(29{:}59{\cdot}60)^2$ = 3236401.
[E 1,2] Square of middle apparent latitude $(3{:}47{\cdot}60)^2$ = 51529.
[E 2,1] Square root of the difference: 1785.
[B 2,6] Convert to time 1785·60/42179 = 2:32, preliminary half duration.

During this time the Moon moves relative to the node 2:32·(760:32 + 3:11)/60 = 32:15.
This corresponds to a change in latitude of 32:15/13 = 2:28. During the eclipse the lunar latitude will decrease as the Moon is approaching the descending node.
The true latitude at the beginning is 3:58 + 2:28 = 6:26 (north) [B 2,7].
The true latitude at the end is 3:58 – 2:28 = 1:30 (north) [B 2,8].
Preliminary time of the beginning 0:32 – 2:32 = –2:0, before noon [B 2,9].
Preliminary time of the end 0:32 + 2:32 = 3:4, after noon [B 2,10].

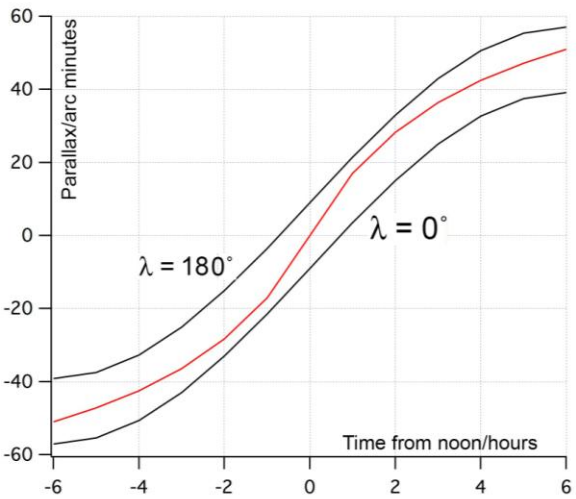

Figure 2: Parallax in longitude.

6.9 Latitude Parallax Corrections

Repeating the procedures for parallax in latitude we have:
Nonagesimal longitude at the beginning 147° 12′ – 6·2:0 = 135° 12′.
Nonagesimal declination 16° 26′ [B 2, 11].
Nonagesimal longitude at the end 147° 12′ + 6·3:4 = 165° 36′.
Nonagesimal declination 5° 45′ [B 2, 12].
Argument for beginning parallax 16° 26′ – 21° 32′ = –5° 6′ (south) [B 2,13].
Argument for end parallax 5° 45′ – 21° 32′ = –15° 47′ (south) [B 2,14].
Parallax correction at the beginning 4:4 (south) [B 3,1].
Parallax correction at the end 13:12 (south) [B 3,2].
Apparent latitude at the beginning 6:26 – 4:4 = 2:22 (north) [B 3,3].
Apparent latitude at the end 1:30 – 13:12 = –11:42 (south) [B 3,4].

6.10 Time Corrections

[E 1,3] Square of latitude at the beginning $(2{:}22{\cdot}60)^2$ = 20164.
[E 1,4] Square of latitude at the end $(11{:}42{\cdot}60)^2$ = 492804.
[E 2,3] $\sqrt{3236401 - 20164}$ = 1793. Beginning of the eclipse.
[E 2,4] $\sqrt{3236401 - 492804}$ = 1656. End of the eclipse.
[B 3,5] Eclipsed part at the beginning 29:59 – 2:22 = 27:37.
[B 3,6] Eclipsed part at the end 29:59 – 11:42 = 18:17.
[B 3,7] Conversion to time from the true conjunction 1793·60/42179 = 2:33.
[B 3,8] Conversion to time from the true conjunction 1656·60/42179 = 2:21.
[B 3,9] 30:19 – 2:33 = 27:46, time from midnight
[B 3,10] 30:19 + 2:21 = 32:40, time from midnight

As counted from noon the times in [B 3,7] and [B 3,8] become
[B 3,11] 2:33 – 0:19 = 2:14 = 134
[B 3,12] 2:21 + 0:19 = 2:40 = 160

Using the formula (1) to compute the longitudinal parallax correction we get
[B 3,13] 1:17
[B 3,14] 1:28
The total duration of the beginning phase is then 2:14 + 1:17 = 3:31 and of the end phase 2:40 + 1:28 = 4:8.

[C 1,1] Beginning of the eclipse after midnight 30:0 – 3:31 = 26:29.
[C 1,2] Middle eclipse 30:32.
[C 1,3] End of the eclipse 30:0 + 4:8 = 34:8.

[C 2,1] Quarter day – beginning phase = 7:56 – 3:31 = 4:25.
[C 2,2] Middle time from noon 0:32.
[C 2,3] End time from noon 4:8.

[C 3,1] Western time of the beginning 10:35:36
[C 3,2] Western time of the middle 12:12:48
[C 3,1] Western time of the end 1:39:12

Modern calculations give 10:23 a.m., 12:7 a.m., and 1:43 p.m. respectively, local true solar time.

6.11 Grid D, Shadow Calculations

The tropical longitude of the Sun is 147° 12′, zodiacal sign 4.
Half day D = 15:52 = 952.
[D 1,1] The time of the beginning from sunrise 15:52 – 3:31 = 12:21
[D 1,2] The time of the beginning before noon 3:31.
[D 1,3] H = 3:31 = 211, sign 4, 4 *nadis* gives

M = 563.
[D 1,4] $D·M$ = 952·563 = 535976.
[D 1,5] $D – H$ = 952 – 211 = 741.
[D 1,6] Shadow 3:47.

[D 2,1] The time of the middle eclipse from noon 0:32
[D 2,2] The time of the middle eclipse after noon 0:32.
[D 2,3] H = 0:32 = 32, sign 4, 1 *nadi* gives M = 571.
[D 2,4] $D·M$ = 952·571 = 543292.
[D 2,5] $D – H$ = 952 – 32 = 920.
[D 2,6] Shadow 1:27.

[D 3,1] The time of the end from noon 4:8
[D 3,2] The time of the beginning after noon 4:8.
[D 3,3] H = 4:8 = 248, sign 4 , 4 *nadi* 2 gives M = 563.
[D 3,4] $D·M$ = 952·563 = 535976.
[D 3,5] $D – H$ = 952 – 248 = 704.
[D 3,6] Shadow 4:25.

7 THE BURMESE SOLAR ECLIPSE PARALLAX CORRECTIONS

The Burmese parallax corrections represent a large simplification as compared with the analogous *Suryasiddhanta* corrections and it is therefore interesting to compare them with parallaxes computed using modern astronomy. How accurate are they?

The parallax in latitude and longitude of the Moon in general depends on the observer's latitude, φ the longitude of the Sun, λ, that in a solar eclipse is equal to that of the Moon, the time from noon h, and the obliquity ε of the ecliptic. We here neglect the dependence on the distance of the Moon from the Earth.

7.1 The Parallax in Longitude

As shown above, for the parallax in longitude the Burmese use a very simple function:

$$n = 7 \cdot v / (600 + |v|) \qquad (7)$$

where v is the time in *vinadis* after noon, and n the parallax in *nadis*. Since 1 *vinadi* = 1/150 hour and the mean elongation motion is 730′ per day we can rewrite this formula as

$$\delta\lambda \approx 85.2 \cdot h/(4 + |h|) \qquad (8)$$

where now h is the time after noon in hours and $\delta\lambda$ the longitudinal parallax in arc minutes. The Burmese formula is explicitly independent of the longitude of the Sun.

We compare the value of this function with the corresponding modern function for parallax in longitude (Meeus, 2000: 98–100) being a function of the geographical latitude φ, the solar longitude λ, and the time from noon h.

We use φ = 23.2°, the geographical latitude of Ujjain, but our result is quite insensitive of this choice. All latitudes of Burmese sites are quite close to 20°, and the manuscript has 21° 32′. The graph of the parallax function versus the time in hours from noon (Figure 2) for a fixed solar longitude is a sigmoid curve. Different solar longitudes give similar parallel curves but displaced slightly upwards or downwards. For simplicity we only show the extreme cases, the bottom black curve being the parallax for solar longitude 0° and the upper black curve the parallax for solar longitude 180°. The red curve is the Burmese longitudinal parallax, which is a kind of average of the modern values and quite closely approximates the modern parallax for solar longitudes 90° and 270°. The horizontal axis in this diagram is the time in hours from noon, and the vertical axis is the parallax in arc minutes. Negative hours are times before noon.

The error of the Burmese longitudinal parallax is at most about 10′, which corresponds to about 20 minutes in time.

7.2 The Parallax in Latitude

The Burmese parallax in latitude depends, as does the modern parallax, on the solar longitude λ, the observer's geographical latitude φ and the time h from noon. We have again taken the observer's latitude as 23.2° and compare parallaxes for λ = 0°, 30°, 60°, 90°, 180°, 210°, 240°, 270° (see Figures 3a–h). Graphs for other longitudes that are multiples of 30° are identical to the others but with the sign of the time axis reversed. The black curves show the modern parallax and the red curves the Burmese one.

The Burmese algorithm has a maximum discrepancy of about 5′. The main part of this discrepancy is due to the Burmese use of a horizontal parallax value of 49′ instead of the modern value of 57′.

8 CONCLUSIONS

A general impression one gets from the calculations above is that they are of surprisingly good quality. There are very few computational or typographical errors. The computational methods show a delicate balance between the need for accuracy and clever approximation shortcuts for simplifying the calculations. This is especially evident in the solar eclipse calculation and in the corrections for parallax.

The shadow calculations seem to be a characteristic of Burma and give a very simple and interesting solution to a complicated mathematical problem.

9 ACKNOWLEDGEMENTS

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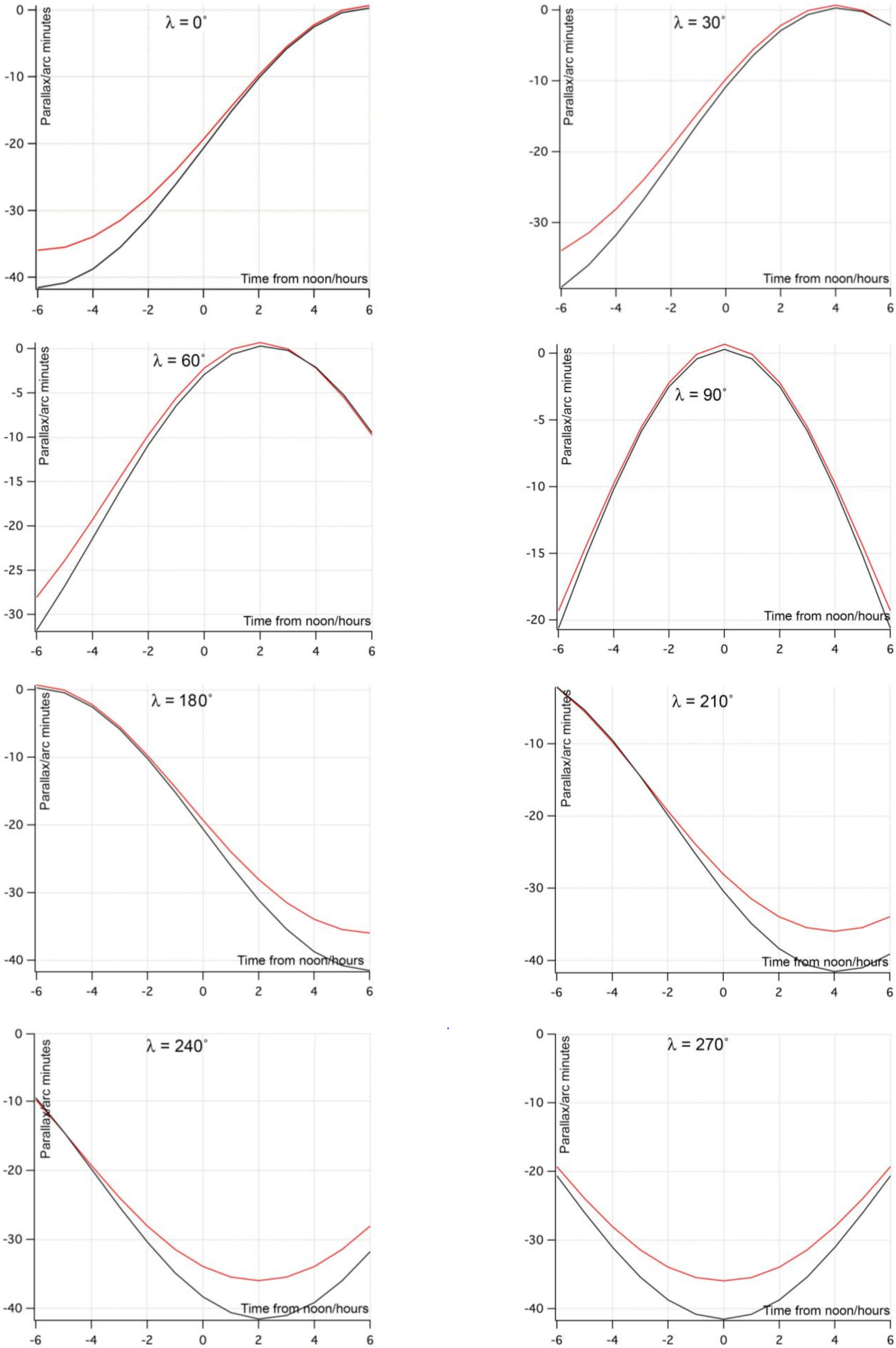

Figures 3a–3h: Parallax in latitude.

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11 APPENDICES

11.1 Appendix 1

Partial lunar eclipse grids Burmese Era 1296 *sutin* 102, 26 July 1934.

See Tables 8A–D.

Table 8 A–D: Trancription of lunar eclipse panels A – D.

A	1	2	3
1	1296	51:56	3:11
2	5035	5986:14	48166
3	85	16943:9	2
4	1	1	1370:42
5	102	53	122:37
6	6038:10	16961:43	305:32
7	16945:4	17238:2	16:22
8	5932:53	59:08	13:38
9	4361:58	790:35	8:11
10	3	57:04	6:49
11	21	859:50	0:12 5:59

B	1	2	3
1	16786:14	84:18	19:23
2	13:07	59:01	27:07
3	16:53	25:18	3:16
4	16773:45	23:15	3:43
5	17238:44	10:28	12538681
6	0	3:30	4605316
7	35:46	39:38	2304324
8	33:43	31:54	5654884

C	1	2	3
1	13:37	5:26	5:26:48
2	16:53	0:31	6:45:20
3	20:36	4:14	8:14:24

D	1	2	3
1	13:37	0:31	4:14
2	13:37	13:07	9:24
3	301	310	331
4	295582	253580	270758
5	165	31	254
6	25:02:00	137:09	18:14

11. 2 Appendix 2

Annular solar eclipse grids Burmese Era 1295, *sutin* 128, 21 August 1933.

See Tables 9 A–E.

Table 9 A – E: Transcription of solar eclipse panels A – E.

A	1	2	3
1	1295	98:54	760:32
2	5034	7462:33	3:11
3	292	7739:07	42179
4	0	3	2
5	128	23	1369:48
6	7561:27	280:13	147:12
7	7742:47	7458:54	15:52
8	3664:02	18317:22	14:08
9	3242:38	59:08	7:56
10	3	790:35	7:04
11	16	57:33	1:07

B	1	2	3
1	0:19	30:10	4:04
2	30:19	29:49	13:12
3	0:13	29:59	2:22
4	0:32	0:10	11:42
5	6:46	26:12	27:37
6	0:2	2:32	18:17
7	7465:40	6:26	2:33
8	18317:20	1:30	2:21
9	1	2:00	27:46
10	3:58	3:04	32:40
11	11:50	16:26	2:14
12	9:42	5:45	2:40
13	7:45	5:06	1:17
14	3:47	15:47	1:28

C	1	2	3
1	26:29	4:25	10:35:36
2	30:32	0:32	12:12:48
3	34:08	4:08	1:39:12

D	1	2	3
1	12:21	0:32	4:08
2	3:31	0:32	4:08
3	563	571	563
4	535976	543592	535976
5	741	920	704
6	3:47	1:27	4:25

E	1	2
1	3236401	1785
2	51529	
3	20164	1793
4	492804	1656

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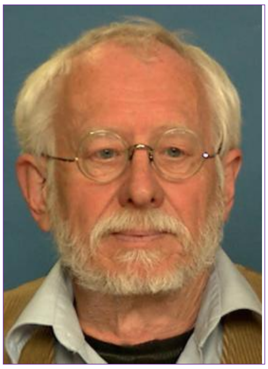

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AN HISTORICAL PERSPECTIVE ON THE SUSPECTED METEORITE IMPACT SITES OF TENNESSEE. 2: THE HOWELL STRUCTURE

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Abstract: The Howell Structure is a suspected meteorite impact site in Tennessee, USA, and came to the attention of geologists during the 1930s. It was first investigated by Born and Wilson in 1937, and the few subsequent investigations that have occurred at this extensively eroded site have revealed the presence of breccias and the possible existence of shatter cones. However, cores drilled in the 1960s have recently been analyzed, and these provide evidence of shock metamorphism, suggesting that the Howell Structure is the eroded scar of a meteorite impact.

Keywords: Howell Structure, Tennessee, meteorite impact site,

1 INTRODUCTION

The State of Tennessee, located in the south-eastern United States, contains two confirmed meteorite impact sites, Wells Creek and Flynn Creek, and two suspected impact sites, Dycus and Howell (e.g. see Berwind, 2006, 2007; Deane et al., 2004; 2006; Evenick et al., 2004; Evenick, 2006; Ford et al., 2012; 2013; 2014; Milam et al., 2006; Mitchum, 1951; Price, 1991; Roddy, 1977a; 1977b; Schedl et al., 2010; Schieber and Over, 2005; Stearns et al., 1968; Wilson, 1953; Wilson and Stearns, 1966; 1968; and Woodruff, 1968). However, recently-published evidence derived from cores drilled at the Howell Structure in the 1960s suggests that this, too, may be meteorite impact scar. This site and the other three confirmed or suspected Tennessee impact sites are shown in Figure 1.

Three of these sites are found on the Highland Rim escarpment which surrounds the Nashville Central Basin in middle Tennessee, while the fourth site, the Howell Structure, is located on one of the numerous isolated Highland Rim residual areas that lie within the Central Basin, near its south-eastern boundary. Meteorite impacts most certainly also occurred elsewhere in the state, but as Woodruff (1968) has observed, the structural features of such sites would have been obliterated to the east of the Highland Rim, in the deformed rocks of the Appalachians, while impact craters in the western part of the state would have been covered by coastal plain marine and transitional sediments during the Mississippian Embayment (Miller, 1974). In this paper we present an historical review of investigations that have been carried out at the Howell Structure.

The Howell Structure is an "…intensely deformed area …" located in the Highland Rim of south-central Tennessee (Born and Wilson, 1939: 371). It

> … is a roughly circular feature about 2.5 km in diameter, comprising brecciated, deformed, and disturbed sedimentary strata … centered on the unincorporated village of Howell … (Deane et al., 2004: 1).

The regional dip in this area "… is to the south and is at an average angle of considerably less than 1° …" (Born and Wilson, 1939: 375).

Large creeks, such as Cane and Norris, have eroded valleys in this section of the Highland Rim to almost the level of the Nashville Central Basin (Born and Wilson, 1939). Although "No large creeks flow across the structure proper … Cane Creek borders the western and southern limits, and Buchanan Creek borders the easternmost areas. The tributaries of Cane Creek dissect a large percent of the deformed area …"

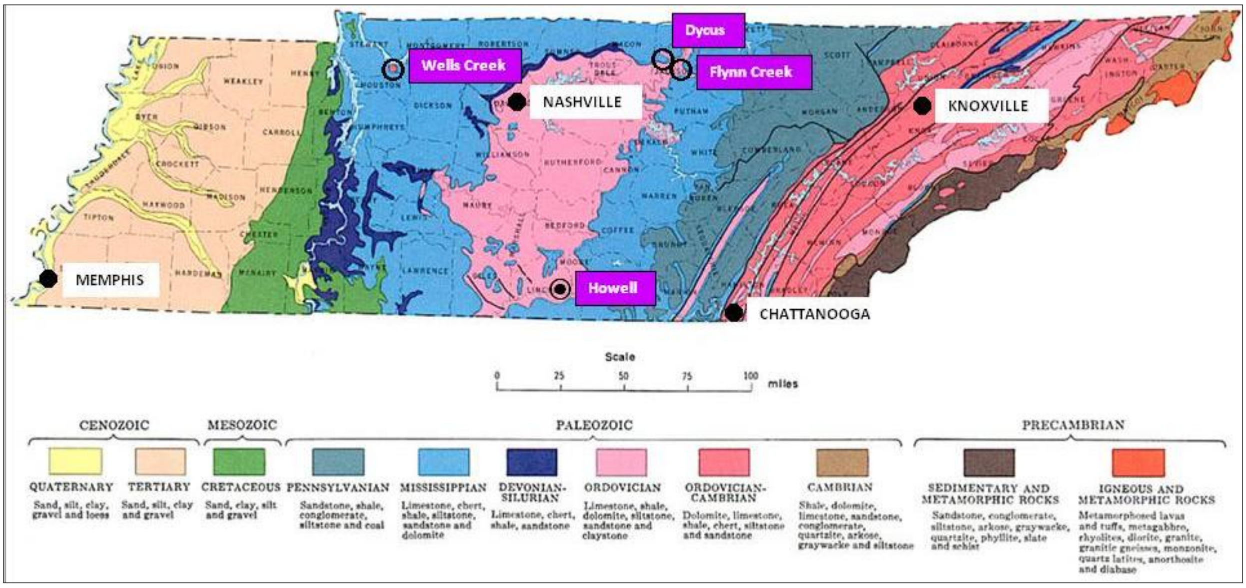

Figure 1: Generalized geological map of Tennessee showing the locations of the four largest cities (black dots) and the three confirmed meteorite impact sites (Flynn Creek, Wells Creek and Howell), and the Dycus suspected meteorite impact site. The Howell Structure, the subject of this paper, is located on a Highland Rim outlier remnant. The Highland Rim is the sky blue region on the map (base map after Tennessee Department Conservation, Division of Geology, 1966).

(Woodruff, 1968: 4). Narrow ridges between the creeks and streams are remnants of the Highland Rim with an average elevation of some 100 meters above the eroded valleys and Howell, for the most part, is some 16 meters above these valley floors (Born and Wilson, 1939; Woodruff, 1968). Deane et al. (2004: 1) note that

> The western two-thirds of the Howell Structure occur [*sic*] in rolling, grass-covered pasturland, while the eastern one-third consists of forested hills rising 130 m above the surrounding terrain. Exposures are limited …

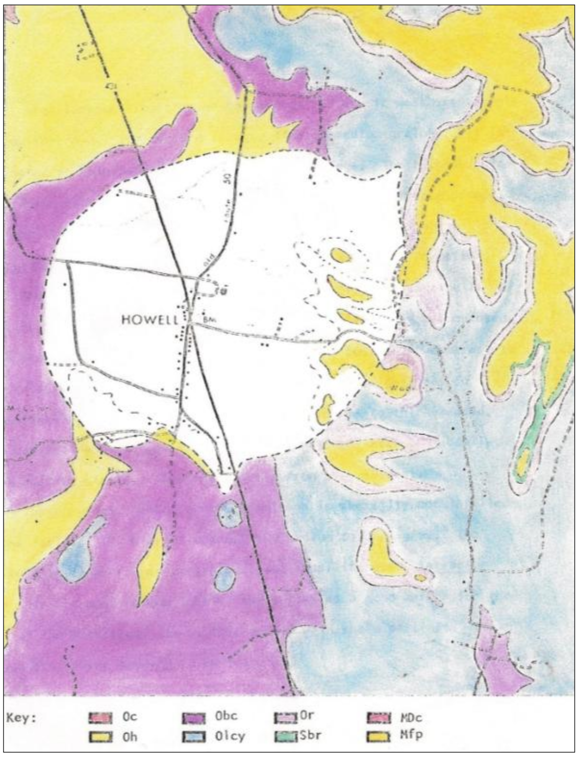

Figure 2: A geological map of the Howell region showing the area of deformation. Scale 1:24000 (after Woodruff, 1968).

2 HISTORICAL CONTEXT

Mr J.W. Young, of Fayetteville, Tennessee, ~10 km from Howell, was the first to notice this interesting, but "… small area of intricate structure …" (Born and Wilson, 1939: 371). He showed the Howell Structure to several geologists and discussed it with others, including Wilson and Born, sometime around 1934. As a result, the first known detailed map of the Structure and surrounding area was completed in 1937 by Born and Wilson. However, they did not come to a conclusion as to its origin, merely stating that

> While no conclusive evidence has been observed to support either the cryptovolcanic or the meteoritic hypothesis of origin of the Howell structure … [it] is considered tentatively as an example of the cryptovolcanic structures as interpreted by Bucher … (ibid.).

Detailed geological mapping of this area was undertaken again from 1964 to 1965 by Wilson and R.H. Barnes from the Tennessee Division of Geology, assisted by R.A. Miller and C.E.L. McCary (Deane et al., 2004; Woodruff, 1968). Figure 2 is the map prepared by Wilson and Barnes, with additions by C.M. Woodruff (1968).

The next serious study of the Howell Structure was undertaken in 1967 by Woodruff and supervised by R.G. Stearns, in order "… to map in detail the limits of deformation …" (Woodruff, 1968: 1). Woodruff (ibid.) noted that

> At the same time, geologists of the National Aeronautics and Space Administration began to do field reconnaissance work in preparation for core drilling to determine the nature of the structure at depth …

The lead geologist was J. Bensko, from NASA's Marshall Space Center in Huntsville, Alabama.

In late 2003 B. Deane, P. Lee, K.A. Milam, J.C. Evenick, and R.L. Zawislak carried out a study of the Howell Structure, including an aerial survey, in order to locate "… evidence of shock metamorphism in local lithologies …" (Deane et al., 2004: 1–2).

Finally, in 2015 Milam et al. published the results of their investigation of cores drilled by NASA scientists in the 1960s and limestone breccia samples supplied by R.G. Stearns. Through these new lines of investigation they were able to assemble what we regard as strong, but not conclusive, evidence for the impact origin of the Howell Structure.

3 MORPHOLOGY, STRATIGRAPHY, AND AGE

When he carried out his study, Woodruff (1968: 57) regarded the Howell Structure as a suspected site of impact, since its "… original morphology has been completely obliterated by the various geologic processes that have worked on the area …" The stratigraphy of the Highland Rim in which the Howell Structure is located is

> … primarily composed of flat-lying limestones, dolomites, and shales, and to a much lesser extent, of cherts, siltstones, mudstones, and very fine-grained to conglomeratic sandstones. Strata range from Upper Ordovician to Lower Mississippian in age and contain several prominent unconformities … (Deane et al., 2004: 1).

Woodruff (1968: 6) found similar strata, and rock units that he encountered at Howell included

> … the Hermitage Formation of the Nashville Group of the Ordovician System, through the Fort Payne Formation of the Mississippian System.

Figure 3 is Appendix A from Miller (1974: 59) showing a composite stratigraphical section for Middle Tennessee which includes rock units essential to the understanding of the Howell Structure. Note that the Stones (Black) River Group which includes Carters Limestone and the Nashville (Trenton) Group which includes the Hermitage Formation, Bigby-Cannon Limestone, and Catheys Formation, are from the Middle Ordovician. The Richmond Group is not specified on this particular stratigraphic section, but according to the U.S. Geological Survey is in the Upper Ordovician and includes the Mannie Shale, Fernvale Limestone, Sequatchie Formation, and Arnheim Formation. The Brassfield Limestone is Lower Silurian. Shown between the Pegram Formation of the Middle Devonian and the Chattanooga Shale of the Upper Devonian is a major unconformity found throughout Middle Tennessee. The Fort Payne Formation is Lower Mississippian. Note that in United States common usage, the Carbonifeorus System is divided into the Mississippian (early Carboniferous) and Pennsylvanian (late Carboniferous). Unfortunately, rocks that are exposed on the surface and

> … extend beneath the surface throughout Tennessee and other areas of the east-central United States … are referred to by other names elsewhere. (Miller, 1974: 19).

These include the Nashville/Trenton and Stones River/Black River Groups. Woodruff (1968: 52) points out one difficult issue related to the Howell Structure: "One does not know how much of the entire stratigraphic section was actually present at the time of explosion." He states that there could have been as much as 90 additional meters of Silurian at the time of the event, which adds even greater uncertainty to our understanding of the Howell Structure (ibid.).

The Howell Structure is "… a small area of highly disturbed, contorted, and brecciated strata." (Born and Wilson, 1939: 371). After studying and mapping the area in detail, Born and Wilson (ibid.) provided the following description:

> The salient structural feature is a circular area of intensely deformed Black River [Ordovician] and Trenton rocks, which have been uplifted approximately 100 feet [30 meters] above their normal positions. This circular area is composed of jumbled blocks of limestone imbedded in a matrix of shatter breccia. The major deformation is believed to have been Post-Trenton and pre-Fernvale in age. Overlying the shattered strata is the Fernvale Formation, the relative thickness and lithology of which point directly toward deposition in a graded crater.

During their investigation, Born and Wilson (ibid) also determined that "The younger Silurian and Mississippian formations are relatively undisturbed." They did not mention the cave located in the northeastern corner of the disturbance, which was noted in 2003 by Deane et al. (2004).

Born and Wilson (1939: 375) describe the structural features of Howell in three parts:

(1) the underlying, intensely-deformed rocks, which include Black River and Trenton strata;
(2) the Fernvale Formation; and
(3) the Chattanooga Shale and Fort Payne Chert.

Their investigation indicated that the

> … first series is separated from the second by a marked nonconformity with maximum differential relief of 100 feet [30 meters] within ½ mile [0.8 km] … (Born and Wilson, 1939: 375).

The plane of the nonconformity coincided with the pre-Fernvale surface. Figure 4 shows the structural cross section of the Howell Structure, as determined by Born and Wilson (1939: 376).

Born and Wilson note that "The much brecciated rocks of Black River and Trenton age are limited to a circular area about 1 mile [1.6 km] in diameter …" (ibid.), and the strata of these groups occur in blocks that vary from small fragments up

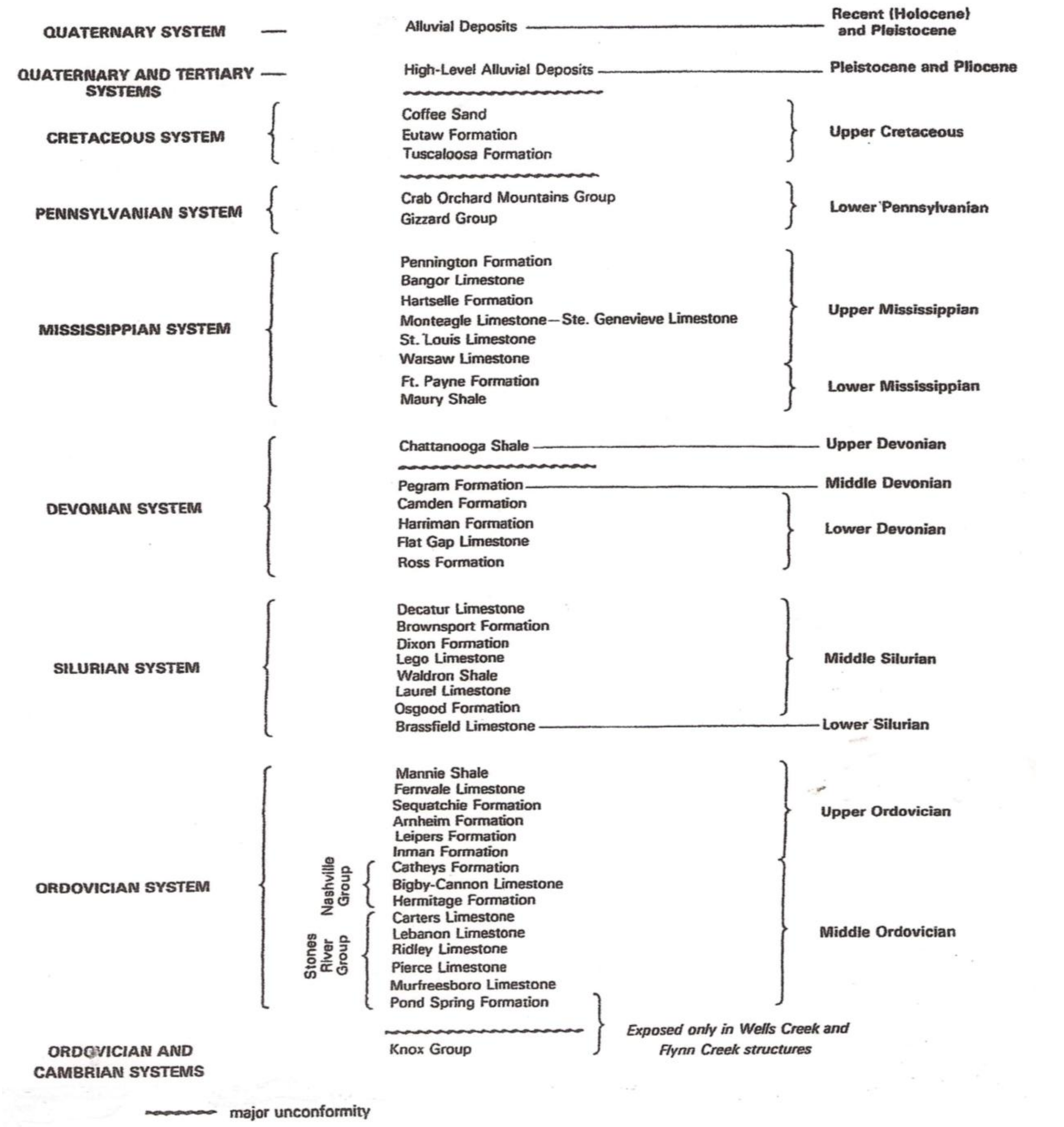

Figure 3: A composite stratigraphical section for Middle Tennessee (after Miller, 1974: 59).

to 20 feet [6 meters] or more. The blocks abut against each other at greatly-varying angles of strike and dip, with individual blocks showing

> … contortion and warping of bedding planes … [and] blocks of the Hermitage Formation have been rotated in respect to each other with resulting small-scale thrust-faulting … (ibid.).

This faulting, however, seems to be restricted to adjacent blocks that are in actual contact with each other:

> These blocks of limestone are imbedded in a matrix of shatter breccia composed of smaller fragments of limestone in a groundmass of powdered limestone. The breccia and the powdered limestone have been forced to flow around the blocks and along fractures within them, somewhat as in dike intrusion.
>
> This circular area of jumbled, brecciated, and unbrecciated limestone has been uplifted vertically in part, so that blocks of Carters Limestone are now in juxtaposition with the surrounding undisturbed Cannon Limestone outside the brecciated area. The maximum uplift was approximately 100 feet [30 meters]. Some blocks of Trenton limestone occur at the same level, or even below, their normal horizon, but these blocks are believed to have fallen or rolled to these positions at the time of origin of the crater.
>
> A rather definite break occurs between the

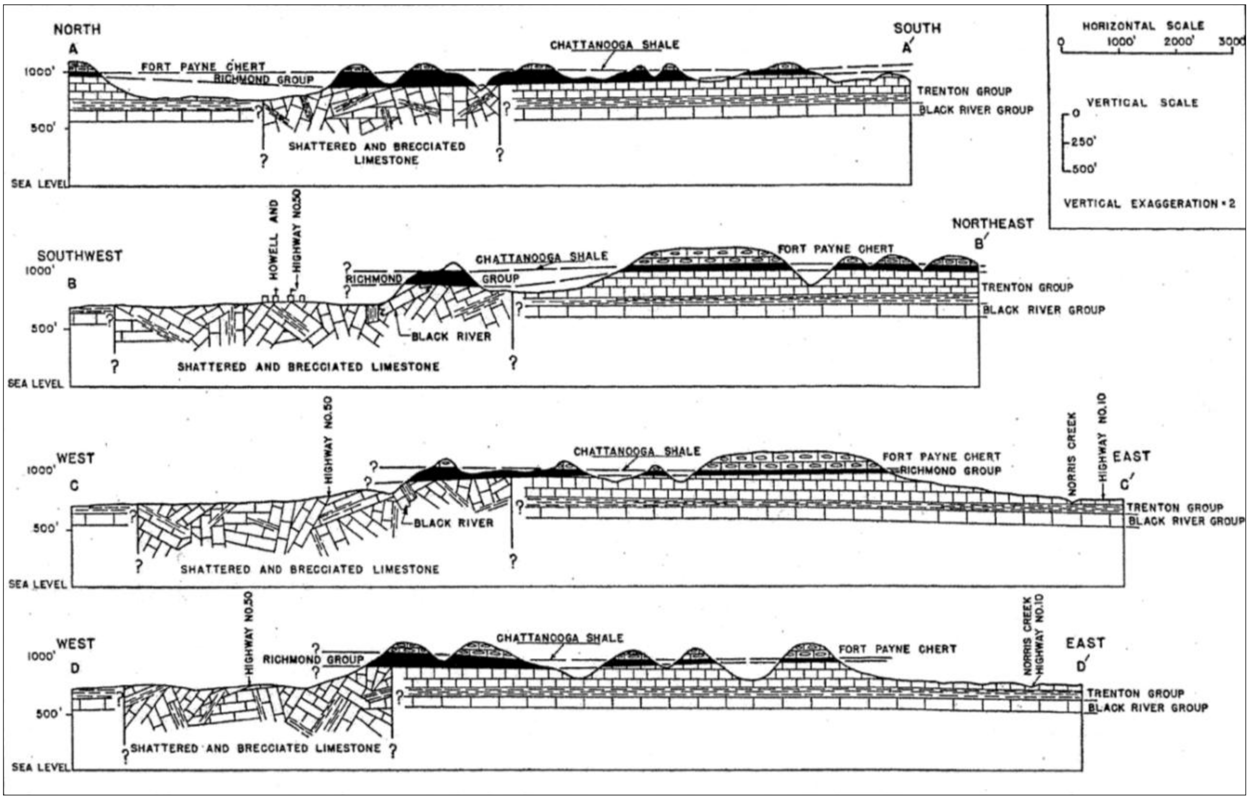

Figure 4: Structural cross-sections across the Howell Structure (after Born and Wilson, 1939: 376).

> jumbled and brecciated limestone within the circumference of the Howell disturbance and the surrounding normal limestone of the Cannon and Catheys formations.

Born and Wilson (1939: 376) note that "The Fernvale Formation rests nonconformably upon the underlying, greatly-deformed Trenton and Black River strata." However, the Fernvale Formation, is only preserved in the eastern section of the Howell Structure, as well as to the east of the disturbance, so its extensive removal "… prevents conclusive determination of its former extent, thickness, and structural details …" (Born and Wilson, 1939: 377). Mapping of the region that surrounds the Howell Structure shows that the Fernvale Formation is noticeably absent, indicating that its preservation in the disturbed area is "… due to unusual local conditions." (ibid.). Born and Wilson (ibid.) point out that

> … the rapid thickening of Fernvale from 15 to 115 feet [5 to 35 meters] toward the deformed area suggests some genetic relationship between the local abnormal thickness of Fernvale and the deformed area.

They conclude that a closed crater some 30 meters deep and 1.6 km in diameter existed in pre-Fernvale times. This 30 meter depth would be that of the crater at the start of the Fernvale deposition, so it can be inferred that the crater's original pre-erosion depth would have been greater:

> This crater must have been exposed to appreciable erosion before Fernvale deposition began, for its sides were not steep but rather were graded, as indicated by the abnormally thick Fernvale extending southeastward beyond the circumference of intense deformation that probably marked the limits of the crater. (ibid.).

The crater is thought to have filled with Fernvale sediments while flooded by the Fernvale sea (ibid.). The lower shale unit was not deposited for a long period of time, though, as "… the sea was soon freed from silt, and the clear-water limestone unit was deposited," (ibid.). Around 10 to 11 meters of this limestone unit were deposited before silt and quartz pebbles were subsequently brought in by the sea from a distant source. This last deposition completely filled the crater before the sea retreated.

The Fernvale limestone breccia is believed in part to have been the result of contemporary brecciation:

> One significant fact is that, even though locally brecciated, this limestone is a continuous unit that deposited over the strongly deformed rocks. Also, the elevation of the Fernvale limestone averages lower within the circular area of deformation than outside, where it overlies normal strata, indicating that the Fernvale did not participate in the uplift that locally raised rocks of the Black River and Trenton Groups above their normal levels. (Born and Wilson, 1939: 377).

The thick shale overlying this limestone locally has dips as great as 45°. Born and Wilson (1939) believe these dips are due to tilting and slumping that took place within the shale due to the settling and subsequent re-adjustment of the underlying deformed strata. They also state, though, that

> … it may be necessary to postulate a mild post-Fernvale and pre-Chattanooga renewal of activity to account for such high dips … (Born and Wilson, 1939: 377).

It should be noted that if this subsequent activity was involved in the formation of the crater, then a meteoritic origin for the Howell Structure was not indicated. The overlying Chattanooga Shale and Fort Payne Chert formations show no brecciation, although they are warped, but Born and Wilson (1939) conclude that this warping had no relation to the pre-Fernvale crater.

Born and Wilson 1939: 377) state that the localized forces which brecciated the Black River and Trenton limestone

> … obviously operated after the deposition of the Catheys Formation… [but] As the Leipers Formation is not present today in this mapped area, it is impossible to date the brecciation relative to this formation … (ibid.).

They point out, however, that since

> … the Leipers Formation is believed to have covered most, or all, of central Tennessee … a post-Catheys, pre-Leipers crater should have been filled with Leipers sediments. (ibid.).

Born and Wilson (1939: 377–378) conclude that the age of the Howell Structure must be determined from the following restraints:

> Even though the Fernvale limestone unit is locally brecciated and high dips occur in the Fernvale shale unit, the major deformation, when viewed from a study of all known facts as well as these anomalies, would appear to have been pre-Fernvale. There is no basis for argument for a post-Fernvale date for the maximum deformation, but there is some basis for believing in a post-Fernvale renewal of the activity, which was so great in pre-Fernvale times. If this did occur, it would have an important bearing on the problem of origin of the deformative forces; but, unfortunately, the data are not sufficient to prove that the initial strong pre-Fernvale deformation was followed by a mild post-Fernvale renewal of deformation.
>
> In summary, it is believed that the major deformation in the Howell disturbance may be dated as post-Catheys (probably post-Leipers) and pre-Fernvale, with possibly post-Fernvale and pre-Chattanooga recurrence in a mild form.

Born and Wilson (1939: 380) note that

> If the Leipers formation were deposited prior to the explosion, as is believed to have been the case, it was removed by post explosion erosion. No evidence is available for dating the explosion with regard to the Arnheim Formation.

Summarizing their findings at the Howell site, Born and Wilson (1939: 380) state that an explosion occurred,

> … blowing out a crater at least 100 feet [30 meters] in depth and 1 mile [1.6 kilometers] in diameter, and piling up limestone debris around the crater … [Subsequent] Removal of this debris (and possibly the Leipers Formation from the surrounding area) and the grading of the crater walls by erosion … [occurred before] Deposition of the Fernvale Formation, filling the crater level with the surrounding floor of the Fernvale sea … (Born and Wilson, 1939: 380).

A 1961 United States Geological Survey, Branch of Astrogeology report includes the following entry:

> Field examination of the Howell disturbance, Tennessee, by E.M. Shoemaker, R.E. Eggleton, and D.J. Milton, in company with C.W. Wilson Jr. of Vanderbilt University, led to the conclusion that if this structure is of impact origin, as has been suggested by Wilson and others, the structure was probably formed at a time when the epi-continental Ordovician sea had significant depth at the site of the Howell disturbance. (Schaber, 2005: 31).

Woodruff (1968: 44–45) undertook the next major study of the area and mapped the Howell Structure's limits by including

> … all expressions of deformation beyond an established 'norm' as being within the structure … all dips greater than those of the normal regional dip, all fracturing, folding, faulting, overturning, and brecciation.

Woodruff (1968: 46) states that

> The structure limits cannot be interpolated with ease from any one point to another. Interpolation is necessary, even though undesirable, in some areas because of lack of outcrops.

Woodruff (1968: 46–47) determined that the Howell Structure was roughly circular and somewhat irregular in outline, as shown in Figure 2. In locations where the Structure's boundaries seemed to deviate from an idealized circular outline, Woodruff (1968: 49) believed that the

> … deviation might be due to dip of the structure at depth, which would give an irregular trace conforming to topography. Such irregularities might also be due to the vicissitudes of shock in rock layers at depth.

He also determined that Howell is "… slightly elliptical with the axis of the ellipse trending slightly northeast …" (Woodruff, 1968: 47). The Structure's minor axis is around 1.8 km and trends north-south, while the major axis is about 2.5 km and trends approximately north 45 degrees east. Woodruff did not find an appreciable uplift between the rock units within the Howell Structure and the surrounding undisturbed strata, although he did suggest further investigation in order to verify this finding.

Woodruff (1968: 50) constructed an idealized cross-section of the Howell Structure by assum-

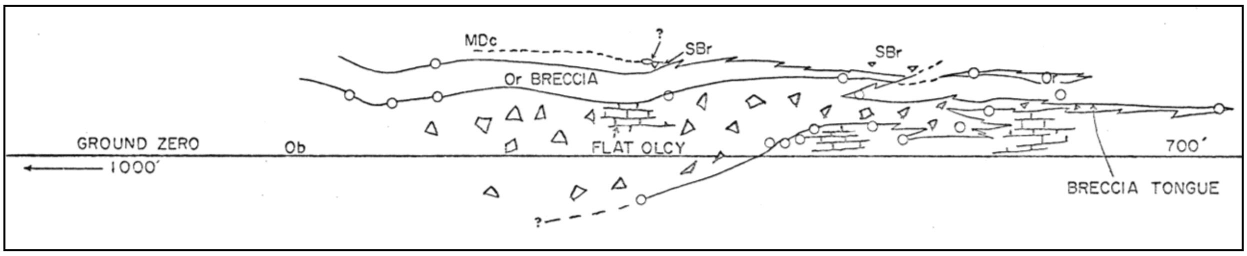

Figure 5: An idealized cross-section across the eastern half of the Howell Structure assuming radial symmetry. The series of small circles are control points (after Woodruff, 1968: 51).

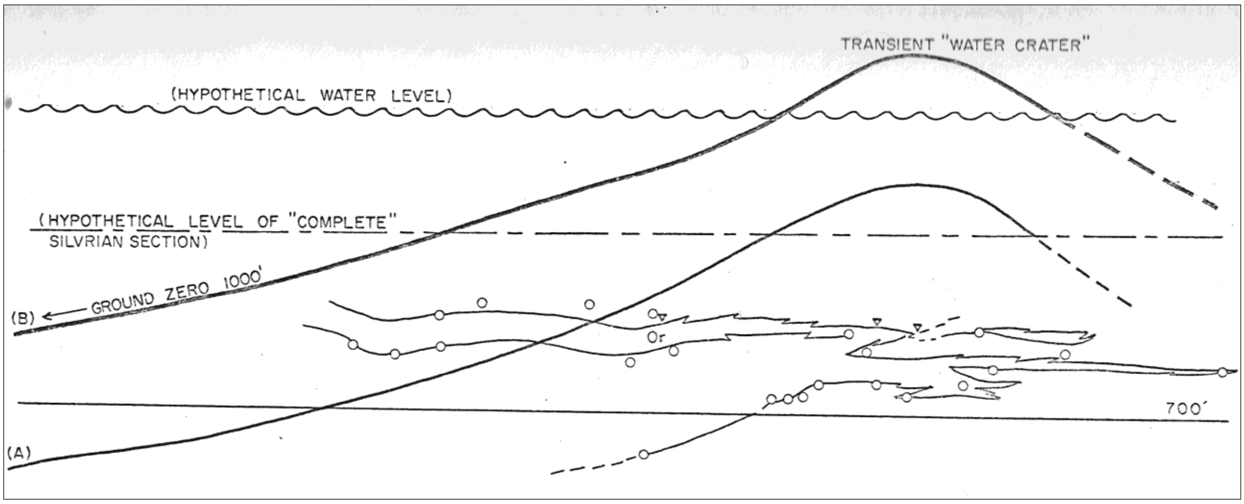

Figure 6: Two hypothetical Howell half-craters superimposed on the idealized cross-section across the eastern half of the Howell Structure. (A) assumes 300 feet of Silurian strata to have been present, and (B) assumes 400 feet of water above these Silurian strata (after Woodruff, 1968: 55).

ing that the Structure possesses "… basic radial symmetry …" and by utilizing "… topographic elevations of the outcrops …" from his compilation map. The eastern half of his cross-section is seen in Figure 5. Woodruff (ibid.) notes that as with the surface boundaries, the resulting drawing shows irregular deformation limits at depth, and he discusses the implications:

> This irregularity could be an artifact of the projection technique, but may well be real and due to a propensity of shock to be transmitted along bedding planes, or at least parallel to bedding. The irregularity may be due to the vagaries in behavior of different lithologic types when subjected to such forces … Only extensive subsurface information will demonstrate whether such boundaries actually exist. (ibid.).

If Woodruff's idealized cross-section is correct, then "… the zone of deformations is not as deep as would be expected …" (ibid.), but Woodruff (1968: 52) does note that "One does not know how much of the stratigraphic section was actually present at the time of explosion." Based on the complete Silurian section found in the Western Valley of Tennessee, there may have been as much as 90 meters of Silurian strata present at the time of the Howell event. Another possibility is that Howell "… at the time of impact (or explosion) was under water …" (ibid.). Figure 6 shows the eastern side of the idealized cross-section by Woodruff (1968: 55), with two superimposed half craters assuming (a) 90 meters of Silurian strata and (b) 90 meters of Silurian strata under another 120 meters of water. Woodruff (1968: 57) continues:

> … the depth of water would be equivalent to a certain amount of rock in dissipating the shock. At the same time, no indication of deformation would remain in water after the event …

Woodruff noticed a 'gradation zone' from 18 to 45 or so meters between the breccias and normal, undisturbed rock as he mapped stratigraphic units from " … normal flat-lying beds into zones of intense deformation …" (Woodruff, 1968: 45). "This same relationship seems to hold true in subsurface work …" according to a personal communication between Bensko and Woodruff (1968: 3, 45) regarding the Howell core which was drilled by a crew from the National Aeronautics and Space Administration's Marshall Space Center located in nearby Huntsville, Alabama. Most of the questions concerning the Howell Structure's limits of deformation at depth require subsurface data which Woodruff (1969: 49) points out are not extensive since such data requires

> … drilling into a section of deformed rock and continuation of the drilling until undisturbed rock layers are reached … only one such NASA drill hole was available …"

Bensko informed Woodruff

> … that the drill hole penetrated past the breccias into undisturbed bedrock, and that there was a zone of gradation between the breccias and the normal bedding … (Deane et al., 2004: 2; cf. Woodruff, 1968: 65).

According to Woodruff (1968: 57),

> Essentially, all geomorphological indications of deformation are expressed in joint, and/or fault controlled stream lineations and joint and fault control of escarpments …

and he cites several striking examples of joints controlling the stream pattern within the Howell Structure:

> Cane Creek turns about 80 degrees, reflecting a joint pattern radiating outward from near the center of the structure. Again on Cane creek, but outside the northwestern limits of the structure, is another such elbow turn, where the joint similarly appears to radiate outward from the center of the structure. Striking joint control is further seen in the tributary of Cane Creek that cuts the northern portion of the structure … The joint pattern again appears to radiate.
>
> These features indicate an event of sufficient magnitude to give rise to a more or less radiating set of joint fractures in surrounding otherwise undisturbed rocks. (ibid.).

This finding rules out localized sedimentary processes that would have caused slumping and brecciation. Other geomorphological indications of structure according to Woodruff are also joint and/or fault controlled within the area of deformation. These are

> … the apparent alignment of the dissected escarpments on the eastern ridges making up the drainage divide between Cane and Norris Creeks … (Woodruff, 1968: 58).

He notes that these features also radiate from a central area in the Structure.

Woodruff (1968: 23) discusses the age of the Howell Structure based on stratigraphical relationships:

> On the western two-thirds, erosion has cut deep into the roots of the structure completely obliterating most geomorphological indications of deformation. However, on the high ground on the southern and eastern side, the structure is buried by undeformed Fort Payne chert of Mississippian age. This is valuable because it limits the structure to a pre-Fort Payne time of origin. However, certain problems have arisen in dealing with rock units older than Fort Payne.

In his discussion, Woodruff (1968: 23) notes that Born and Wilson recorded the finding of strong dips, local faults and some brecciation in the Richmond Group of rocks at Howell and "… that the geologic sequence of events was further confused by the presence of tongues of the Fayetteville channel of Richmond Age." He then explains how he arrives at an age for the Howell Structure:

> Born and Wilson (1939) placed the age of the structure as being post-Leipers and pre-Richmond. The fact that the Richmond Group occurs as a continuous belt of rocks (and can be mapped as such) overlying the much more intensely brecciated older Ordovician rocks and the fact that this belt of Richmond contains only blocks and fragments of Richmond (never blocks of older Ordovician age) led them to this conclusion. They attributed the deformation of the Richmond to contemporaneous brecciation that occurred shortly after the partial consolidation of the Richmond as a result of readjustments in the underlying jumbled breccia of older Ordovician rocks and also to a possible mild renewal of the forces that caused the original major deformation (volcanic origin required for this).
>
> The present writer has now asserted that the age of the structure is definitely post-Richmond – indeed post-Silurian, on the strength of the discovery of brecciated lenses of chert, identified by Wilson as being in the Brassfield Formation (Silurian). Also, another zone, which may represent an intensely deformed area of still younger age, has been found by this writer. This consists of a mixed zone of chert, sand, various sulfides, and possibly even carbonaceous shale material. Petrographic study shows planar features cutting across quartz grain boundaries, and the possible presence of glass, and/or isotropized quartz. The zone has been postulated by Stearns as being a mixture of Silurian (Brassfield) and Devonian (basal sand of the Chattanooga Shale). The most realistic appraisal of a "normal" stratigraphic position for the so-called "mixed zone" would be in the basal sand of the Chattanooga Shale. This still gives a striking parallel in time of deformation with the Flynn Creek structure. (Woodruff, 1968: 23, 27).

Woodruff (1968: 28) concludes that the age of the Howell Structure

> … may be stated with authority as being post-Brassfield, and possibly into the upper Devonian time … Also, it is safe to say that the structure is pre-Fort Payne.

A possible explanation of the 'mixed zone' discussed above "… is that it may be the fossilized crater rim, buried and thus preserved from erosion by the Fort Payne chert." (Woodruff, 1968: 27). The possibility that this 'mixed zone' may be composed of rim material is indicated by petrographic studies, and based on samples that are possibly reworked rim material Woddruff (1968: 63–64) concludes:

> It contains fragments from Brassfield chert, and basal sand of the Chattanooga Shale. The quartz grains that are deformed are probably of Devonian age, probably from the

> basal sand member, but it is believed that the Chattanooga Shale is post-deformation in age. This gives the outstanding age control that was hoped for from the beginning. The age can be bracketed into a time zone in the uppermost Devonian. It is known to be pre-Fort Payne (Mississippian), and is probably pre-Chattanooga (Devonian-Mississippian). This means that the Howell event could exactly coincide with the Flynn Creek structure in age, as the Flynn Creek crater is filled with material of Chattanooga age…
>
> The rock units exposed in the Howell area range from the Hermitage Formation of Ordovician age to the Fort Payne Formation of Mississippian age. The units involved in the deformation range from the Hermitage through the Brassfield of Silurian age. Another younger rock unit, considered to be a mixed zone between Silurian and Devonian and Mississippian units was found. Constituent members of that rock unit were also deformed. The geological age of the structure has been placed as certainly post-Lower Silurian and probably post-lower Devonian. It is probably pre-Chattanooga and is certainly pre-Fort Payne Chert (Mississippian).

In another discussion of the age of the Howell Structure, Miller (1974) points out that the adjacent Fort Payne rocks, which are Lower Mississippian, are not structurally disturbed, indicating that the Structure's origin is pre-Mississippian and that Silurian rocks in the Howell Structure are brecciated, indicating it is post Silurian. Miller (1974: 56) also compares the Howell Structure's age to that of Flynn Creek, a confirmed impact site in Tennessee, noting that Flynn Creek "… formed in Middle to Late Devonian time (350–375 million years ago), for it is filled with Chattanooga Shale …" Miller (ibid.) concludes that

> … the Howell Structure may be very close in age to the one at Flynn Creek, or some time in the Devonian Period, possibly just prior to deposition of the Chattanooga Shale …

Miller also notes that Howell, unlike the larger Flynn Creek and Wells Creek impact structures in Tennessee, is only 2.1 km in diameter and that there are some dissimilarities between this and the other Tennessee impact sites. He points out that

> There is no distinct central uplift, although intense brecciation and other disturbances of the rocks have possibly concealed or obliterated an otherwise more definitive uplift … (ibid.).

However, on the Earth the transition from a simple to a complex crater occurs around a diameter of 2 km in sediments and 4 km in massive crystalline rocks (French, 1998: 24). Howell might just be a simple crater and as such would not possess a central uplift.

Miller (1974: 56) also states that "Although there are faults within the Howell Structure, there are no clearly definable circular faults surrounding it …" However, we dispute this, as there are three more or less parallel faults to the southwest of Howell that are seemingly centered on the Structure, and although there is no published information that would suggest that the faults are in any way associated with the Howell Structure, their proximity to it is interesting. The distances of the faults from the Structure, as measured on a 1:250,000 map, are approximately 6.4, 22.5, and 38.6 kilometers, but they are not concentric to the Howell Structure, and since they are situated on the S-SW periphery of the Nashville Basin another possibility is that they may have been formed during the uplift of the Nashville Dome, and thus are related to that structure. If this was so, their proximity to the Howell Structure may merely be coincidental. Figure 7 shows a generalized tectonic map of the southern interior lowlands of the United States, and includes the Howell Structure, the three faults and the Nashville Dome.

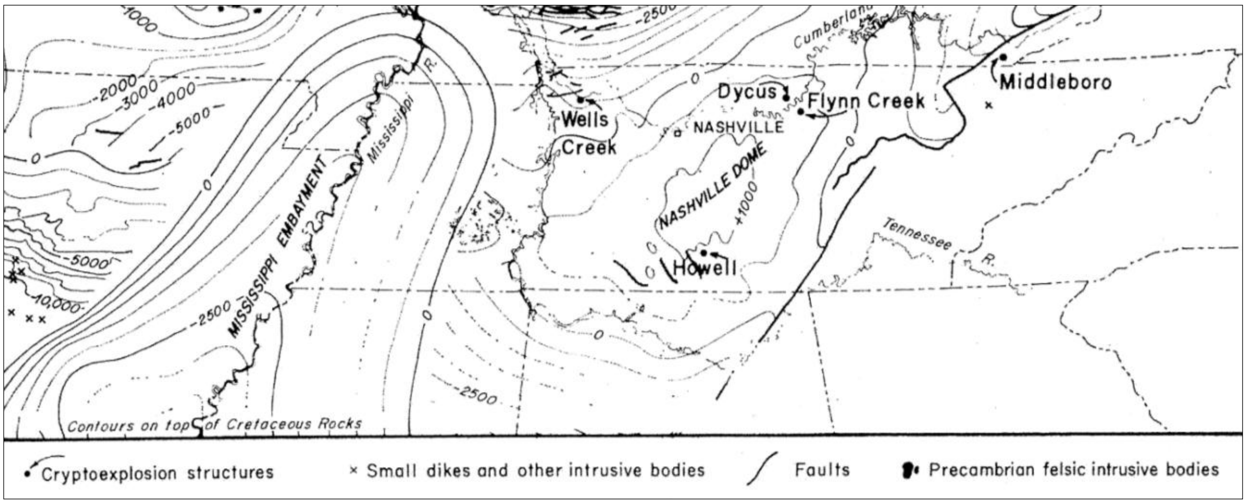

Figure 7: A generalized tectonic map of the southern interior lowlands of the United States which shows the locations of the Howell Structure and the Nashville Dome with respect to the three concentric faults (after Roddy, 1968: 293)

4 CRATERING MECHANICS

As Croft (1977: 1279) points out, "Impact cratering, an extremely complex phenomenon worthy of study in its own right, acquires great significance when studied in the context of planetary surfaces and planetary formation …" After decades of controversy, a modern understanding of the high energies associated with impact cratering finally led investigators to the realization that impact crater excavation is similar to an explosion (Hoyt, 1987; Melosh, 1989). We now have a good idea of the basic cratering process.

Let us now examine this for a terrestrial (rather than a marine) non-oblique impact, so that we can determine features of the initial impact and the form of the crater that is now represented by the Howell Structure (on the assumption that it is a highly-eroded meteorite impact scar). There are four different aspects to consider, and these are discussed separately below.

4.1 Impact Velocity and Energy

The Earth's atmosphere provides protection against small meteorites, but is no match for the more massive ones which enter the atmosphere carrying large amounts of kinetic energy. Loss of mass due to ablation depends on a meteoroid's composition, size, mass, altitude, and entry velocity. The density of Earth's atmosphere varies from 10^{-13} g/cm^3 at an altitude of 200 km to 10^{-3} g/cm^3 at ground level and meteoroids entering the Earth's atmosphere have masses ranging from ~10^{-18} to ~10^{15} kilograms (Popova, 2005). Meteoroids larger than ~100 m and ~10^9 kg lose only a small part of their initial mass and energy while traveling through the atmosphere.

The sufficiently-massive cosmic bodies are not significantly slowed by friction in the Earth's atmosphere and so impact the ground at cosmic velocities, typically tens of kilometers per second (French, 1998). The maximum possible impact velocity of an impactor gravitationally bound to the Sun is 72 km/sec (Collins et al., 2005). However, the average asteroidal impact velocity on Earth is 17 km/sec (Collins et al., 2004). A meteorite's kinetic energy changes with the square of its velocity. This energy is released upon impact and, if sufficiently high, will result in an explosion. Even if a meteoroid does not survive to impact the Earth's surface, but instead explodes in the air low over the Earth's surface, powerful shock waves and radiation fluxes can still occur which may result in fires, and the destruction of objects on the Earth's surface (Nemchinov et al., 1999).

For large meteoroids, ablation from the surface is not significant because of shielding by the vapor produced and so the mass of the meteoroid or its fragments changes little with fragmentation (ibid.). Modeling indicates that the size of a dense vapor cloud formed around a meteoroid is around 5–10 times its size (Popova, 2004: 311). Vapor parameters depend on the meteoroid's size, velocity, altitude and composition. According to Nemchinov et al. (1999), the actual velocity, V, including atmospheric retarding effects, of a meteoroid of mass M, with cross sectional area S, at a height of Z_r below the defined atmosphere Z (where Z = 0 at the Earth's surface), where the expected velocity is V_r, for a trajectory of angle θ, is given by:

$$V^2 = V_r^2 \exp^{[-m_a/m_0 \sin\theta]} \qquad (1)$$

where C_D is the drag coefficient and the effective mass per unit of area of the meteoroid is found by $m_0 = M/SC_D$. In the exponent, the mass of the atmospheric column per unit area, m_a, is defined by the integral of the density of air, ρ_a, so $m_a(Z) = \int_Z^{Z_r} \rho_a \, dZ$ (Nemchinov et al., 1999: 1196). Retardation begins where the specific mass of the atmosphere becomes comparable to the specific mass of the meteoroid.

Blast waves generated by high-velocity meteoroids in the atmosphere are similar to shock waves generated by a line charge (Ivanov, 1991). The blast wave generated during the 1908 Tunguska event when a meteoroid, perhaps a comet, decelerated and exploded above Earth's surface rather than impacting it, starting a forest fire and felling trees in a 50 × 60 km area in central Russia. For a high-velocity meteoroid, the distance scale of its atmospheric blast/shock wave, λ, can be found by:

$$\lambda = [\eta(e/P_a)]^{1/2} \qquad (2)$$

where P_a is the ambient atmospheric pressure, e is the energy of the explosion or deceleration per unit length of the trajectory, and η is the efficiency of the transformation of this energy to blast waves. For high-velocity bodies, η = 2 (ibid.). Shock vapor is produced by a high-velocity impact. Expanding shock vapor in turn generates atmospheric shock waves. If impact velocity is greater than 30 km/sec for a projectile impacting 'typical igneous rock', then the mass that is vaporized may be found by:

$$M_V = 0.05\, E \qquad (3)$$

where M_V is the mass of the vapor and E is the kinetic energy of the impactor in units of TNT equivalent (ibid.).

Meteoritic material strengths and densities differ from one meteorite to another and even within one body. Strengths of different pieces of the same meteorite can differ by a factor of 2–3 correlating weakly with the meteorite's chemical-petrological composition (Nemchinov et al., 1999). The surprising result is that some stony meteorites are stronger than some iron meteorites. Also, the strength of a large meteoroid or its fragments is lower than the strength of the small specimens on which experiments are made. The characteristic loads for which bodies of mass M break up in the atmosphere is lower than the strength limits of the small specimens of a meteorite σ_s of mass $m_s << M$. The variation of strength of a meteoroid of mass M can be found by:

$$\sigma = \sigma_s (m_s/M)^{\alpha} \quad (4)$$

where α is determined by the degree of homogeneity of a body. The more homogeneous a meteoroid is, the smaller α will be, with a good estimate being α = ¼ (Nemchinov et al., 1999). However, if α is established on specimens of different dimensions in the range of 1–10 cm, extension of dependence to bodies with dimensions of 1–100 m can result in significant errors.

A terrestrial meteorite impact crater is not formed by the impact itself, but by the blast of "… superheated, compressed air and other vaporized matter." (Baldwin, 1949: 135).

> The known terrestrial meteorite craters were all blasted into being by the almost instantaneous release of the kinetic energy of motion of the [impacting] mass. (Baldwin, 1949: 68).

According to Baldwin (1949: 97) the few relatively modern meteorite impact craters recognized on Earth show evidence of "… tremendous explosive activity …" including the radial distribution of explosively-shattered meteorite and target rock fragments as well as blocks of target material spread over an area ten times the resulting crater's radius.

An impact crater's radius and depth depends on the energy of impact as well as the density, composition, and size of the impactor and the surface composition and gravitational acceleration of the planet (de Vet and de Bruyn, 2007; Masaitis, 2005). Surprisingly, de Vet and de Bruyn (2007) found that when a spherical projectile is dropped vertically into a container of granular material, glass beads, the excavation energy required for crater formation is only a small fraction (0.1%–0.5%) of the projectile's kinetic energy. For a flat surface defined to have the vertical coordinate z = 0, so that a crater's interior has z < 0, the excavation energy, E_x, required to eject the crater volume out of the crater and deposit it on the surrounding surface is given by:

$$E_x = \pi \rho_b g \int_0^R z(r)^2 r \, dr \quad (5)$$

where ρ_b is the bulk density of the granular material, r is the radial distance, and R_0 is the crater's radius at z = 0. While both are dependent on impact energy, a crater's radius depends on the projectile size, and depth depends on projectile density. The rim height was found to depend only on the projectile's size (de Vet and de Bruyn, 2007).

The mass of the meteorite needed to account for a given impact crater is inversely proportional to the striking velocity of the meteorite. As a meteorite penetrates Earth's layers, it initially moves faster than the impact-induced shock waves, compressing an ever increasing amount of target rock. This material combined with the meteorite's mass will slow rapidly, but momentum will be maintained as the combined mass increases. Baldwin (1949: 139) states that "Essentially no momentum will be lost during this interval …" Momentum is the product of the mass and velocity of an object, therefore a higher-velocity meteorite will form a larger crater than a meteorite of equal mass moving at a lower velocity.

In hypervelocity impact experiments carried out on low density materials, the penetration track of the projectile becomes longer as the target medium density is lowered (Kadono, 1999). At low impact velocity, V_0, the strength of a projectile, Y_p, is greater than the dynamic impact pressure, so the projectile penetrates the target intact and the resulting crater is narrow and deep. Assuming a spherical projectile of diameter D_p, and density ρ_p, collides vertically with a surface having target strength, Y_t, and target density, ρ_t, and the initial impact pressure, P_0, is low enough for the projectile to remain intact after target penetration, then according to Kadono and Fujiwara (2005: 1311), the resulting crater depth/projectile diameter ratio, T/D_p, can be determined by:

$$T/D_p \sim (⅓)(\rho_p V_0^2/Y_t) \quad (6)$$

With increasing impact velocity, the point at which the initial impact pressure, P_0, equals Y_p, the deformation or fragmentation of the projectile begins (Kadono and Fujiwara, 2005). As the impact velocity is further increased, the projectile shatters and penetration depth decreases. If the initial impact pressure, P_0, is higher than the projectile strength, Y_p, then the situation is similar to cratering with chemical explosives. Where U_p is the shock wave velocity, C_{Rp} is the rarefaction velocity, and α is the attenuation rate of pressure, the crater depth/projectile diameter ratio, T/D_p, becomes:

$$T/D_p \sim (\rho_p/\rho_t)(P_0/Y_p)^{1/\alpha}(Y_p/Y_t)^{1/\alpha} \ln[1+ (\rho_t V_0/\rho_p)(1/U_p + 1/C_{Rp})] \quad (7)$$

Numerical simulations show α ~3 for high velocity impacts and experimental values obtained give α ~2–3, which is not surprising since this cube-root scaling form is often realized in chemical explosive cratering (Kadono and Fujiwara, 2005: 1312). After impact, strong shocks propagate into the target and projectile which brings them to a common pressure P (Melosh, 1989: 54). The rarefaction wave speed, C_{Rp}, can be found by:

$$C_{Rp} = [(K_0 + nP)/\rho_{Cp}]^{1/2} \quad (8)$$

where the projectile bulk modulus is $K_0 = \rho_{0p}C_p^{\,2}$ and $n = 4S_p\text{–}1$ utilizing the uncompressed density of the projectile, ρ_{0p}, the compressed density of the projectile, ρ_{Cp}, and empirically determined parameters of the projectile material C_p and S_p. This same equation can give the rarefaction speed in the target if the target's parameters C_t, S_t, and ρ_{0t} are used instead. For an iron projectile impacting a Gabbroic anorthosite target, C_t = 7.71 km/sec, S_t = 1.05, ρ_{0t} = 3.965 Mg/m^3, C_p = 4.05 km/sec, S_p = 1.41, and ρ_{0p} = 7.8 Mg/m^3 where S is dimensionless (Melosh, 1989: 56–57).

Shoemaker (1983) utilized data from the Jangle U nuclear crater in Yucca Flat, Nevada, USA, in the following equation used to determine the diameter, D_t, of a terrestrial impact crater.

$$D_t = c_f K_n (W\rho_a/\rho_t)^{1/3.4} \quad (9)$$

In this equation, the kinetic energy of a projectile of diameter d, density ρ, and velocity v, all measured in cgs units, is represented by $W = (^1/_{12})(\pi d^3 \rho v^2)/(4.19 \times 10^{10})$ kilotons TNT equivalent. The scaling coefficient, K_n = 0.074 km kilotons$^{-1/3.4}$, is an empirical constant derived from the diameter and explosive yield for the Jangle U nuclear crater. The estimated density of the alluvium at the Jangle U site is ρ_a = 1.8 g/cm^3 and ρ_t is the mean density of the target rocks. The crater collapse factor, c_f, is considered to be 1 for craters with diameter $\leq$3km and 1.3 for craters with diameter $\geq$4 km. Shoemaker considered 30% to be a conservative estimate for the diameter enlargement of an impact crater due to wall collapse

When these large quantities of energy are released quickly and close to Earth's surface, a rapid and orderly series of events is initiated that will result in an explosion crater. This process is continuous but can be divided into three main stages: contact and compression, crater excavation and material ejection, followed by modification of the transient crater (Gault et al., 1968; French, 1998; Melosh, 1989). Craters at the end of the excavation/ejection stage are unstable due to the steepness of their walls and experience some modification due to collapse, so craters at this stage are referred to as transient craters. Transient craters will experience initial modification to the 'final' crater form as well as continued modifications that are due to normal geological processes (French, 1998). The area of destruction due to impact is much smaller than the size of the final crater due to the modifications which start almost immediately after impact (ibid.).

4.2 Contact and Compression

The first stage begins when a meteorite makes contact with the target surface and compresses it creating shock waves through conservation of energy (French, 1998). High pressures develop along the interface as the target rock's resistance begins to decelerate the impactor. A hemispherical shock front spreads and propagates during the time that the meteorite's initial kinetic energy is transferred to the target rock, which is compressed, distorted, heated and accelerated (ibid.).

Immediately after initial contact, two shocks actually propagate away from the meteorite-target interface, one reflected back into the impactor and the other downward into the target material (ibid.). By the time the impactor and target interface has reached a depth of approximately one-half of the impactor's original diameter, the meteorite itself is engulfed by the shock wave which is in turn reflected as a rarefaction or release wave when it reaches the meteorite's rear surface. A free surface cannot sustain a state of stress, so a rarefaction wave allows for decompression from the high pressure state behind the shock wave to ambient pressure (Gault et al., 1968). Unloading to near zero pressure from the high pressures created during compression may cause both the meteorite and target rock to melt or vaporize (French, 1998). As the shock waves travel through target rock and their velocity drops to that of sound, 5–8 km/s, the shock waves become elastic or seismic waves (ibid.). Weak disturbances produce elastic waves in solids or sound waves in liquids. Stronger disturbances cause plastic waves and irreversible deformation in the solids through which they travel. The strongest disturbances produce shock waves which travel faster in uncompressed material and are, therefore, supersonic (Melosh, 1989).

The relationships between parameters across a shock were derived by P.H. Hugoniot in 1897. His equations, along with the equation of state, are used to model the impact cratering process (Pierazzo and Collins, 2003). The Hugoniot equations use the conservation of mass, momentum and energy across a shock front to relate the density ρ, pressure P, and internal energy per unit mass E, in front of the shock wave to the values of these same variables after the shock wave has passed (Melosh, 1989). The reference frame is usually chosen so that the unshocked material is at rest and shock velocity, U, and particle velocity, u_ρ, are unknown. Density is sometimes expressed as specific volume $V = 1/\rho$. For initial density ρ_0, pressure P_0, and internal energy E_0, conservation of mass leads to the first Hugoniot equation:

$$\rho(U - u_\rho) = \rho_0 U \quad (10)$$

Conservation of momentum leads to the derivation of the second Hugoniot equation:

$$P - P_0 = \rho_0 U u_\rho \quad (11)$$

Conservation of energy leads to the third Hugoniot equation:

$$E - E_0 = (P + P_0)(V_0 - V)/2 \quad (12)$$

An equation of state relates the thermodynamic variables for pressure, density or specific volume, and specific internal energy or temperature T. As Melosh (1989: 230) notes,

> The equation of state is different for different materials and is a complex function of the molecular and atomic structure of the given substance.

The response of a given material to an impact shock is governed by its equation of state since the above Hugoniot equations are the same for all materials (ibid.). The Tillotson equation of state was derived specifically for high-velocity impact computations and also has parameters which allow for the description of unloading of shocked material into the vapor phase (ibid.). The first form of the equation, used when material is compressed to higher density than its zero-pressure form, $\rho/\rho_0 \geq 1$, and the energy density, E, is less than the energy of incipient vaporization, is:

$$P = [a + b/(E/(E_0\eta^2) + 1)]\rho E + A\mu + B\mu^2 \quad (13)$$

In this equation $\eta = \rho/\rho_0$ and $\mu = \eta - 1$. The Tillotson parameters are a, b, A, B, and E_0, however, E_0 is not the initial energy density, it is a parameter often close to the vaporization energy (ibid.). The parameter a is usually equal to 0.5 based on observational data. The second form of the Tillotson equation is utilized when material is expanded to lower density, that is $\rho/\rho_0 \leq 1$, and internal energy exceeds the energy of complete vaporization. Here, the pressure is found by:

$$P = a\rho E + \{b\rho E/(E_0\eta^2) + 1) + A\mu e^{-\beta(\rho_0/\rho - 1)}\} e^{-\alpha(\rho_0/\rho - 1)^2} \quad (14)$$

The constants α and β control the rate of convergence of this second equation to the perfect gas law (ibid.).

Contact and compression is the shortest stage of the impact cratering process. At the point of impact, the Earth itself offers strong resistance to meteoritic penetration, so a meteorite's rate of deceleration is quite rapid, and

> Even the high-velocity meteoritic masses moving more rapidly than the velocity of shock waves in the earth's crust must be brought to rest within a very small fraction of a second. (Baldwin, 1963: 9).

Moreover,

> The contact/compression stage lasts no more than a few seconds, even for impacts of very large objects … For most impact events, the entire contact/compression stage is over in less than a second … (French, 1998: 19).

This stage ":… lasts a second or more only for the very largest impacts …" (Melosh, 1989: 46), and its duration is given by:

$$\tau = L/v_i \quad (15)$$

where v_i is the meteorite's initial velocity and τ is the time required for the impactor to travel through the target rock a distance equal to its diameter L in a vertical impact. Note that $v_f = 0$.

The kinetic energy of a high-velocity meteorite that is transformed into compression waves and heat energy may be practically unlimited, although most of the meteorite's kinetic energy is stored in the compressed rock rather than transformed into heat. According to Baldwin (1963: 69–70) during an impact event,

> … much of the energy is transmitted in shock waves through the crust and air and thence gradually converted into heat [and] … It is only after the velocity drops below that of the shock waves that the phenomenon of heat enters the picture.

Estimates are that around "… 25–50% of the projectile's original kinetic energy was converted into heat …" during the Chicxulub impact event (French, 1998: 8). Hot rock may be buried, though, at a depth that is as great as the final crater depth. Melt layers near the surface would cool quickly, but the cooling time for deeply-buried layers would be much slower. "Melt in the breccias lens underlying a 15-km diameter crater is thus about 100,000 years." (Melosh: 1989: 129).

The meteorite's kinetic energy is distributed over both the impactor and the target rock. Some of the kinetic energy becomes internal energy during compression and can initiate shock-metamorphic effects in the rock (French, 1998). The shock wave in target rock propagates outward in a hemispherical shape with the center on average about one impactor diameter below the surface. In solid rock, the impactor will penetrate

> … no more than 1–2× its own diameter before its kinetic energy is transferred to the target rocks by shock waves generated at the interface between projectile and target … (French, 1998: 18).

When the shock wave traveling through the meteorite reaches the rear surface, it is reflected back into the now-compressed impactor as a rarefaction or release wave unloading the impactor from the high shock pressures. The contact and compression stage is considered to be over when the release wave hits the front of the impactor (French, 1998). After the release wave reaches the leading edge of the impactor and completely unloads it,

> … the projectile itself plays no further role in the formation of the impact crater, and the

> actual excavation of the crater is carried out by the shock waves expanding through the target rocks … (French: 1998: 19).

At this point, the remaining energy, around 90% of the total energy of the impactor, is thus transferred to the target (Melosh, 1989). As the impactor unloads from the high pressures it may expand into the vapor phase (ibid.). In fact, if the shock pressures are sufficient for the vaporization of the meteorite, the vapor will expand out of the crater as a high-speed vapor plume (ibid.).

The onset of 'jetting', a hydrodynamic ejection of material at high velocities, occurs with the appearance of rarefaction waves (Gault et al., 1968). The jet comes from the interface of the compressed target rock and the impactor, which is the region that has been subjected to the highest pressures, and therefore the highest temperatures. The jet, therefore, includes material in a liquid state and superheated vapor.

It is during the contact and compression stage of impact that the largest shock pressures are attained and these pressures are far greater than pressures generated during volcanic or chemical explosions. The hemispherical shock wave that propagates through the target rock weakens with expansion, but

> Rock-hard substances suddenly become compressed to unusual densities. Matter acts as though it were liquid, or at least extremely plastic … Compression effects will make rock rebound like rubber … (Baldwin, 1963: 6).

A change in the physical and chemical properties of a solid induced by a shock wave is called a shock effect. Impact or shock metamorphism results in shock effects generally seen on the scale of mineral grains and represents unequivocal evidence of meteoritic impact (Stöffler and Langenhorst, 1994). Quartz is the most reliable indicator of shock metamorphism because it is an abundant, widely distributed rock-forming mineral and displays the greatest variety of well-defined permanent shock effects. The stable form of SiO_2 in rocks of Earth's upper continental crust is trigonal α-quartz which behaves differently under shock compression than in static laboratory experiments and natural tectonic environments (ibid.).

Stöffler and Langenhorst (ibid.) propose the following petrographic classifications for shocked quartz. In the low pressure regime: planar microstructures divide into planar fractures (PF), planar deformation features (PDF) which are subdivided into non-decorated PDFs and decorated PDFs, and mosaicism, which is a highly-irregular mottled optical extinction pattern. PFs appear in parallel sets of open fissures and spacing per grain for PFs is greater than 15 μm, typically more than 20 μm. Fractures are evidence of very weakly-shocked quartz and should not be considered as diagnostic shock effects. Having said that, sets of multiple PFs *are* the product of impact-generated shock waves. Natural quartz from non-impact settings does not generally show PFs, or cleavage, and this rarity —or complete absence—of cleavage in natural quartz from non-impact settings indicates that PFs, when intensely developed in multiple sets, can be used as indicators of shock metamorphism and meteorite impact (French and Koeberl, 2010; French et al., 2004). This is especially important for the study of structures showing no other evidence of shock metamorphism, such as the Rock Elm Structure in Wisconsin.

PDFs occur as multiple sets of parallel, planar optical discontinuities, which are in fact amorphous lamellae, with spacing that ranges from 2 to 10 μm. With increasing shock intensity, PDFs become more closely spaced. Another type of PDF consists of thin multiple lamellae of Brazil twins (ibid.). Stöffler and Langenhorst (1994: 168) state that

> It is absolutely mandatory that any claim to have observed shock-induced PDFs in quartz at least must provide data on the crystallographic orientation and the (clearly defined) frequency of PDFs based on stereographic projections of universal or spindle stage data.

In the high pressure regime, shock effects include: diaplectic quartz glass (shock-amorphized quartz), the high-pressure polymorphs coesite and stishovite, silica glass (lechatelierite) and the condensation products of shocked vaporized quartz (Stöffler and Langenhorst, 1994). Stishovite is formed at lower pressures than coesite because stishovite is formed during shock compression and coesite crystallizes during pressure release. French and Koeberl (2010) note that even though post-stishovite phases have recently been reported from deep-seated mantle rocks under ultra-high pressure, stishovite remains an excellent indicator of impact when found in sediments or upper crustal rocks. Table 1 lists shock pressure and effects during impact.

4.3 Excavation and Ejection

The high pressures of the contact and compression stage decline rapidly during the excavation stage as the shock wave expands and weakens due to being spread over a larger volume of target material. Excavation begins and the crater cavity opens, forming the transient crater as ejecta begin to move upward and outward (French, 1998). The shock pressures are greatest directly below the impact site, but do not vary much over the expanding hemispherical shell (Melosh, 1989). As pressure increases, yield strength for intact target rock increases, however the strength of rock, both intact and fragmented, decreases

Table 1: Shock pressures and their effects (after French, 1998: 33).

Approximate Shock Pressure (GPa)	Estimated Postshock Temperature (°C)*	Effects
2–6	<100	Rock fracturing; breccia formation
		Shatter cones
5–7	100	Mineral fracturing: (0001) and $\{10\bar{1}1\}$ in quartz
8–10	100	Basal Brazil twins (0001)
10	100*	
		Quartz with PDFs $\{10\bar{1}3\}$
12–15	150	Quartz → stishovite
13	150	Graphite → cubic diamond
20	170*	
		Quartz with PDFs $\{10\bar{1}2\}$, etc. Quartz, feldspar with reduced refractive indexes, lowered birefringence
>30	275	Quartz → coesite
35	300	
		Diaplectic quartz, feldspar glasses
45	900	Normal (melted) feldspar glass (vesiculated)
60	>1500	Rock glasses, crystallized melt rocks (quenched from liquids)
80–100	>2500	Rock glasses (condensed from vapor)

* For dense nonporous rocks. For porous rocks (e.g., sandstones), postshock temperatures = 700°C (P = 10 GPa) and 1560°C (P = 20 GPa). Data from *Stöffler* (1984), Table 3; *Melosh* (1989), Table 3.2; *Stöffler and Langenhorst* (1994), Table 8, p. 175.

with increasing temperature (Collins et al., 2004). Target rocks are heterogeneous and so respond non-uniformly to shock and deformation during the cratering process, resulting in a range of deformation features displayed in any particular zone (ibid.).

The shock wave continues to expand throughout excavation degrading into a stress wave and then into an elastic wave. The rate of decline of the strength of the shock wave determines the amount of vaporized or melted target rock, and

> The mass of melt is roughly ten times larger than the mass of vapor. This general relation is a simple geometrical consequence of the rate of decline of pressure with radius. (Melosh, 1989: 64).

Energy available to drive the expanding shock decreases as it spreads and is consumed in heating, melting and vaporizing material. An excavation flow begins after the shock wave has passed the now-shocked target materials, and the first ejecta to leave an impact crater is the vaporized meteorite and target material expanding out of the growing crater.

> Impact velocities must exceed about 10 km/second for significant amounts of vaporization in either silicate or water ice impactors or targets. (Melosh, 1989: 68).

A gas plume will move faster than the classic ejecta and enclose the expanding crater in an atmosphere of vaporized meteorite and target rock (ibid.). Although jetting initiates mass ejection from the forming crater, most of the ejected material is removed later under lower stress conditions and with modest ejection velocities (Gault et al., 1968). The ejected material moves up and out from the growing crater in a steady flow that develops into an inverted, conical-shaped debris curtain above the target surface.

Fractured rock is weaker than intact rock and porous rock, when compressed, initially compacts with no associated rise in strength (Collins et al., 2004). Porous target material is not an effective translator of shock waves, consequently, the shock exists only in the vicinity of the projectile (Kadono, 1999). Porous target material contains a solid component and a void-space component. Wünnemann et al. (2006) investigated the effect of porosity and internal friction on transient crater formation through numerical modeling and found that both play a role in limiting crater growth, especially in cases where gravity is much less than the Earth's gravity. Their porous-compaction, ε-alpha, model accounts for the collapse of pore space by assuming the compaction function depends, not on pressure, but on volumetric strain. The crushing of a large volume fraction of void space in porous targets absorbs shock waves and results in higher post-shock temperatures than impacts into non-porous targets. More energy is required to produce impact craters of the same size in porous targets than in non-porous targets.

The volume fraction of void space in target material, or porosity, ϕ, for a target of total volume V_T, with solid component volume V_S and pore space volume V_V, is given by:

$$\phi = (V_T - V_S)/V_T = V_V/V_T \qquad (16)$$

If ϕ, = 0, then there is no void space in the target, whereas ϕ = 1 implies no solid component. Therefore, if ρ_T is the bulk density of porous rock and ρ_S is its solid component density, then

$$\rho_T = \rho_S(1 - \phi) \qquad (17)$$

Changes in the bulk density of porous target material are due to both the compaction of pore space and compression of the solid component. In an idealized example, all pore space is crushed out before any compression of the solid component takes place.

The amount of resistance to volume change and amount of irreversible work done in porous versus non-porous material is different because it is easier to compact a porous material than to compress a non-porous sample of the same material. The ε-alpha model is a way of describing the crushing of pore space as a function of compressive stress (Wünnemann et al., 2006). The P-alpha model provides a simple way of computing the compaction of void space in porous material from applied pressure, P. In this model, a distension parameter, α, is given by:

$$\alpha = 1/(1 - \phi) = V_T/V_S = \rho_S/\rho_T \qquad (18)$$

So, for some amount of porosity, $0 < \phi < 1$, the model indicates $\alpha > 1$ (ibid.).

The greater amount of irreversible work performed on porous target material raises its internal energy to a higher level as compared to non-porous material. In non-porous target material, the kinetic energy of impact results in rapid material compression giving rise to the generation and propagation of a shock wave. In porous material, most of the impact energy is utilized in the irreversible crushing of void space. Shock waves decay more rapidly in porous material due to the compaction of pore space. Therefore, a crater formed in porous material is deeper and smaller in diameter than one formed in non-porous material by the same amount of impact energy since the lower bulk density of the porous material allows for the deeper penetration of the projectile (Wünnemann et al., 2006). It is also possible that lower shock pressures in porous target material may result in less resistance due to friction. The ε-alpha model indicates that the effect of porosity is to reduce the diameter of a transient crater in porous relative to non-porous material uniformly for all projectile sizes and all gravitational accelerations. However, when internal friction is varied independently, the reduction of transient crater size becomes more significant with decreasing gravity and projectile size (ibid.).

A projectile appears as a point source when any crater-related phenomena occur far from the point of impact (Housen and Holsapple, 2011). Small craters in cohesive materials form in a 'strength regime', because it is the impactors' material strength, Y, which determines the crater size. For larger craters, gravitational forces dominate any strength, so gravity, g, determines the crater size in the 'gravity regime' (ibid.). There are various strength measures of a material including compressive, shear, tensile, and others. The effect of target properties such as strength and porosity on ejecta is not understood, nor is the effect of speed. Housen and Holsapple (ibid.) developed a point-source scaling model for ejecta mass and velocity distribution to fit data for materials distinguished by porosity. Energy is lost during compaction of pore spaces which results in a reduction of ejection speeds. For launch position, x, at which a particle with ejection velocity v crosses through the plane of the original target surface of density ρ, and a, U and δ are the impactor's radius, velocity, and mass density respectively, the ejecta velocity distribution can be described by either

$$v/U = C_1[x/a(\rho/\delta)^{v}]^{-1/\mu} \qquad (19)$$

where C_1 is a constant determined from fits to data and the exponent μ depends on the high pressure properties of the target, or

$$v/(gR)^{1/2} = C_2(x/R)^{-1/\mu} \qquad (20)$$

where R is the apparent radius of the final crater. The choice of which equation to use depends on whether the impactor properties or the crater size is known (Housen and Holsapple, 2011). Experimental results indicate that $\mu \sim 0.41$ for dry soils and $\mu \sim 0.55$ for non-porous materials such as metal, water or rock. Though it has not yet been determined, it is expected that $\mu < 0.4$ for highly porous materials.

In high-speed impacts, the impactor and part of the target rock vaporize and expand back out of the forming crater as a hot gas, while other target rocks are melted and line the crater or accumulate in a pool at the bottom. As the hot gas expands, around 50% of it condenses into liquid droplets or solid particles while the rest may end up as free atoms and molecules in the atmosphere or in space (Melosh, 1989). Nininger discovered large quantities of 100–200 μm nickel-iron spherules surrounding the Barringer Crater in Arizona in 1946 and believed that "… they condensed from the nickel-iron projectile that produced the crater, and their abundance supports his view." (Melosh, 1989: 70). He also notes that the spherules, however, may have "… originally formed from splashes of melted, but not vaporized, nickel-iron." (ibid.).

Ejecta begins to cover the surrounding area as the excavation opens a transient crater that is many times larger than the meteorite (Melosh, 1989). Excavation is completed in seconds to minutes depending upon crater size (French, 1998). The impact-induced shock wave expands hemispherically away from the shock point reaching the surface, which is a "… plane of zero pressure …", producing a rarefaction wave

> … equal in strength but of opposite sign to the shock wave, which starts downward from the surface as soon as the shock wave arrives. (Melosh, 1989: 71).

The sum of the pressures exerted by these two waves is zero on the surface; however, the rarefaction wave propagates downward fracturing the rock as it goes, and

> Where the stresses in the tensional release wave exceed the mechanical strength of the target rocks, the release wave is accompanied by fracturing and shattering of the target rock … (French: 1998: 20).

This causes the brecciation and fracturing found in impact structures, as the target rock is usually not crushed by the shock wave. Instead,

> … the rarefaction following the shock propagation downward and outward many times the crater depth or diameter, fracturing the rock *in tension* as it goes. (Melosh, 1989: 72).

Near-surface rocks are not only shattered, but are ejected at high speed due to the wave "… reflection process which converts some of the initial shock-wave energy to kinetic energy …" (French, 1998: 20). As the shock wave passes through, it leaves the target rock behind in motion, so this zone near the surface is "… the source of an extraordinary body of ejecta." (Melosh, 1989: 73). The excavation flow is considered to be ejected when it rises above the original target surface

Debris ejected from an impact crater is deposited with the greatest thickness along the crater rim, thinning out with increasing distance from the crater. If the ejecta forms a continuous deposit, then it is referred to as an 'ejecta blanket'. Impact crater debris tends to travel together after ejection forming, as stated earlier, an ejecta curtain with the greater proportion of melt glass and highly-shocked fragments occurring higher up in the curtain (Melosh, 1989). If an ejecta curtain forms, it has the shape of an inverted cone because

> Ejecta from near the impact site travels at high speed, whereas ejecta emerging at larger distances travels at lower velocities …" (Melosh, 1989: 75).

Melosh (ibid.) notes that high-velocity ejecta are usually highly shocked, but even the lowest velocity ejecta which will form the crater rim will contain some highly-shocked impact melt (cf. French, 1998).

Crater rims are not composed only of material ejected from the crater during excavation, but also of rock that has been pushed outward and upward. Strong compressive forces press horizontally outward from the excavating crater causing rock to fracture and then be squeezed upwards. According to Baldwin (1949) the radially-outward dip of the upraised crater rim is indicative of an impact event. About half of the rim height is due to structural uplift of target rock which is greatest beneath the crest of the crater rim and then decreases with increasing distance from the point of impact, dropping off to "… zero approximately 1.3 to 1.7 crater radii (center-to-rim-crest radius) from the crater's center." (Melosh, 1989: 87). In addition, brecciated rock is emplaced into fractures and dikes beneath the crater floor and rim during the brief time of low vertical stress after target material is thrown upward but has yet to settle back on the floor and on growing rim of the crater (French, 1998). Only the top one-third of the transient crater material is ejected, and the "… rest of the crater is excavated by displacement of target material downward and outward beneath the crater rim." (Melosh, 1989: 88).

The rest of the rim height is due to the ejecta that then lands on top of this uplift. Some of the ejected debris moves at such low speed that it retains its stratigraphy and forms an "… overturned flap …" seen as an area of "… inverted rock units." (Melosh, 1989: 87). If this material collapses into the crater, however, an overturned fold may not survive the modification stage. Ejecta that land beyond the crater rim mix into jumbled breccia that includes material from the target surface.

According to Melosh (1989: 88), crater rim height, h, for uncollapsed simple craters where D is the crater's rim-to-rim diameter, is given by

$$h = 0.036D \qquad (21)$$

This formula was derived from measurements "… of many lunar, terrestrial, explosion, and laboratory impact craters." (ibid.). For larger transient craters that experience a sub-sequent collapse as the overturned flap and rim crest slide down into the crater, the equation's coefficient and power of *D* varies depending on the surface material and gravity. According to Melosh (ibid.), for a lunar crater with a dia-meter of over 15 km, this equation takes the form

$$h = 0.236 D^{0.399} \quad (22)$$

Ejecta deposits consist of broken rock fragments, called clasts, mixed with glass. Though small rock fragments dominate the ejecta, clast size can reach many meters in diameter; in fact, the largest fragments that are ejected may form secondary craters. The larger impact craters can be accompanied by one or even more secondary craters that form clusters or lines. Secondary craters usually have steeper slopes in the direction of the primary crater becoming more circular with increasing distance from the primary. Secondary crater clusters also become more widely dispersed with increasing distance from the primary (Melosh, 1989). Clast size also decreases with increasing distance from the crater, "… an expectation that has been quantitatively verified in numerous small-scale impact experiments …" and at the Barringer Crater in Arizona (Melosh, 1989: 91). According to Baldwin (1963: 69), there is "… always a radial distribution of both meteoritic matter and crustal rock scattered over perhaps ten times the radius of the crater proper."

Crater depth is determined by the resistance of the underlying target material, but, the crater will still continue to grow in diameter after its maximum depth has been reached (Melosh, 1989). The result is a crater that is wider than it is deep. According to Melosh (ibid.), the time, T_d, required for this maximum depth, *H*, to be reached is

$$T_d \approx (2H/g)^{½} \quad (23)$$

This is basically the equation for free fall of an object falling from a height, *H*, with an initial velocity of zero, and with an acceleration due to gravity, *g*. Melosh (ibid.) also states that the time, T_f, for the transient crater with final diameter, *D*, to be completed is

$$T_f \approx (2D/g)^{½} \quad (24)$$

French (1998: 20) notes that

> The excavation stage, although longer than the contact/compression stage, is still brief by geological standards …

Depending on the transient crater size, the entire excavation process takes only a few seconds for a simple crater to less than two minutes for a transient crater that is 200 kilometers in diameter (ibid.). Gault et al. (1968) suggest that formation times for large planetary cratering events scale directly with the square root of the crater dimensions, which would indicate that the Barringer Meteor Crater formed in around 10 seconds.

The diameter of the modified final crater is rarely the same as the diameter of the transient crater that forms during the excavation stage. The collapse of the transient crater due to gravity

> … may enlarge this diameter by roughly 20 percent for small, bowl-shaped simple craters or by as much as 30 to 70 percent for the larger, more thoroughly collapsed complex craters. (Melosh, 1989: 112).

Figure 8 shows a transient crater and the final modified simple crater it would form according to Melosh (1989). After the initial modification is complete, "… the diameter of the final crater is many times larger (typically 20–30×) than the diameter of the projectile itself …" (French, 1998: 20).

4.4 Crater Modification

The excavation/ejection stage ends as soon as the transient crater has reached its maximum size (French, 1998: 23). The final stage of impact crater formation involves modification due to gravity and the elastic rebound of compressed rock layers. Masaitis (2005) points out that later modification should be divided into early and late stage modification since gravitational adjustment, viscous relaxation and doming, cooling, solidification, and compaction of the hot disturbed bed rock, fallback, and material ejected from the crater may continue for thousands of years.

After the transient crater has formed by excavation and the ejecta has been launched, the debris momentarily halts and then begins to move downward. In simple craters, this motion involv-

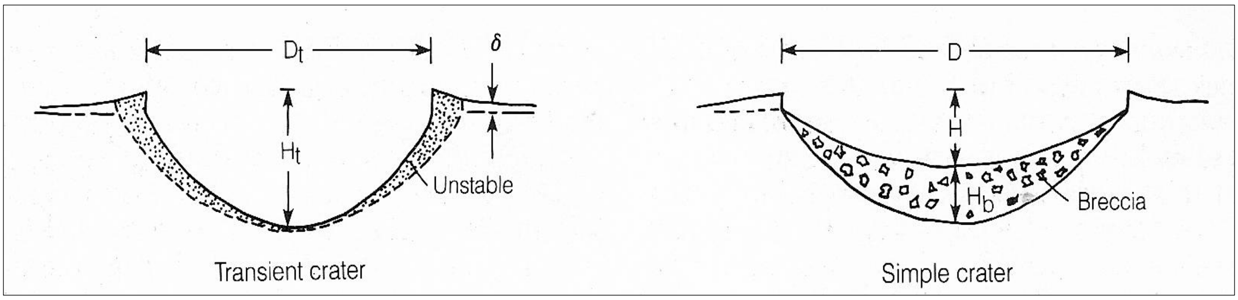

Figure 8: Diagrams showing a transient crater and the resulting simple crater (after Melosh, 1989: 129).

es fallback ejecta and debris sliding down the transient crater walls resulting in "... a bowl-shap ed depression, partially filled with complex breccias and bodies of impact melt ..." (French, 1998: 20). Modified simple craters are rimmed, bowl-shaped pits that are not very different from the transient craters that formed them (French, 1998). Figure 8 shows the difference between the transient and final simple crater, the primary difference between the two being the breccia lens that covers the floor of a modified simple crater. The breccia lens consists of broken rock mixed with shocked fragments and impact melt that slides back into the crater along with part of the inner rim. The slope of the crater walls gradually decreases in the direction of the crater's center until the floor becomes flat. The thickness of the breccia lens is about half of the rim top-to-floor depth (ibid.). The final simple crater size "... is only slightly larger in diameter than the transient crater but is significantly shallower." (Melosh, 1989: 129).

In matching observational data to model predictions, Collins et al. (2005) found a first order approximation of the final rim-to-rim diameter, D_{fr}, for a simple crater in relation to the transient crater diameter, D_{tc}, measured at the pre-impact surface, is given by:

$$D_{fr} \approx 1.25 D_{tc} \quad (25)$$

For a 'fresh' complex crater measured from rim crest to rim crest, where D_c is the diameter at which the transition from a simple to a complex crater occurs, that is 3.2 km on Earth (ibid.):

$$D_{fr} \approx 1.17 D_{tc}^{1.13} / D_c^{0.13} \quad (26)$$

Pilkington and Grieve (1992) use known morphometrical scaling relationships to develop models relating impact crater diameter, D, and the effect of gravity. The true impact crater floor, marked by the base of the allochthonous breccia lens, may be filled with post-impact sediments. For this apparent crater depth, d_a, and true crater depth, d_t, (both in km) of simple craters the following empirical relationships, independent of target lithology, have been determined:

$$d_a = 0.13 D^{1.06} \quad (27)$$

$$d_t = 0.28 D^{1.02} \quad (28)$$

For complex craters formed in sedimentary lithologies

$$d_a = 0.12 D^{0.3} \quad (29)$$

$$d_t = 0.20 D^{0.4} \quad (30)$$

and for complex craters formed in crystalline lithologies

$$d_a = 0.15 D^{0.4} \quad (31)$$

$$d_t = 0.52 D^{0.2} \quad (32)$$

While simple craters experience primarily the collapse of the steep crater rim, larger transient craters are completely altered in appearance upon collapse producing central peaks surrounded by a flat floor and terraced walls due to slumping. A complex crater's final depth is shallow and the width much greater than that of the transient crater preceding collapse, as shown in Figure 9. However, this diagram is an over-simplification since it does not show the terraced walls and central uplift that are typical of a complex crater (see Figure 10). Terrestrial complex craters have depths >0.5 km, but their central peaks are seldom higher than the crater rim and are usually closer in height to the elevation of the unaltered area surrounding the crater (Melosh, 1989). Central peak diameter is 0.22 $\pm$ 0.03 of the crater's diameter and is "… apparently independent of the planet on which the crater forms." (Melosh, 1989: 132). This statement includes not only the Earth,

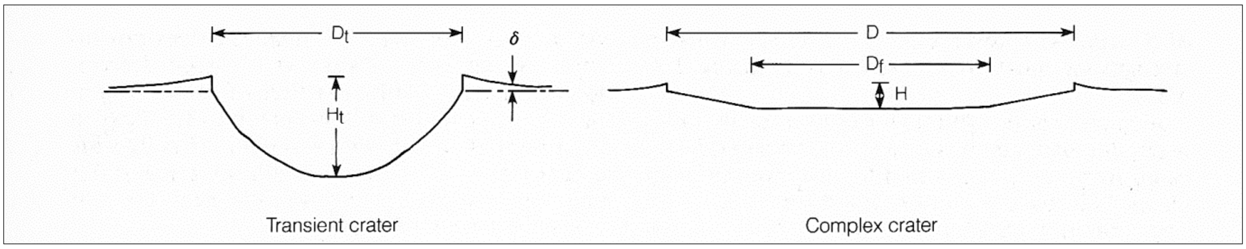

Figure 9: These diagrams show the final crater diameter, D, of a complex crater compared to the smaller diameter, D_t, of the transient crater, and the transient crater's depth, H_t, which is greater than the complex crater depth, H (after Melosh, 1989: 144).

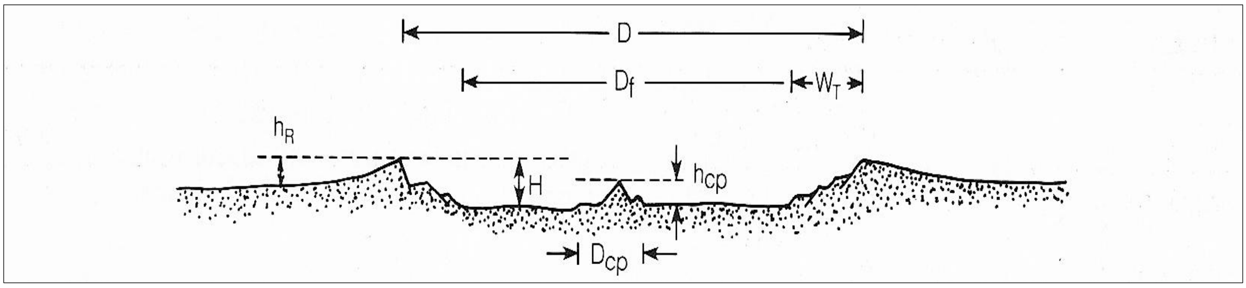

Figure 10: The final form of a complex crater, including the central uplift and terraced walls. Here W_t is the width of the terraced zone, D_{cp} is the diameter of the central uplift and h_{cp} is its height (after Melosh, 1989: 132).

Mercury, and Mars, but also our Moon and perhaps Ganymede and Callisto (ibid.). For larger craters, the diameter of an inner peak ring is about half the crater rim diameter or $D_{PR} = (½) D_F$ (ibid.).

The sudden onset of complex crater collapse indicates that a definite strength threshold has been exceeded beneath craters larger than a critical size (Melosh, 1989). This strength threshold (*ST*), in kg/ms^2, can be estimated by dividing the negative buoyancy force associated with the crater cavity by the area of a hemisphere enclosing the crater, that is:

$$ST = (\pi/8)\rho g H D^2/(\pi/2)D^2 = \rho g H/4 \quad (33)$$

for rim-to-rim diameter *D*, rim-to-floor depth *H*, and density *ρ*, where *g* is the acceleration due to gravity. Slip-line analysis applied to the collapse of impact craters gives an accurate description of their collapse (Melosh, 1989). Materials fail when the shear strength exceeds a defined yield stress called cohesion, *c*. In terms of the transient crater diameter D_t and height H_t, parabolic craters are stable until the parameter $\rho g H_t/c > 5$. Slope failure, that is when a rim segment slides into the crater producing a terrace, occurs for $10 > \rho g H_t/c > 5$. If $\rho g H_t/c > 15$, then "… the floor beneath the center of the crater rises almost vertically upward as the rim slumps downward …" (ibid.). For a transient crater diameter $D_t = 0.27 H_t$:

$$0 \leq D_t \leq 13.5\ c/\rho g, \text{ stable} \quad (34)$$

$$13.5 \leq D_t < 27\ c/\rho g, \text{ slope failure} \quad (35)$$

$$27 \leq D_t < 40\ c/\rho g, \text{ floor failure} \quad (36)$$

Final depth of a complex crater, *H*, is independent of the initial crater's diameter and is found by:

$$H \sim 5c/\rho g \sim H_{threshold} \quad (37)$$

Roddy and Davis (1977: 744) determined that *in situ* shatter cones "… point in the direction of the shock wave source with their axes normal to direction of shock wave propagation." French (1998) agrees that the orientations of shatter cones axes found in rock surrounding terrestrial complex craters point to the location of the source of the shock wave that formed them. The mapping of shatter cones often show them pointing upward or even outward in the crater's central region, and

> The simplest explanation of this observation is that the rock units were uplifted and tilted away from the crater center following the passage of the shock wave … (Melosh, 1989: 140).

If the original crater shape is reconstructed from the orientation of shatter cones, then the crater is found to originally have a deep bowl shape with a depth/diameter ratio about equal to that of the transient crater (ibid.). Terrestrial crater structural studies indicate that modification from the transient to the complex crater involves the extensive and general collapse of the initially-deep transient crater, and is achieved by uplift of target rock under the crater center and by rock nearer the crater's rim slumping downwards and inwards (ibid.)

The central uplifts found in terrestrial complex craters are composed of fractured and deformed rock that was originally under the transient crater. This rock has been uplifted a distance that is comparable to the transient crater depth and is not a breccia mix like that found in simple craters. Melosh (1989) also notes that the central stratigraphic uplift, SU, referred to as the height, *h*, in this equation, can be related to the final diameter of the crater, *D*, by

$$h_{SU} = 0.06D^{1.1} \quad (38)$$

The stratigraphic uplift is about half the depth of the transient crater (ibid.). From a study of 24 complex terrestrial impact structures, Grieve and Pilkington (1996) suggest that structural uplift (*StU*) where *D* is the rim diameter of the impact structure is given by:

$$StU = 0.086D^{1.03} \quad (39)$$

French (1998: 25) points out "… the two equations [38 and 39] are virtually identical, and a value of $StU = 0.1D$ is a reasonable approximation to either." He also states that even in the largest structures,

> … both theoretical and field studies indicate that central uplifts form in only a few minutes, almost instantaneously by geological standards (ibid.).

According to Baldwin (1949: 149), during the contact/compression stage of an impact event, a great deal of momentum is transferred to the compressed target rock which then rebounds during the initial modification stage to become fixed as a structural dome. When the tremendously-hot and compressed plug of rock and meteorite explodes violently, it results in "… a series of concentric waves …" moving outward in all directions which will result in ring synclines and anticlines in rock at the site of impact (Baldwin, 1949: 99). Anticlines fold downwards on both sides and synclines fold upwards on both sides from a median line of rock strata. The largest structures have more than one ring surrounding the impact site and are referred to as multi-ring basins (French, 1998).

Central peaks form in the modification stage of impact according to Milam and Deane (2005), as follows. During the contact/compression stage, deformation causes weakening of the rock which allows for the movement of large blocks of rock in the central area of the impact crater. The target rock typically is fractured, faulted and shows signs of melting and shock deformation.

When the resulting pressure is released, a rebound of target material occurs allowing large blocks of rock to move upwards. The "… major faults are likely responsible and represent the final stages of central uplift formation." (Milam and Deane, 2005: 2). This rock then becomes fixed structurally as it is damped by tension fractures. They also note that an uplift is often surrounded by a ring syncline and possibly an anticline. If the central peak is over-steepened or weak, then it may collapse forming a series of structural ring structures in sedimentary target rock since it is much less resistant to horizontal movement than crystalline rock (Ferriere et al., 2011). Luizi is a confirmed impact structure in the Democratic Republic of Congo that displays just such structural rings: a ~2 km wide central ring surrounding a central depression along with a ~5.2 km intermediate ring which is in turn surrounded by an annular depression and an elevated rim some 17 km in diameter.

French (1998) agrees that it is during the modification stage after the excavation and ejection of target rock that the central uplift will rise. Once a meteorite impacts a solid surface and blasts out a large impact crater, the underlying rock is compressed downwards and outwards and then rebounds upwards and inwards. The rock cannot fall back to its original position since that original space is now filled in by rock that has moved in from the sides. French (1998: 24) gives the following description:

> A simple model of the formation of a complex crater and its central uplift is presented by the familiar slow-motion movies of a drop of liquid hitting a liquid surface … There is the same initial cavity formation, the same outward and downward ejection of target material, the same upward rebound of the central cavity floor, and the same collapse of the periphery back into the cavity.

During impact,

> Rock-hard substances suddenly become compressed to unusual densities. Matter acts as though it were liquid, or at least extremely plastic … Compression effects will make rock rebound like rubber … (Baldwin, 1963: 6).

As stated, Baldwin (1963:107) suggests that rebound is responsible for central uplifts. In this scenario, rocks below the crater have been strongly compressed by the impact force and then spring back when the stress is relieved, causing the crater floor to move upward forming a structural dome. Most structures exhibit this shock-wave rebound pattern with a central dome when enough time has passed for erosion to expose the basement structure, and in the central regions a jumble of shattered and brecciated rock is found. The impact structures we study today, though, may not give a true indication of the original appearance of complex craters since it is only the basement structure of an impact crater that is visible after extensive erosion, and

> The fact that all the highly eroded impact structures show a central rebound dome does not imply that all the original craters exhibited central peaks. (Baldwin, 1963: 108).

If enough fallback breccias filled the crater, the peaks may have not have been of a sufficient height to extend through the breccias.

Melosh (1989: 141) makes an interesting observation:

> This process has no obvious dependence on gravity or crater size, and so probably cannot explain the central peaks of complex craters …

although it may explain central peak formation in impact craters where the impactor made only a very shallow penetration of the target rock. Melosh instead believes that geological and morphological evidence supports complex crater development from a bowl-shaped transient crater, and that it is gravity driven (ibid.). Melosh (1989: 142) gives the following equation for time, T, required for the rise of the central peak:

$$T \leq (D/g)^{1/2} \qquad (40)$$

and he believes that the crater floor uplift starts before the rim is fully formed. This would indicate that the complete parabolic transient crater never completely forms, since the uplift begins as soon as the final transient depth is reached and before the rim is completed.

Melosh (ibid.) also notes that breccia lenses are not found in the centers of complex craters, indicating a collapse that is so rapid that there is not enough time for debris to slide down the transient crater walls. Instead, breccia in complex craters fills a ring depression located between the crater's rim and central uplift. Complex crater floors are covered with breccias and melt rock that lie in the same stratigraphic sequence that lined the transient cavity (ibid).

Melosh (1989) believes that the terraces surrounding the crater floor form quickly, before the impact melt has time to solidify. He points out that complex crater

> … terraces fade smoothly into the solidified impact melt covering the crater floor without any sign of disruption by movement after the melt solidified … (Melosh, 1989: 142).

Crater terraces are widest near the rim and tend to narrow toward the central region.

Melosh (1989: 143) points out that rock debris motion within a forming crater is apparently "… fluidlike, involving rapid uplift of a central peak, analogous to the central jet that forms when a cavity in water collapses …", which is in agreement with Baldwin (1963) and French (1998), indicating that if central peaks do form by a hydrodynamic mechanism then the rock beneath the crater must behave as a fluid during uplift. Unlike the flow in a fluid, however, the flow in a forming crater is 'frozen' at some point depending upon the crater's size and the viscosity of this fluid, and "The central peak is, in effect, a damped harmonic oscillator …" (Melosh, 1989: 147).

One early idea that was proposed for the fluid-like behavior of rock debris in impact craters was that it was

> … fluidized by impact melt. The debris flows briefly as a melt-solid slurry until it cools and solidifies … (Melosh, 1989: 151).

Although some impact melt is found on complex crater floors, it is only rarely found in central uplifts or in the stratigraphical uplift region beneath the crater where the fluidization would be required. Melosh (1989: 154) suggests that "… crater collapse facilitated by acoustic fluidization."

Although the crater collapse process is reasonably well understood for the smaller, simple craters, the collapse of complex impact craters is still a poorly-understood process that has a profound influence on the final morphology of the crater (Collins et al., 2004). This is due to the fact that there has not been a direct observation of complex crater collapse in recorded history, and the limitations of small-scale laboratory experiments. Since crater collapse is gravitationally driven, small-scale experiments cannot be extrapolated meaningfully to the scale of complex craters. There is evidence that natural rock is weaker on scales of tens to hundreds of meters with respect to laboratory strength measurements of centimeter-scale rock samples. The best avenues for studying complex crater collapse are computer simulations and observational analysis of impact structures, however, damage due to impact must be carefully interpreted when numerical modeling is utilized (ibid.).

Shatter cones have been considered proof of impact for decades; however, their formation is still not well understood. Numerical simulations of impact using the hydrocode SALE 2D, enhanced by the Grady-Kipp-Melosh fragmentation model, suggest that shatter cones are initiated by heterogeneities in the target rock (Baratoux and Melosh, 2003). With pressures of 3-6 GPa, if the shock wave travels faster in target rock than in the heterogeneity by a minimum factor of around 2 and the dimensions of the heterogeneity are comparable to the width of the shock wave, both of which are smaller than the resulting shatter cone, then according to the model a shatter cone will form. Based on this model, the apical angles of shatter cones seem to depend on the properties of the heterogeneity and the decay time of the shock wave. The angle of the shatter cone, θ, may be found by:

$$\theta(t) = 2 \arccos (1-\beta\tau/\delta t) \qquad (41)$$

where τ is the rise time and $\beta\tau$ is the decay time of the stress wave, and δt is the time elapsed since contact between the shock front and the heterogeneity (ibid). The authors suggest that this model should be validated by new measurements of the shapes, sizes and distribution of shatter cones in various impact sites.

Collins et al. (2005) have developed a Web-based program that calculates regional environmental devastation of a terrestrial impact requiring only six descriptors: meteoroid diameter and density, meteoroid velocity before atmospheric entry, impact angle, the distance from impact at which the environmental effects are to be calculated, and whether the target is sedimentary rock, crystalline rock, or a water layer above rock. The most far-reaching environmental consequence is seismic shaking since ejecta deposit thickness and air-blast pressure decay more rapidly with distance than does seismic ground motion. The most devastating effect is thermal radiation close to the impact site. Melosh (1989: 212) gives the radius, R (in meters), of a vapor cloud formed in a high velocity impact as:

$$R = [(3V_i/2\pi)(P_i/P_a)^{1/\gamma}]^{⅓} \qquad (42)$$

where V_i and P_i are the initial pressure and volume of the gas, P_a is the pressure of the ambient atmosphere, and γ is the ratio of specific heats of the gas. If the energy, E_a (in joules), deposited in the atmosphere by the vapor plume is known, then (ibid.)

$$R = 0.009E_a^{⅓} \qquad (43)$$

4.5 The Howell Structure as a Meteorite Impact Scar

Back in 1937, Boon and Albritton pointed out that long after a meteorite crater and its associated ejecta and meteorite fragments have been removed by erosion and weathering, an impact structure, or 'meteorite scar', may persist in the geologic record. Figure 11 is a cross-section through a hypothetical meteorite impact crater according to Boon and Albritton, but the actual appearance of the crater remnant will depend on the extent to which it has been eroded. It is

> … only in the initial stage (along the profile AA) that the crater clearly reflects its origin in the rim of ejected material, silica glass, and meteorite fragments distributed around it. The scar will become inconspicuous when the country is denuded to level BB. When the area is down to the level CC the underlying structures begin to appear, and when the depth DD is reached the central uplift and ring folds become apparent. Should erosion proceed to depths below those affected by the

meteoritic disturbance, the scar would be obliterated.. (Boon and Albritton, 1937: 56).

Given the age of the surrounding lithostratigraphic units, the extent of erosion during the ensuing years and the lack of any surface evidence of a central uplift, the Howell Structure is represented by the DD transect in Figure 11.

5 CRYPTO-CONTROVERSIES

Fossil meteorite craters display certain characteristic features, such as circular limits of deformation, and faults and joint sets that are within a crater's area of deformation and to some lesser extent outside of the area of deformation, that usually "… demonstrate a striking radial symmetry …" (Woodruff, 1968: 19). Dietz (1960: 1781) points out, however, that

> … the formation of a chaotic, circular structure, extensive brecciation, and intense shattering are all suggestive of meteorite impact but are hardly definitive.

In addition, an actual impact structure may not be easily recognized due to subsequent geological processes:

> The actual crater morphology of such features may have been destroyed until only the "roots" are exposed, as is the case at Wells Creek, or the crater floor may have been preserved (but at the same time kept from view) by crater filling as is seen at Flynn Creek. (Woodruff, 1968: 18).

Cryptoexplosive structures have been attributed to various mechanisms, including salt-doming. Born and Wilson (1939) believe that the Wells Creek, Flynn Creek and Howell sites were not formed as a result of salt-doming:

> In a region where salt beds are unknown, either at the surface or in subsurface drilling records, salt domes could hardly be expected to occur. Furthermore, salt-doming is not believed to be sufficiently explosive to blow out a crater 2 miles [3.2 km] in diameter and 300 feet [90 meters] deep, as in the Flynn Creek disturbance. (Born and Wilson, 1939: 379).

Woodruff (1968: 17) agrees, stating that

> Although there are some who would attribute the deformation to such geologic processes as salt dome collapse, these ideas have been discredited because of gross lack of evidence …

Woodruff (1968: 17–18) then addresses the remaining possibilities for the origin of Howell and similar sites:

> Generally, there are two schools of thought about the origins of the roughly circular, highly deformed areas as seen at Howell, Wells Creek Basin, Flynn Creek, and many others … One school attributes the origin to meteor impact, the other attributes the origin to "cryptovolcanic explosions" yielding a breccia pipe from depth.
>
> The meteoritic hypothesis brings to bear on the subject the concept of shock metamorphism … Shock processes, unlike classical metamorphic processes, occur over time intervals of "from a few microseconds to a fraction of a minute."
>
> The problem in dealing with such areas of deformation in the field is to define characteristics that are unique to the shock processes and characteristics unique to "cryptovolcanic

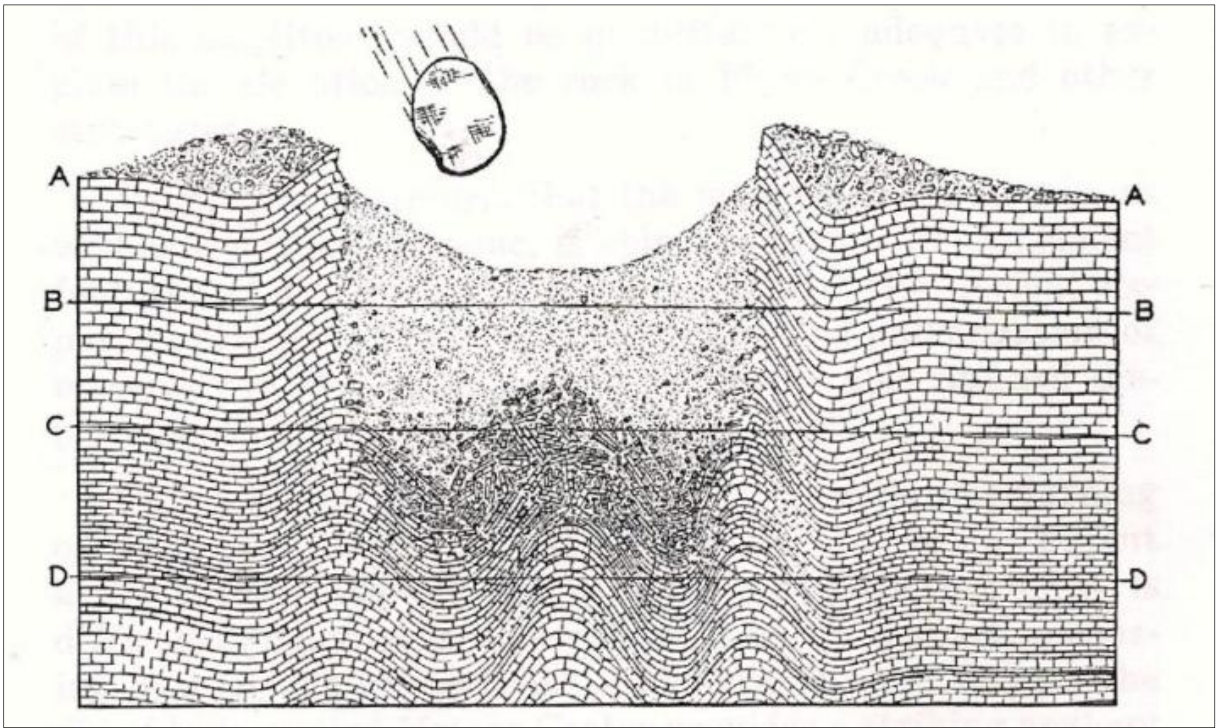

Figure 11: A section through a typical explosive impact crater caused by a meteorite (after Boon and Albritton, 1937: 57).

> processes." In finding one or another of the features, the structure can then be classified as either of "terrestrial" or of "shock" origin. In reality, however, the differentiation of the structure into the two types is not so clear cut. What a geologist has to deal with usually are only remnants of structural features that have been exposed to geologic processes for millions of years. All one finds are either greatly eroded structural features, or features that have been buried during subsequent ages. After such processes as erosion, deposition of new sediments, and possibly other structural events have sufficiently clouded the issue, the differences between features caused by shock processes in a fraction of a second, and slower formed tectonic features (and even salt dome collapse structures) become insignificant, and similar features in common become striking.

Woodruff (1968: 18) believes that

> The process that affected the Howell area in particular and certain other structures in general, were believed sufficiently explosive to have formed a crater.

Born and Wilson (1939: 379) agree, stating that they believe

> … the Flynn Creek and Howell craters, with associated injected breccias and powdered limestone, require extremely violent explosive action.

They also point out that any explanation for the structural features found at the Howell site must be able to account for the following:

> (1) a circular mass of jumbled and brecciated limestone, part of which has been uplifted approximately 100 feet [30 meters] relative to surrounding strata; (2) the shattering of Black River and Trenton limestone into blocks and the irregular jostling of these blocks; (3) the pulverizing of much of the limestone into "rock flour"; (4) the unusual ability of breccia and rock powder to force their way into fractures; and (5) the formation of a crater 1 mile [1.6 km] in diameter and more than 100 feet [30 meters] in depth, centered over the brecciated area. (Born and Wilson, 1939: 378).

Born and Wilson (ibid.) note that the above features are characteristic of the cryprovolcanic structures described by Bucher (1936), "… as well as the Wells Creek basin and the Flynn Creek disturbances in Tennessee …" which are both confirmed sites of meteorite impact. Born and Wilson (1939: 380) attribute the Howell Structure to

> An explosion, blowing out a crater at least 100 feet [30 meters] in depth and 1 mile [1.6 km] in diameter, and piling up limestone debris around the crater …

and they conclude:

> The writers recognize difficulties in both the cryptovolcanic and the meteoritic hypotheses and for the time being, prefer to maintain as neutral a position as possible until more data are found. Unfortunately, the Howell disturbance does not present new features that will aid greatly in determining the origin of this group of structures. (ibid.).

They also note that the possibility of a

> … post-Fernvale and pre-Chattanooga renewal of the same localized force that formed the pre-Fernvale crater would support the cryptovolcanic hypothesis … (ibid.).

Woodruff (1968: 19) also addresses the possible cryptovolcanic genesis of structures such as Howell:

> The presence of volcanic material may seem to be strong evidence toward the hypothesis. However, the presence of volcanic matter associated with the "fossil crater" is not unequivocal for that origin. Shock processes might well cause extensive fracturing at depth, and thus cause a drastic change in pressure which in turn might affect the geothermal gradient. Partial melting might occur with ready-made fissures for access to the surface.

Woodruff (1968: 29) also states:

> From the other evidence available – depth of deformation, roughly circular plan view and radial symmetry of geologic features, most of the Howell breccia has been categorized by this writer as being of shock type.

This would indicate that Howell is "… the ancient eroded equivalent of a meteor impact crater …" which then requires an in-depth investigation of the breccias found at Howell for confirmation (ibid.).

6 HOWELL BRECCIAS

Breccia is rock that consists of angular fragments in a fine-grained matrix. Though commonly found in confirmed impact structures, breccia is not unique to impact sites:

> Breccia may be formed by diverse processes, ranging from explosions of nuclear magnitude to collapse of solution cavities and including diagenetic breccias, fault breccias and volcanic breccias … (Woodruff, 1968: 29).

Woodruff (ibid.) points out that the end result of all of these processes is the same, but examination of the breccias themsleves does not usually give any indication of their geological origin so other evidence must be examined and considered in order to determine the genesis.

Woodruff (1968: 19) makes the interesting comment that when it comes to impact structures, breccia

> … which is so prevalent that it is used (or misused) as indication of what rocks have been affected by the structural event and which rocks have not … [is utilized in determining] the limits of deformation both laterally and vertically.

He continues, noting that

> … the extreme case of deformation is seen as breccia, and it is this criterion that has heretofore been the determining factor as to the limits of the structural features … (Woodruff, 1968: 22).

Woodruff (1968: 23) considers "… the best criterion for deformation at Howell is the presence of breccia." Meanwhile, the actual breccias found at the Howell site provide the best way of determining which rock units were deformed by an explosive event and which rock units were not involved. Woodruff (ibid.) also notes that

> … the discovery of breccia in upper-most Ordovician, Silurian, and maybe in Devonian units is of importance … mainly because of their addition to the knowledge of the extent and age of the deformation …

Born and Wilson (1939: 373) found that breccias composed of angular fragments of limestone occupied a circular area 1 mile [1.6 km] in diameter and centering around Howell, and that

> The fragments range in size from shot up to large blocks many feet in dimension and occur in a matrix of powdered limestone. Much of this breccia consists of small, angular to subangular fragments the size of walnuts. Within this type of shatter breccia occur large angular blocks of limestone that may or may not be brecciated. Many of these blocks of limestone are cut by dikelike stringers, or veins, of injected powder breccias, which suggest forceful intrusion along fractures while the injected material had a "mushlike" consistency.

However, Woodruff points out that even if Howell is an impact structure, not all of the breccia is necessarily due to shock processes. The various breccia types may be

> … a primary feature, pre-deformation, or as a secondary feature, post-deformation. One is very likely to find fault breccias, slump breccias, or collapse breccias associated with such a structure … (Woodruff, 1968: 29).

Woodruff then focuses his discussion on the formation of various types of breccias in events that are sufficiently catastrophic to yield craters. Breccias can be fragmented and granulated in place or form as "… fall back – particles thrown into the air by the explosion, but resettling into the crater proper …" (Woodruff, 1968: 30). He points out that crater fill could consist of a 'hodge-podge' of fall back, in-wash or crater rim material, and he believes that if any reworked rim material is still present at the Howell site, then it will be found only on the high ridges in the eastern section of the structure.

Woodruff (1968: 31) reports that in breccia formation,

> The same stratigraphic unit may be found to react differently to the deforming forces in different areas, reflecting various "zones" of deformation …

both laterally and vertically. He points out that "Zones may be seen in which bedding and other stratigraphic features are preserved with breccias injecting joints and bedding planes …" (ibid.), and he explains his interpretation of some of the breccia characteristics as follows:

> This retention of "relict" features with brecciation superimposed either concordantly or discordantly has been taken to indicate the fringes of deformation, especially at depth. In other words it would be where the deformation "dies with a whimper" and the forces are not sufficient to obliterate the pre-disturbance sedimentary features. (Woodruff, 1968: 31–32).

Woodruff describes the Howell breccias as generally being composed of angular to subangular fragments that grade in particle size from 'pea-size' up to blocks several meters across embedded in a matrix which most often has a sugary appearance that is gray-brown, but occasionally distinctly pink in color. He also points out that "Certain rock units may be recognized as being matrix material of certain breccias …" (ibid.). Some of the Howell breccias found by Woodruff were homogeneous, while others were mixtures of lithogies. As an example, he notes that

> … the Catheys-Leipers breccias present a hodge-podge of lithogies, in which the fragments appear to be of one rock type while the matrix appears to be another … (Woodruff, 1968: 32).

In contrast, "… the Fernvale Limestone yields a homogeneous breccia …" (ibid.).

Fossil remains were found within the brecciated rocks. A specific point of interest noted by Woodruff is that although 'fossil hash' would be expected to be preserved in breccia where fossiliferous rock units existed before the explosive event occurred, "… in at least two locations large fossils (coral heads) have been found within the breccia …" (ibid.). These coral heads are "… widely separated in stratigraphic extent …" with one sample intact within the breccia and the other with Favosites coral heads that are up to 15 cm in diameter (ibid.). Miller (1974: 22) explains that

> Corals appeared for the first time in the geologic column in Tennessee during the Ordovician time and grew in abundance in what is now the Central Basin area.

There are several different breccia types that were found and photographed by Woodruff at the Howell Structure. He describes the Howell Mega Breccia as being large blocks of rock broken apart and

> … disarranged at random orientations to one

Figure 12: A photograph of the typical Howell 'mega-breccia' matrix (after Woodruff, 1968: 34).

> another … with more 'normal' fine breccias filling the interstices between the blocks. (Woodruff, 1968: 33).

The mega-breccia blocks may themselves be brecciated. Figure 12 shows a photograph taken by Woodruff (1968: 34) at Howell of the typical 'mega-breccia' matrix he found there. Next he describes Crush Breccia or Injection Breccia by noting that "… the rocks seem to have been granulated in place without significant movement of rock material …" (ibid.). Figure 13 shows an example of the crush breccia Woodruff (1968, 35) located in Howell, which often displays relict bedding. Woodruff (1968: 36) notes that large quantities of vein injection breccia are seen in the crush-breccia, especially in creek beds, and that the veins cut across still-preserved bedding features. Figure 14 is a photograph taken by Woodruff (1968: 37) which shows a possible breccia injection vein that crosses relict bedding. Figure 15 shows what Woodruff (1968: 38) describes as a "Breccia vein showing flow pattern of fine-grained brecciated particles around larger fragments." Woodruff (1968: 33) interprets this finding to indicate that the crush-breccia rock units most likely experienced greater pressure and "… could only readjust on a small scale to the shock." In contrast,

> … the mega-breccia may generally represent a shallower zone of the deformation, and could readjust to the shock by a bulk movement of rock material … (Woodruff, 1968: 33, 36).

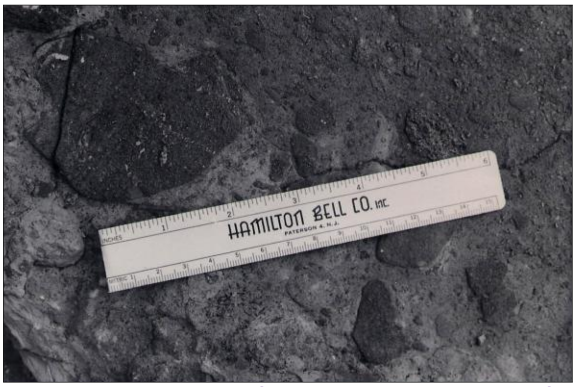

Figure 13: A photograph of the Howell 'crush breccia' (after Woodruff, 1968: 35).

The Plum Pudding Breccia Woodruff only saw in the Fernvale Limestone breccias. He states that

> … this feature was attributed to slump and crater fill … [and] the rock unit consists entirely of ferruginous limestone fragments in a matrix of the same material … (ibid.).

Figure 16 shows two photographs Woodruff (1968: 39) took of the plum-pudding breccia. The first shows it in an outcrop, and the second is a close up which shows the fragments and matrix with identical lithologies.

An unexpected finding by Woodruff involves the mix, or lack thereof, of breccias of various stratigraphic units involved in the Howell Structure:

> One would expect in dealing with an area which has been subjected to as severe a shock as meteor impact, that breccia formed would consist of a random mixture of all stratigraphic units involved. There should, it would seem, be no means of distinction between pre-deformation rock units. Certainly contacts between brecciated rock units should be virtually impossible to find. However, this writer has observed that at Howell, formation masses and even contacts are often traceable across the structure …
>
> This feature of the Howell structure is especially evident in the rocks of the Richmond Group, which were once considered post-deformation as they appear to have been deposited upon the structure proper. Even though this writer has demonstrated that the structure originated long after the Ordovician Richmond was deposited, the integrity of the mapped units in a distinct area still holds true. The same formational mass "integrity" may be generally true for the older Ordivician rock units. This has been locally observed but not fully investigated …
>
> The major problem in this assertion is the absence of a widespread zone of mixed Richmond and Nashville rocks to match the lithologic zones in brecciated older Ordovician units …
>
> Only in scattered localities have Fernvale fragments been found in lower "Nashville" breccias …
>
> One other zone that may be classified as a mixed zone is the rock in the area of high ground which as mentioned before, appears to have chert and sand mixed with certain sulfides, clays and carbonaceous material.
>
> This may be a mixed zone of reworked lithologies present before deformation. These lithologies might include Silurian (Brassfield), and Devonian (Hardin sandstone or basal sand of Chattanooga Shale), all of which could have lain within a few feet of each other before deformation. This would, of course, entail an unconformity in that no Silurian and Devonian would have been present between the Brassfield and the Chattanooga. (Woodruff, 1968: 36,

Figure 14: A photograph which shows a possible breccia injection vein that crosses relict bedding (after Woodruff, 1968: 37).

40–41).

Miller (1974: 25–26) also notes this unconformity in the geologic history of Tennessee:

> All of the Silurian rocks in Tennessee formed in marine or near shore environments …
>
> There was uplift of the land and some erosion at the end of Silurian time … but in most places it is not possible to determine how much, for two subsequent major episodes of erosion during the Devonian in some places removed all the rocks overlying the Middle Ordovician …
>
> There was renewed uplift after the deposition of the Pegram sediments, and this new episode of erosion was to result in one of the most

Figure 15: A photograph of a "Breccia vein showing flow pattern of fine-grained brecciated particles around larger fragments." (after Woodruff, 1968: 38).

> important unconformities in Paleozoic rocks of this region. Much of the Devonian sediments, as well as extensive areas of Silurian and Ordovician rocks, were removed by erosion.
>
> When the Late Devonian sea advanced across the land, conditions had changed dramatically compared with other invasions of the ocean, and the environment was like few others in all of the geologic history of this region. The sea eventually spread over much of the east-central United States, depositing a black, carbonaceous mud over hundreds of thousands of square miles. This black mud, containing rotted organic matter, became the Chattanooga Shale.

Woodruff (1968: 41) again notes an unusual feature of the Howell Structure:

> It has been noticed in studying the Howell structure that the courser-grained rock units are more apt to be brecciated whereas the finer-grained rocks are less likely to be so deformed …

Woodruff (ibid.) noticed this phenomenon in the "… dove-like cryptocrystalline limestones …" which were not often brecciated. Occasionally Woodruff came across fragments of the 'dove' mixed with a brecciated unit and at least at one location he decided that the 'dove' was itself the breccia matrix.

Figure 16: Photographs of 'plum-pudding breccias'; the right hand image is a close-up view that shows identical lithologies of fragments and matrix (after Woodruff, 1968: 39).

> However, the dove-like zones (beds) have remained intact. The dove, therefore, has maintained its own lithologic integrity … (ibid.).

The puzzling aspect was that these seemingly-undisturbed units were within the area of most intense deformation. Woodruff (1968: 41–42, 44) discusses the possible mechanisms through which this unexpected result could have occurred:

> This has led to speculation by some observers that the structure may have been caused by diagenetic processes such as slumping of unconsolidated sediments, repeated time and time again during geologic time. By this speculation, there would be periods of deposition between the times during which the breccias were formed. The rocks deposited during these inter-breccia periods would be the undisturbed crypto-grained dove-like units … However, this sedimentary hypothesis cannot explain the extreme localization of deformation within a circular area and the presence of some radiating joint patterns as seen and measured in outcrops in creek beds bordering the structure.

Figure 17: A photograph of a breccia sill (after Woodruff, 1968: 43).

> Localized solution activity is also unsatisfactory in that it would seem to call for uplift, before the process of solution could work in such a limited area. No such uplift is observed.
>
> The explanation of that phenomenon may be better dealt with in terms of the more explosive processes, which are believed to have taken place here. One such explanation would be that the undisturbed bed [lying] flat upon [the] breccia is another example of breccia injection. Under great pressures breccia might behave as a slurry and may cross lithologic features. It has been mentioned that "breccia injection veins" have been observed; this then would be an example of a "breccia sill …"
>
> Another hypothesis concerning such a phenomenon would be the inconsistent behavior of shock waves in rocks of different lithologic types. Generally, the cryptograined rocks are not brecciated, although subjected to forces capable of granulating coarser rocks. Therefore, this writer postulates that there is a definite relationship between rock textures and shock transmission. Thus, the fine-grained dove-like limestones transmit the shock waves, but at the same time are not affected by the shock in a noticeable way. The coarser-grained units then receive the trans-mitted wave and amplify it from one grain boundary to the next, causing fragmentation. (The parallel that this writer draws is the behavior of earthquake waves in areas of sound bedrock as opposed to earthquake behavior in loose alluvial fill. The bedrock areas act as a unit in transmitting the wave, while the loosely consolidated material amplifies the "shock," causing the greatest destruction). The coarser-grained rocks do not behave as a distinct unit; the dove-like members do.

Figure 17 is a photograph taken by Woodruff (1968: 43) showing a breccia sill he investigated at the Howell Structure.

In the most recently-published investigation of the Howell Structure breccias, Milam et al. (2015) report on the analysis of limestone breccia samples obtained from Howell surface exposures and provided by R.G. Stearns, Professor Emeritus from Vanderbilt University (Nashville). X-ray diffraction (XRD) spectral analyses of breccias from the Howell Structure were compared with unshocked, optically clear calcite in an effort to identify diffraction peak broadening that can occur in the XRD spectra of shocked carbonates. Initial results for three of seven samples were consistent with shocked calcite. Full width half maximum values for these three samples were consistent with peak broadening observed in limestone from confirmed terrestrial impact sites, including Sierra Madera and Steinheim. However, this magnitude of peak broadening is also observed in some tectonically-deformed non-impact limestones. Milam et al. (ibid.) note that there is no evidence of tectonism in the immediate vicinity of Howell, so shock metamorphism of carbonate breccias due to impact is indicated and an impact origin for the Howell Structure is favored.

7 SHATTER CONES, SHOCKED QUARTZ, AND DRILL CORES

Dietz (1960: 1781) states that

> Volcanic explosions are steam explosions involving pressures of not more than several hundred atmospheres, so it is extremely doubtful that a shock wave can be developed in rock as a part of volcanic phenomena.

He points out that a meteorite impact is capable of generating a shock wave:

> A giant meteorite (that is, one which is not appreciably decelerated by passage through the atmosphere) should on average strike the earth with a velocity of about 15,000 meters per second. A principal effect of this impact is the generation of an intense and high-velocity shock wave which spreads out from the impact point, or "ground zero," and engulfs a great volume of rock before it finally decays into an

elastic wave. (ibid.).

French (1998: 36) states that

> Shatter cones are the only distinctive and unique shock-deformation feature that develops on a megascopic (hand specimen to outcrop) scale.

Dietz (1960: 1782) searched the Howell site for shatter cones as proof of impact, but he found that "Rock outcrops at the Howell structure are too poorly developed to permit any intensive search there …" (ibid.). Miller (1974: 56), however, notes that "Some features that may be shatter cones have been found, but they are indistinct."

Shatter cones have been used as indicators of meteoric impact, and are typically oriented so that the tips of the cones point toward the shock, or 'ground zero', of the meteorite impact. Therefore, "… shattercones are useful in determining … whether the explosion originated from above or below." (Woodruff, 1968: 23). He continues:

> Shattercones have not been previously identified in the Howell area, but this writer has found one location in which crudely formed cones may be present … (ibid.).

Figure 18 shows what Woodruff (1968: 24) calls possible shatter cones. The photographic equipment he used during the 1960s did not produce the clear images he desired, so Figure 19 shows this same photograph with a Mylar film overlay marked to show the features he saw that did not show up as well as he desired on the grainy photograph. Likewise, Figure 20 shows a "Poorly formed shattercone …" and Figure 21 shows the same photograph, again with the features he saw in person indicated by the overlay (Woodruff: 1968: 25). The fact that Woodruff considered this later example to be a poor example of a shatter cone does not preclude an impact origin.

Woodruff searched the Howell site for other evidence of shock, and noticed that the texture and mineralogy of specimens he found on the higher ground located in the northeastern section of the Howell Structure were "… so unlike anything else seen in the Howell area, that thin sections were made for further study …" (Woodruff, 1968: 59). This area is a mixed zone consisting of sand and chert, sulfides and carbonaceous material, and the outcrops here may be fossil rim material or "… a basal lens of the basal sand of the Chattanooga Shale …" which would have been deposited "… in a marsh or in deep stagnant water …" (ibid.). The thin sections studied in this petrographic investigation were found to be "… predominately quartz or other silica material, such as chert …" (Woodruff, 1968: 61).

Figure 18: A photograph of possible shatter cones (after Woodruff, 1968: 24).

Figure 19: Use of an overlay to indicate the features that may be shatter cones (after Woodruff, 1968: 24).

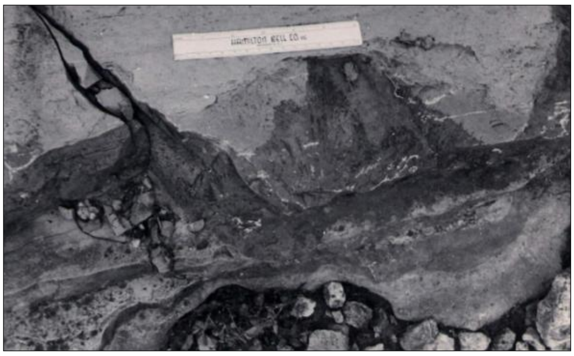

Figure 20: A photograph of a poorly-formed shatter cone (after Woodruff, 1968: 25).

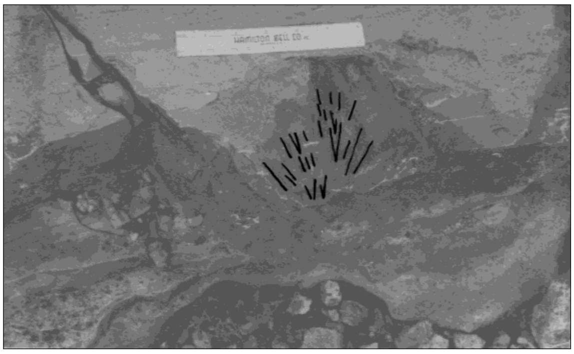

Figure 21: Use of an overlay to indicate the poorly-formed shatter cone (after Woodruff, 1968: 25).

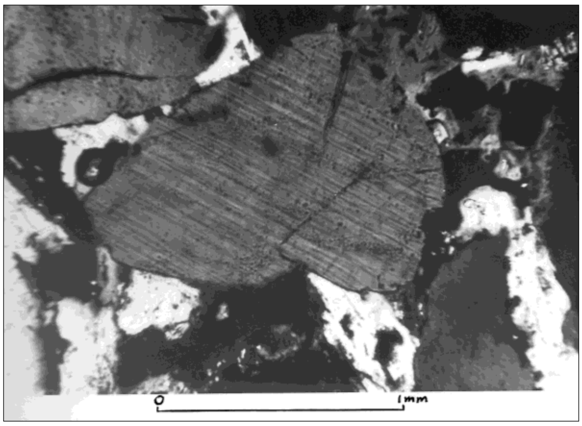

Figure 22: A thin section showing a quartz grain with planar features (after Woodruff: 1968: 62).

This investigation found in some quartz grains "… a definite lineation … or sometimes sets of lineation … so prominent so as to indicate one or two directions of cleavage …" (ibid.). Wilson and Stearns (1968: 153) point out that their investigation of the Wells Creek confirmed impact structure determined that "The most severe deformation noted in quartz is somewhat widely spaced fracturing." Figure 22 shows a thin section of a quartz grain photographed in polarized light displaying planar features (after Woodruff, 1968: 60). Another quartz grain displayed 'patchy extinction', indicating that it was subjected to sufficient stress to granulate and

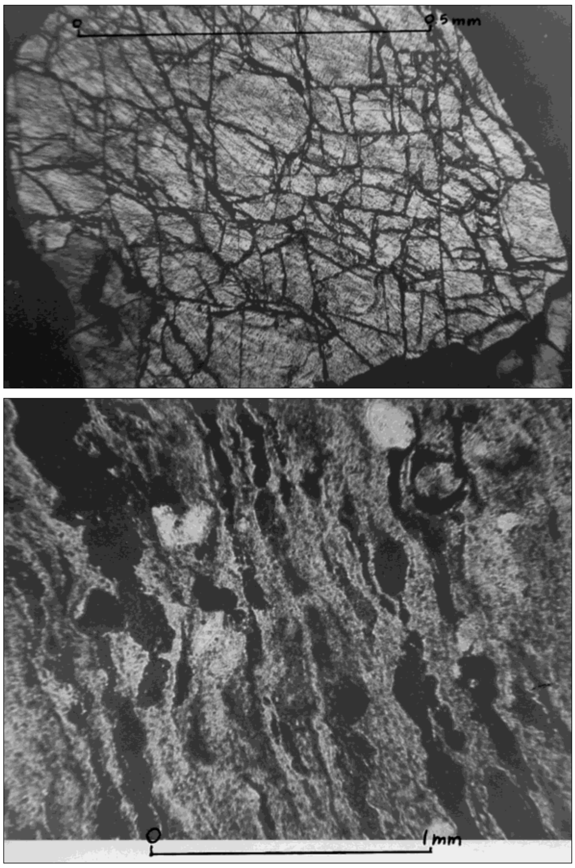

Figure 23: Thin sections showing two quartz grain samples displaying (top) a 'micro-breccia', and (bottom) "… the flow of finely divided particles ..." (after Woodruff: 1968: 63).

then re-indurate so as to retain its original form as a single grain. Woodruff (1968: 61) also found several samples in which

> Other possible indications of shock are seen where certain quartz grains, or what appear to be quartz grains, are partially or entirely isotropized … [and] In certain areas of the thin sections which macroscopically appear to be stringers of glauconite and possibly hematite, it is seen in thin section to consist of something resembling flow of finely divided quartz. The lineation of the glauconite and the flow-like trend of the smaller silicious material aligns with each other. (ibid.).

Woodruff states that some quartz grains were found to be

> … completely fragmented in certain areas of the thin sections … usually where the section is thinner than usual, as around the edge of the section …

and he believes that "This fragmentation may represent incipient fractures due to stress …" (ibid.). Figure 23 shows two samples found by Woodruff at the Howell site. One thin section, photographed in plain light, he calls a micro-breccia, and he states that it is a single quartz grain which displays a "… mosaic of fractures in thin section …" (Woodruff, 1968: 62). The second thin section, photographed in polarized light, shows the "… flow of finely divided particles …" (ibid.). Woodruff (1968: 63) then makes the following observation from his petrographic study:

> The rocks have constituent materials that have been subjected to severe stress, but at the same time, may contain material that has not been so subjected. There, it seems most likely that the material in consideration has been reworked, possibly even reworked rim material.

Woodruff (1968: 65) believes that the results of this petrographic study indicate that shock metamorphism has taken place, but unfortunately "… these thin sections did not survive the passage of 35 years of time and are lost for further study …" (Deane et al., 2004: 2). More samples from Howell were therefore required for a detailed investigation using modern technology.

In 2003, Deane and Milam were members of a team that made two trips to the Howell Structure in order "… to search for evidence of shock metamorphism in local lithologies …" (Deane et al., 2004: 2). The team gathered samples of limestone breccias from creek beds in the central part of the disturbed area, as well as samples of the Leipers and Catheys Formation (a fine-grained, thin to medium-bedded Ordovician limestone exposed at the base of the hills on the eastern side of the site), but could not obtain a micro-brecciated sample similar to the one reported and photographed by Woodruff. But they did find and analyze the 'powdered limestone' breccia reported by Born and Wilson (ibid.). They stated that

> Thin sections were produced for all samples. All observed quartz grains displayed substantial micro-fragmentation. However, no unequivocal evidence of shock metamorphism such as melt, flow, or planar deformation features (PDFs) was found … (ibid.).

Woodruff (1968: 19) points out that in many structures such as Howell, geological processes have removed many of the characteristic features that are considered unequivocal indicators of shock due to impact, including coesite and stishovite, or isotropized quartz. Wilson and Stearns (1968: 152) noted that during their spectrographic study of breccias located within Wells Creek, a confirmed impact structure, no coesite or stishovite was found either, and that

> Although these dense materials were not found, their absence is not considered to preclude an impact origin of the structure …" (ibid.).

Woodruff (1968: 19) notes that "Meteorite fragments would be conclusive evidence, but, unhappily, this is the rarest evidence." Howell is far too old for such fragments to have survived the passage of time. Woodruff (1968: 20), therefore, discusses alternate means of determining whether a structure is the result of a meteorite impact:

> Ultimately, one of the few certain means of determining whether a structure is formed by meteoric or terrestrial process is by subsurface study. If the area of deformation has a lower limit above the (igneous-metamorphic) basement complex it is then concluded to be of meteoric origin. However, this is contingent upon the size of the deformed area. Meteor impact may well yield deformation to such depths as to involve basement and be impractical to drill through.

Woodruff (1968: 65) points out that

> The information gained by NASA's drilling (John Bensko, personal communication) is that the structure has a bottom in stratigraphic sequence and is thus lens-shaped at depth instead of being a breccia pipe.

Since the drill holes at Howell went through breccias and then penetrated into undisturbed rock, an impact origin was suggested, and this was recently confirmed when Bensko made cores available to Milam et al. (2015), and their analyses revealed clear evidence of shock metamorphism.

8 CONCLUDING REMARKS

Woodruff's 'shatter cones' are suggestive at best and no evidence of shocked quartz has been found at the Howell site, but we believe that the clear evidence of shock metamorphism recently assembled by Milam et al. (2015) suggests that the Howell Structure is indeed an old impact site—even though perhaps 80–90% of the crater has been removed by erosion. However, the first author of this paper feels that the evidence for an impact origin, although strong, is still not conclusive, and that for the moment the Howell Structure must remain one of Tennessee's two suspected meteorite impact sites.

Yet not everyone agrees with this conclusion. Based on his own investigations, Woodruff (1968: 29) concluded that the Howell Structure is "… the ancient eroded equivalent of a meteor impact crater …", and he cites the following evidence in support of this origin:

> The criteria used in this conclusion are based on the morphology of the structure, subsurface information, and petrography. The roughly circular-elliptical appearance, and radiating joint patterns are morphological indicators of such an origin, as are breccias, *but neither of these are [sic] conclusive*. (Woodruff, 1968: 65; our italics).

Miller (1974: 56) also concluded that "Overall, the evidence indicates the Howell Structure was formed by meteorite impact."

With so much of the original structure removed by erosion, it may be that proof of meteoric impact will never be forthcoming, but we hope that sites like the Howell Structure will encourage research into impact signatures in limestone that are associated with metamorphism at low shock pressures.

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ASTROMETRY, MORPHOLOGY, AND POLARIMETRY OF COMET DONATI IN 1858

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Abstract: We present unpublished observations of Comet Donati 1858 VI recently recovered in an old storage facility at the University Observatory in Oslo. Carefully-made drawings reveal temporal changes in the appearance of this comet. Fine structures in the tail were noted, some of which were short-lived. Envelopes in the comet's head, apparently due to outgassing from the nucleus, were monitored over several days. Astrometric positions of the comet's head derived by various combinations of telescopes and micrometers reveal a standard deviation of ± 6″. Visual polarimetry of the coma and tail revealed polarized light and determined that the polarization plane contained the comet and the Sun. Thus the polarized light from the comet was reflected sunlight. The observations are discussed in relation to contemporary publications.

Keywords: Comet Donati – astrometry – morphology - polarimetry

1 INTRODUCTION

The University Observatory in Oslo was inaugurated in 1833 when the city was named Christiania. It became the national center in Norway for a number of scientific disciplines, e.g. astronomy, geodesy, geomagnetism, meteorology and applied mathematics. During its 100 years of operation it was led by a succession of five professors. The first four were active in classical astronomy and published astrometric results for stars, planets, asteroids and comets. Some objects were subjected to orbital analyses. Major projects were contributions to the Astronomische Gesellschaft's Zone catalog, a complete re-observation two decades later, and subsequent studies of stellar proper motions. In geodesy there was participation in Struve's meridian arc and the European meridian arc to determine the size and shape of the Earth.

The Observatory was abandoned in 1934 when astronomy moved to the new university campus in Oslo and its present residence in the Institute of Theoretical Astrophysics. Eventually, the original observing pavilions and the instruments were dismantled, and the main building was used for other purposes until 2010. Since then it has been refurbished, and it now serves in a university program to inspire and recruit young people to the sciences. Some of the old instruments have been re-installed to provide an historic time-line in the pedagogical activities. As such, the Observatory is also a collection of historical instruments in many sciences and an element in a museum of university history.

The founder of the Observatory was Christopher Hansteen (1784–1873), Professor of Applied Mathematics from 1816, who conducted astronomical observations in a temporary observing hut between 1815 and 1828 (Pettersen, 2002). The University Observatory was built in 1830–1833 (Enebakk and Pettersen, 2009). Hansteen was the only scientist at the Observatory during its first decade of operation.

2 THE COMET OBSERVERS

In 1844 Carl Fredrik Fearnley (1818–1890) graduated from the University of Oslo and was appointed Observer. He received a University stipend to study abroad during 1849–1852, and spent time with Argelander in Bonn and also visited Munich, Berlin, Königsberg and Pulkovo Observatory in St. Petersburg. Fearnley was appointed a Lecturer in Astronomy at the University of Oslo in 1857. Four years later he became Director of the Observatory (by this time Hansteen was 78 years old). In 1865, at the age of 47, Fearnley was promoted to Professor of Astronomy.

Henrik Mohn (1835–1916) graduated from the University of Oslo in 1858 at the age of 23. He was appointed a University Fellow two years later and Observator in 1861. In 1866 he founded the Institute of Meteorology and held its Professorship from 1866 to 1913.

Oluf Andreas Løwold Pihl (1833–1895) was trained as an engineer in Sweden and England. He moved to Oslo in 1850 as the Director of Oslo Gas Works, at the age of 28, and held this appointment until his death in 1895. Pihl's spacious residence just north of the University Observatory was equipped with a private observing tower which housed a small equatorial refractor.

When Donati's Comet developed into a bright object in the skies in mid-September 1858, Fearnley had been observing it for three weeks. He was a meticulous observer with an exceptional talent for drawing. The 40-yr old university lecturer enlisted the help of his 36-yr old friend Oluf Pihl to study morphological details in the tail and coma during the brightest phase, in early October. And he worked with his talented 23-yr old student Henrik Mohn to conduct the first polarimetric studies of a night-sky object in Norway. Internal reports and drawings related to this observing program have recently been recovered from old storage locations, and they served as the sources for this paper, along with observing reports published in *Astronomische Nachrichten*.

3 THE OBSERVATIONS

Comet C/1858 L1 (Donati) was discovered by Giovanni Battista Donati (1826–1873) in Florence, Italy, on 2 June 1858. It was found to have an elliptical orbit (e = 0.996) with a period of revolution close to 2,000 years. Perihelion took place on 30 September 1858. The comet was closest to the Earth (0.54 AU) on 10 October 1858.

Comet Donati was observed with all available telescopes at the University Observatory in Oslo. In addition, Mohn used a homemade 2.5-cm refractor to initiate his experiments. Pihl's private observatory was equipped with an 8.1-cm refractor by optician H. Krog of Bergen, on an equatorial mounting manufactured by Lohmeyer of Hamburg (Pihl, 1869). Table 1 lists the telescopes at the University Observatory. Positions of the comet were determined relative to reference stars by Fearnley using ring micrometers on several refractors, which ranged in aperture from 10 cm to 19 cm. Filar micrometers with multiple threads were used on the Ertel meridian circle and on the Repsold equatorial refractor. The latter had graduated declination and right ascension circles (diameter 50 cm) for direct reading of celestial coordinates. Fearnley and Pihl also made drawings directly in star atlases in order to accurately determine the orientation and extent of the comet's tail. They did this without telescopic aid and with low power telescopes. At high magnifying power they recorded morphological details and temporal changes in the coma and tail of the comet. Fearnley repeatedly measured the extent of what he interpreted as the nucleus. He also monitored a succession of bright envelopes emanating from the nucleus. Some of the phenomena observed were reported and discussed by Fearnley (1858; 1860a; 1860b). The attempts to study the polarization properties of the light from the comet using his own small refractor, the comet finder and the 19-cm Merz refractor at the University Observatory were described in an unpublished report by Mohn (1858).

3.1 Astrometry

Fearnley (1860b) determined the position of the nucleus of Comet Donati between 26 August and 13 October 1858. He used the Utzschneider alt-azimuth refractor (on 6 nights between 26 August and 5 September, and on 18 September) and the Repsold (on 2 October) and Merz (on 13 October) equatorial refractors equipped with ring micrometers to determine positions of the comet relative to reference stars with known celestial coordinates. He also used a filar micrometer on the Repsold instrument (on 17 nights between 4 September and 10 October) to determine celestial coordinate values with its large graduated circles. On five occasions he used the Ertel meridian circle for the same purpose. The results were published in *Astronomische Nachrichten* and were included in the database compiled by G.W. Hill (1867) for orbit determination. Hill found an elliptical orbit with a period of revolution of 1,950 years for Comet Donati. Coordinates computed from this orbit for the dates and times of Fearnley's individual position determinations were used to generate a list of deviations (observed – calculated) for declination and right ascension, respectively. The scatter of the observations may be expressed by the standard deviations, which are $\pm 5.5''$ in declination and $\pm 5.8''$ in right ascension.

3.2 Visual Observations of Comet Morphology

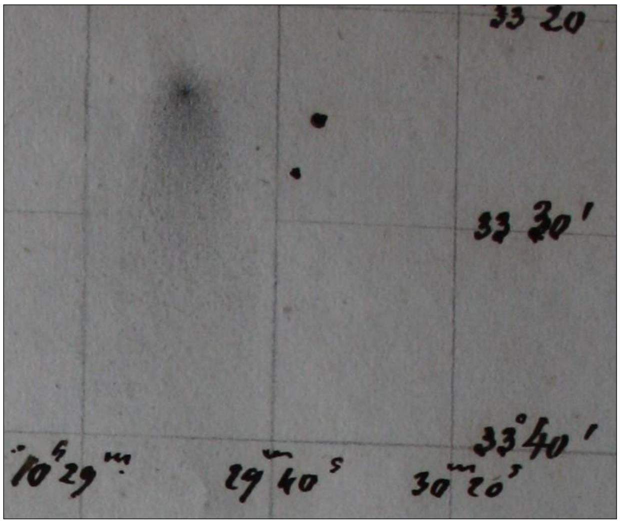
The first drawing was made by Fearnley from visual observations with the Utzschneider 10.7-cm refractor on 27 August, two hours after the full moon rose. The tail appeared 10′–15′ long. On 1 September the tail had grown to 20′–25′ (Figure 1). The comet was visible to the naked eye and was estimated to be magnitude 2–3. In unsteady weather on 5 September the tail appeared 5° long.

On 16 September the comet was drawn on two occasions, separated by 1.5 hours. The 11.7-cm Repsold equatorial was used. The Moon set between the two observations. The motion of the comet is noticeable in Figure 2. The tail is 4.5° long.

On 18 September several telescopes were used at the University Observatory. In the Utzschneider refractor with a ring micrometer the

Table 1: Technical Data for Telescopes at were the University Observatory in Oslo in 1858.

Manufacturer	Mounting	Aperture	Focal length	Auxiliary instruments
Utzschneider refractor	Alt-azimuth	10.7 cm	175 cm	Ring micrometer
Ertel meridian circle	Meridian	10.8 cm	163 cm	Filar micrometer
Repsold refractor	Equatorial	11.8 cm	160 cm	Filar and ring micrometers
Merz comet finder	Equatorial	7.5 cm	70 cm	Polariscope
Merz refractor	Equatorial	18.8 cm	318 cm	Ring micrometer; polariscope



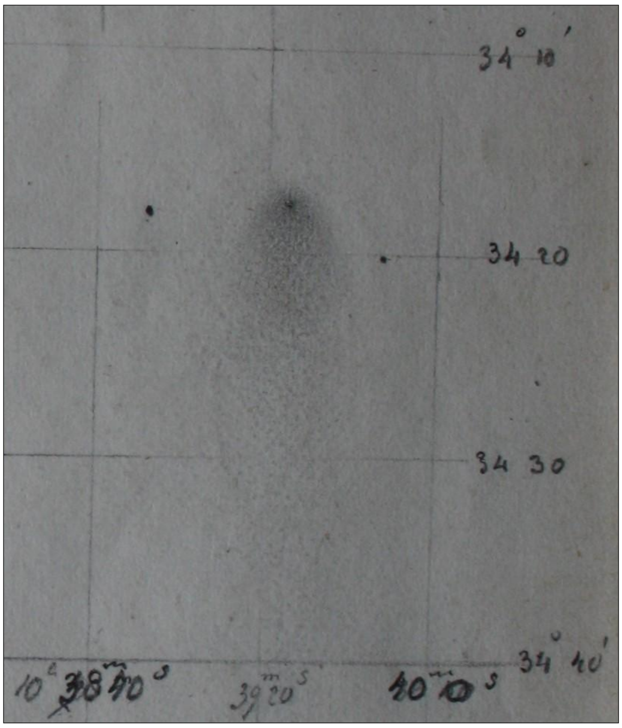


Figure 1: Comet Donati drawn by C.F. Fearnley on 27 August 1858 (left) and on 1 September 1858 (right). Right ascension increases to the right. Declination increases downwards.

nucleus of the comet had a diameter of 15″–16″. At a higher magnification of 150× in the Repsold equatorial refractor equipped with a filar micrometer, the nucleus was 5″–6″ in diameter. The comet finder was used to sketch the entire comet. There were indications of three bright rays extending from the nucleus into the tail. The last drawing focused on the head of the comet and the nearby tail (Figure 3).

The waxing Moon was high in the sky on 19, 20 and 21 September. The yellowish moonlight was accompanied on 20 September by a significant aurora in the region of the comet, which appeared much whiter and stood out despite the bright sky background. The comet finder was used to draw the entire comet, but the tail appeared longer with the naked eye (see Figure 4).

Despite the presence of the full moon a brightening was noticed in front of the nucleus using the Utzschneider refractor on 23 September. The diameter of the nucleus was measured as 30″ on 26 September, but was only 9″ at a magnification of 150× in the Repsold equatorial. The nucleus was surrounded by a faint sphere of diameter 30″ which had the appearance of a fan since a 90° sector was lacking at the rear (tail side) of the nucleus. A larger and even fainter structure was also noted. It continued around, into and along the tail. Outside of this was a very faint veil (the punctuated line in the drawing in Figure 5).

The tail grew markedly on 27, 28, 29 September and on 1 October (Figure 6), when it was longer than 20°. The diameter of the nucleus was measured on 27 September as 8.2″ with high magnification on the Repsold equatorial. The next day another envelope surrounding the nucleus was noted. It had expanded outwards by 1 October.

The remaining observations were made with the Moon below the horizon as new moon occurred on 6 October. On 3 October two circular envelopes were noted around the nucleus, both in the 12-cm Repsold equatorial and in the 19-cm Merz equatorial. One of these was noted also by Pihl, who determined its diameter to be 1′ 28″ with his 8-cm refractor.

On 5 October the envelopes in the inner halo took the shape of a spiral. Further details near the nucleus were noted on 6 and 9 October (Figure 7), using both the Repsold equatorial and the Merz equatorial. The diameter of the nucleus was less than 2″. Pihl remarked in a letter to Fearnley dated 7 October 1858 that on 6 October the diameter of the nebulous circle surrounding the nucleus had increased by 15″ relative to three nights earlier. He also noted a dark linear filament within the tail with weaker parallells on either side. They were inclined to the general direction of the tail and appeared to point towards the Sun.

On 10, 13 and 15 October further developments in the coma were noted (e.g. see Figure 8). By this time the comet was very low in the sky, and observations ended on 15 October.

3.3 Fine Structure in the Coma

Fearnley used the 12-cm Repsold equatorial to monitor changes in the head of the comet. He noted the development of concentric halos expanding out from the nucleus during the last

Figure 2: Comet Donati observed by C.F. Fearnley on 16 September 1858 with the Repsold equatorial refractor. East is right, north is down. Note the motion of the comet in the course of 1.5 hours.

half of September as the comet approached perihelion. On 3 October he used the 19 cm Merz refractor for a detailed visual study at high magnification. He could then determine that the two halos were not concentric circles around the nucleus. In fact, the centers of each halo lined up with the nucleus along a straight line oriented along the radius vector from the comet to the Sun (Fearnley 1860a). By 7 October he had observed four halos expanding outwards from the nucleus. On 9 October there were three halos visible simultaneously. Fearnley also noted a dark spot comparable in size to the nucleus and located 7″ away from it (i.e. between the

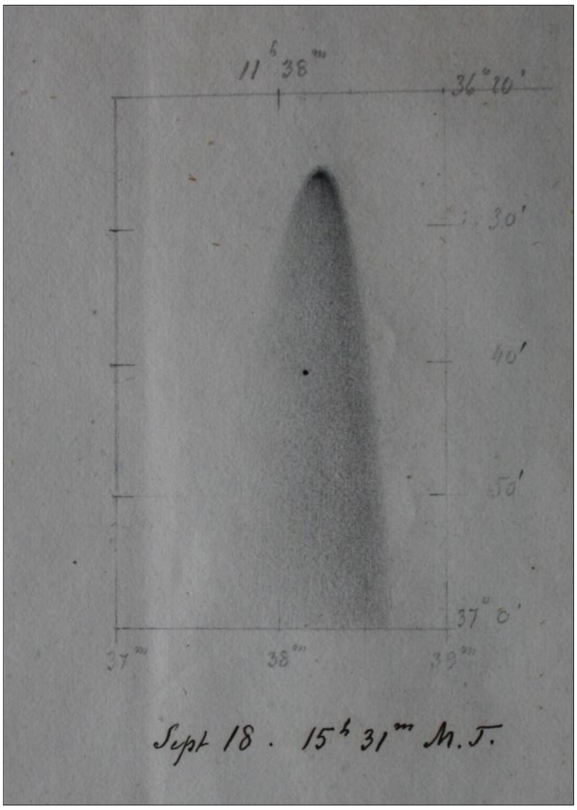


Figure 3: The head of comet Donati drawn by C.F. Fearnley on 18 September 1858 using the 7.5 cm Merz comet finder. The star in the tail is Lalande 22227. East is right, north is down.

Figure 4: Comet Donati on 19, 20 and 21 September as drawn by C.F. Fearnley with the comet finder. East is right, north is down.

nucleus and the first halo). On 5 October it was noticeably larger. On 6 October it had split in two, and by 9 October it had disappeared. The sketches in Figures 9 and 10 illustrate this.

Similar events were reported from other observatories (e.g. see Schmidt, 1862). A subset of these data was analysed by Whipple (1978) on the assumption that the halos represented repetitive ejection of material from a single active area on the nucleus of the comet as it rotated into and out of direct sunlight. He determined a synodic rotation period of 4.6 hours. Whipple (1978) pointed out that such rapid rotation creates a centrifugal force that may cause ejection of material and even break-up of the nucleus. The observation of a secondary nucleus on 3 October, increasing in size by 5 October, and splitting in two by 6 October, may support this view.

3.4 Polarimetry

The majority of observations worldwide of Comet Donati were visual. Although this was the first comet to be photographed (Gasperini et al., 2009), the scientific measurements were all made by visual methods. Comet Donati appeared at the dawn of observational astrophysics which was eventually pioneered by astrophotography and spectroscopy. In Oslo, attempts were made to detect polarized light from the comet. Radiation from celestial objects is often unpolarized, meaning that the orientations of the electrical and magnetic vectors are randomly distributed. The dust and gas of a comet reflects sunlight, however, and the electrical vector is no longer randomly oriented but oscillates at a particular angle which depends on the angle of reflection. The purpose of the polarimetric observations in Oslo was to determine the orientation of the polarization plane.

Henrik Mohn constructed an experimental instrument consisting of an achromatic double-refracting prism with a polished 3.75-mm thick calcite crystal plate in front. This gave two images of the observed object. When polarized, the two images showed complementary colours. The polarization plane could be determined by rotating the polarizer to obtain the maximum intensity difference between the two images.

Mohn tested the instrument on his home-made 2,5-cm achromatic refractor on 5 October. By rotating the prism until the maximum intensity difference was obtained between a yellow and a violet image, the orientation of the polarization plane was found to be a great circle through the comet's head and Arcturus. He derived an angle of 33° between the polarization plane and the declination circle through the comet's head. The small objective lens limited the colour contrast, which contributed to an un-

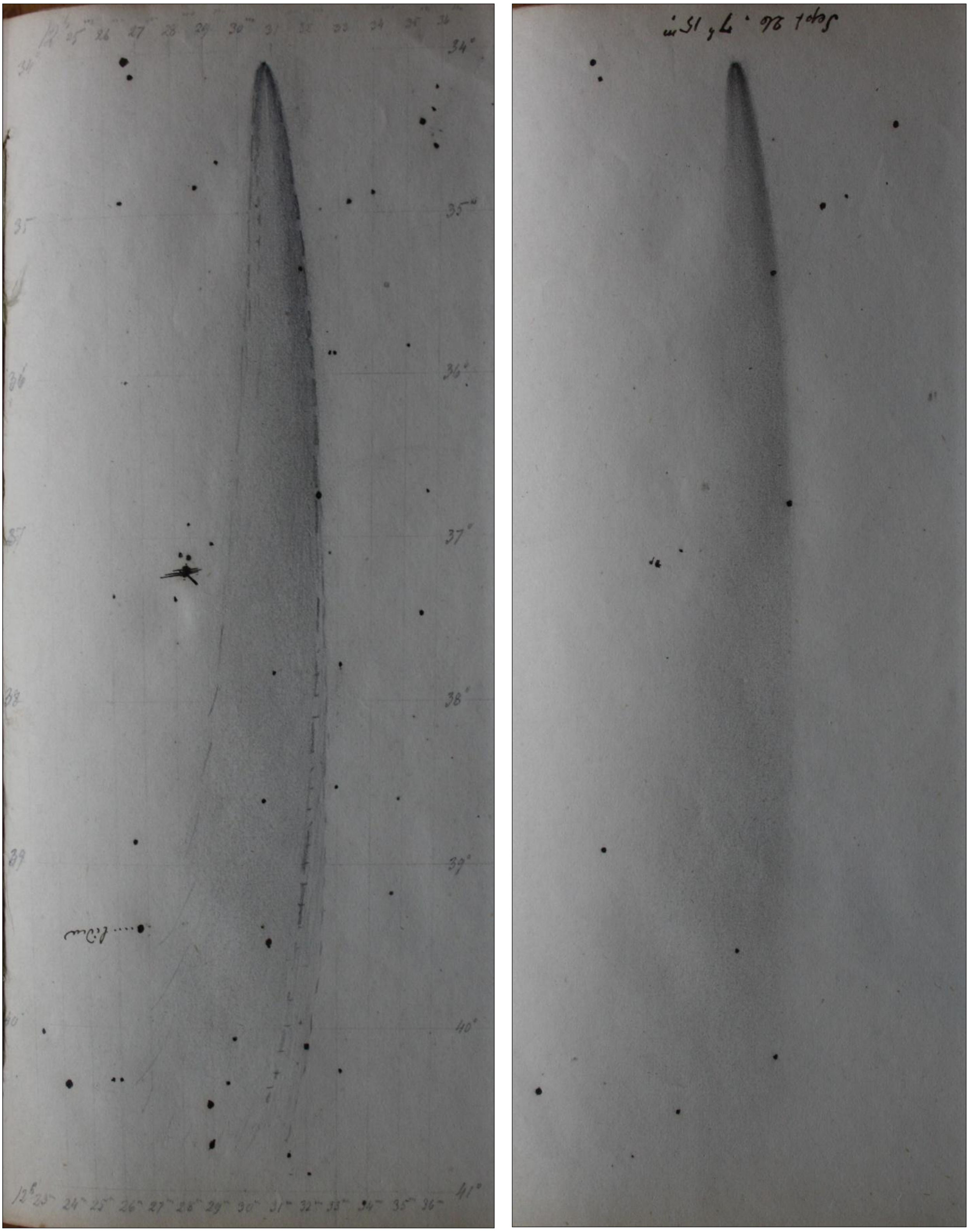
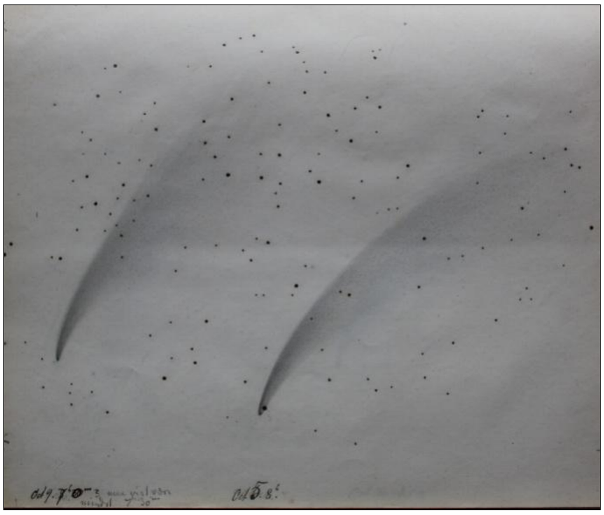


Figure 5: Two different drawings by C.F. Fearnley of Comet Donati on 26 September 1858. On the left is the original field sketch. East is to the right, and north is down.

certain result, which also was affected by coordinate and clock time errors.

During twilight on the next night, 6 October, Mohn mounted his instrument on the Merz 7.5-cm comet finder at the University Observatory. The complementary colours were distinctly noticeable and the light from the comet was strongly polarized. The polarization plane was determined as a great circle through the comet's head and a point between α and β Corona Borealis at declination 28° 36′ and right ascension 231° 15′, which gives an angle of 48° 46′ relative to the declination circle through the comet's head.

Figure 6: Comet Donati on 26, 27, 29 September, and on 1 October 1858 as drawn by C.F. Fearnley. North is upwards, east is towards left. The brightest stars in the upper part belong to Ursa Major.



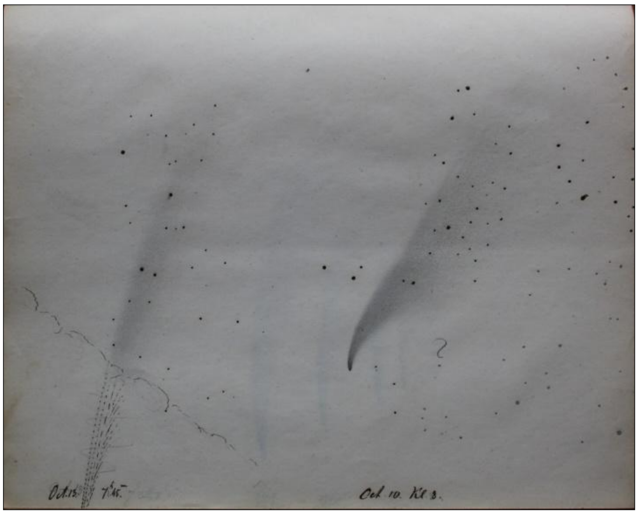


Figure 7 (left): Comet Donati on 5 and 9 October 1858 as drawn by C.F. Fearnley. North is approximately diagonally to the right and upwards. East is towards left and approximately diagonally upwards. The bright star near the comet head on 5 October is Arcturus.

Figure 8 (right): Comet Donati on 10 and 13 October 1858 as drawn by C.F. Fearnley. North is up.

Table 2: Observed and computed angles for the polarization plane.

Date 1858	Observed angle	Computed angle	Difference (O-C)	Angle of reflection
October 5	33.0°	41.7°	-8.7°	58.7°
October 6	48.8°	48.0°	0.8°	59.4°
October 9	75°– 80° (clouds)	66.5°	8.5° – 13.5°	59.6°

The comet's appearance on 5 and 7 October is shown in Figure 7. Arcturus (α Bootes) is near the comet's head on October 5. Above it is ε Bootes and further up and to the left are α and β Corona Borealis. The orientation of the polarization plane is thus almost vertical in Figure 7. When twilight ended, Mohn repeated the observations with Savart's polariscope and obtained the same result. This instrument shows the presence of polarized light by interference patterns which change in intensity according to the relative position between the polariscope and the polarization plane. Fringes parallel to and orthogonal to the polarization plane were observed along the entire tail of the comet as far as ε Bootis (i.e. for about 10°). When the telescope was pointed away from the comet, the interference pattern disappeared.

The instrument was then mounted on the Merz 19-cm refractor at the University Observatory. The complementary colours were easily distinguished. The magnification allowed only parts of the comet to be seen in the telescope field of view but the size of the objective lens ensured enough light for Savart's polariscope. The interference patterns appeared at approximately equal intensity across the field of view. Thus every point on the comet referred to the same polarization plane.

Attempts with Savart's polariscope on the Merz 19-cm refractor were made also on 9 October, but drifting clouds corrupted the results. An uncertain determination of the polarization plane resulted (75°–80° relative to the declination circle through the comet's head).

Mohn's observations proved that the light from the comet was strongly polarized in a plane directed towards the Sun. Reflected sunlight is polarized. A great circle through the comet and the Sun represents the polarization plane. Its position angle was computed from the celestial coordinates of the two objects and may be compared to the observations. The angle of reflection is derived from half the angle (Snell's Law) between the Sun and the Earth as seen from the comet's head. The results are shown in Table 2.

4 SUMMARY AND CONCLUSIONS

Comet C/1858 L1 (Donati) was observed on 30 nights at the University Observatory in Oslo between 26 August and 15 October 1858. Astrometric observations with a precision level of ±6″ were made on 26 nights with various instruments, which resulted in 37 individual positional measurements. Morphological studies of the comet's head and tail were carried out on 20 nights. This time series revealed the development of the tail and episodic events in the coma. The latter was probably repeated outgassing from the comet that manifested itself as expanding envelopes. A possible breakup of the nucleus was observed during one week in October. Polarimetry determined that the light from the comet was reflected sunlight.

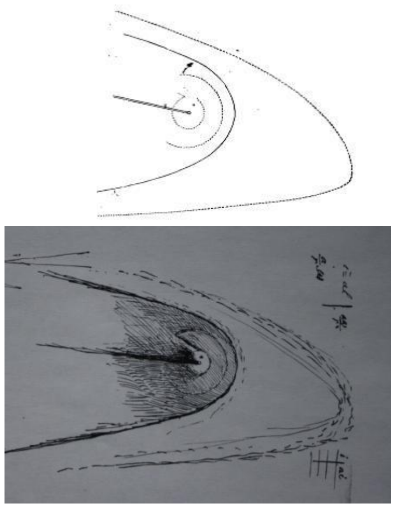


Figure 9: Sketches of the coma on 3 October showing the nucleus, halos, a dark spot, the dark ray in the middle of the tail, and a dark ray above the nucleus that bridges the two inner halos. The upper figure is from *Astronomischen Nachrichten* (Fearnley 1860a), and the lower one is a recently-recovered sketch by Fearnley.

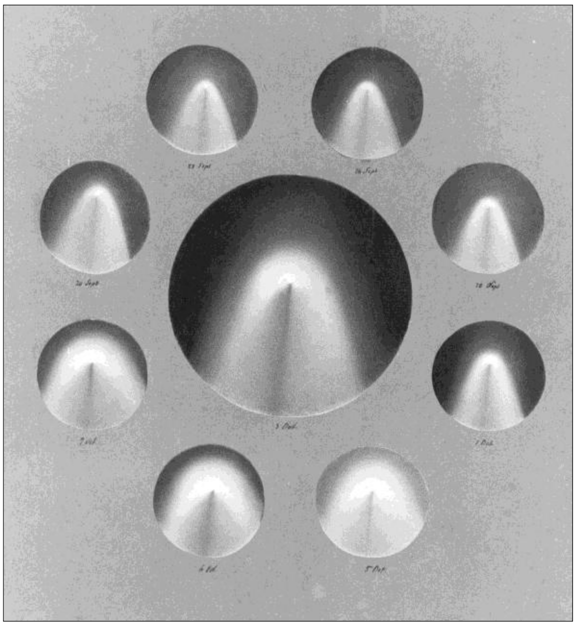


Figure 10: A time series of changes in the coma between 20 September and 7 October, as drawn by C.F. Fearnley.

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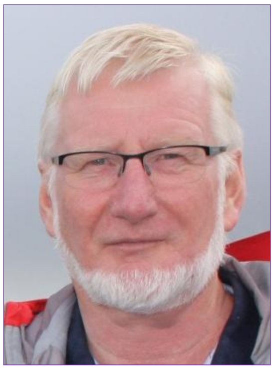

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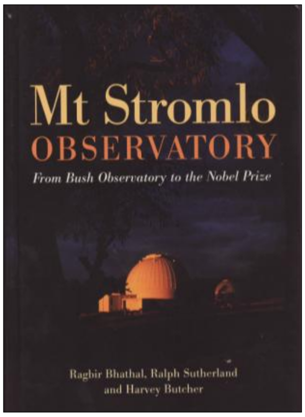
BOOK REVIEWS

***Mt Stromlo Observatory: From Bush Observatory to the Nobel Prize*, by Ragbir Bhathal, Ralph Sutherland and Harvey Butcher. (Melbourne, CSIRO Publishing, 2013), pp. xiv + 330. ISBN 9781486300754 (hard cover), 180 × 250 mm, AU$39.95.**



Mt Stromlo Observatory, near the Australian capital city of Canberra, is one of the great astronomical observatories of the world.

Formed as a solar observatory in 1924, it turned to astrophysics in the 1940s, and for the past decade or so staff have carried out forefront research in 'galactic archaeology' which in 2011 culminated in the Observatory's Brian Schmidt sharing the Nobel Prize for Physics with two U.S. astronomers.

It is now more than a decade since Tom Frame and the late Don Faulkner produced *Stromlo: An Australian Observatory* (2003), so it is good to have a new perspective that also brings us up to date.

Mt Stromlo Observatory: From Bush Observatory to the Nobel Prize, written by a science historian from the University of Western Sydney, a current member of the Stromlo staff and a former Director, recounts the history of Mt Stromlo Observatory in thirteen chronologically-based chapters, each with its own distinctive title.

For those familiar with Australian astronomical history the first two chapters ('A beginning in the bush' and 'A bush observatory', covering collectively the period 1905 to 1929) traverse familiar territory: Geoffrey Duffield's ingenuity in gaining Federal Government approval for the formation of a new solar observatory near Canberra, and its subsequent erection. After lengthy frustrating delays caused partly by WWI, the Commonwealth Solar Observatory was formally established on 1 January 1924, with a suitably-rewarded Duffield as the founding Director. "After almost 18 years Duffield had realized his dream of an observatory …" (page 27), even if the staff had to use temporary facilities at the Hotel Canberra while the Observatory was under construction.

Next is a chapter titled 'Caretaker', which spans the period 1930–1939 when William Rimmer was the Officer-in-Charge (following Duffield's sudden death on 1 August 1929). Fortunately, the Great Depression had relatively little impact on the Observatory, where the solar and ionospheric research programs initiated under Duffield were continued. This chapter introduces Ronald Giovanelli, who was the vibrant Chief of the CSIRO's Division of Applied Physics in the 1960s when I worked in the Division of Radiophysics and we shared the same building in Sydney. Ron was a very productive Visiting Fellow at Stromlo in 1937–1939.

And so we arrive at Chapter 4, 'Second World War: the Observatory becomes an Optical Munitions Factory'. Richard Woolley was the new Director, and the Observatory's role was to support the allied war effort through the design and construction of optical equipment no longer easily accessed from overseas. At Stromlo the staff increased sevenfold, but I was surprised to learn that

> Rather than having a central research institution, the optical work was spread out to *no fewer than 25 establishments*, *including several firms and university physics departments*. (page 64; my italics).

Among the employees was Syd Elwin, who is shown (but not identified) in Figure 4.9. After the war Elwin joined the Sydney Technical College, where he taught optics. During the 1960s, 1970s and 1980s he was one of Australia's leading amateur astronomers, and was a prolific observer of variable stars. In 1982 he was the first recipient of the Bernice Page Medal which would then be awarded every two years by the Astronomical Society of Australia for outstanding research by an amateur. Syd Elwin died in 1990 (Bembrick, 1990).

Chapter 5 ('The change master') tracks Woolley's success in gradually turning Stromlo into an astrophysical observatory following the war, even though "… no one on the staff had any extensive knowledge of stellar astronomy." (page 78). This was the time when the institution changed its name to the Commonwealth, and later, Mt Stromlo Observatory, and when the 30-in reflector, donated many years earlier, finally was refurbished so that it could be used for photoelectric photometry. It also marked the start of substantial U.S. influence at Stromlo, with extended visits by Gerald Kron and Olin Eggen from 1951. Woolley realized that the Observatory's future depended on larger telescopes, culminating—eventually—in the commissioning of the refurbished 'Great Melbourne Telescope' and a Grubb-Parsons 74-in reflector. The 'Great Melbourne Telescope', with its original 48-in speculum mirror, had an interesting history (see Gillespie, 2011), but at Stromlo it featured a short-focus 50-in pyrex mirror. Woolley also convinced Uppsala University to site their new Schmidt at Mt Stromlo, and he arranged the transfer of the Yale-Columbia 26-in refractor from South Africa to Stromlo. Finally, Woolley's other key achievement was to arrange for the Observatory to be transferred from the Department of the Interior to the Australian National University. But this only occurred in January 1957, just over a year after he had left Stromlo in order to accept the post of Astronomer Royal in England.

The new Director was Bart Bok, an international figure who was widely respected for his research in both optical astronomy and radio astronomy. He is the focus of Chapter 6, titled 'The astronomical godfather'. Bok was the first Professor of Astronomy at the Australian National University, and his legacies were the graduate school, that he established; Siding Spring field station; research by Stromlo astronomers on the Milky Way and the Magellanic Clouds; Stromlo's first international symposium, on this latter topic; bringing the 74-in telescope, and later its coudé spectrograph, into operation; the introduction of digital computers; his success in lobbying for the 3.9-m Anglo-Australian Telescope; and his acumen in bringing astronomy before the Australian Parliament and the general public. His public lectures were legendary, and whenever he performed in Sydney I tried to attend. To this day, he remains the most captivating entertaining public speaker I have ever encountered.

In March 1966 Bart Bok and Priscilla returned to the U.S.A., and Stromlo's new Director was a familiar face from earlier years, Olin Eggen. The authors start each chapter with between one and three quotations, often from notable astronomers, highlighting the achievements of the subject of that chapter. One of the three quotations that launches Chapter 7 ('A life on the dome floor') is by Ben Gascoigne, and this is what he has to say about Eggen:

> What I [Ben Gascoigne] think he will be remembered for is the controversy over the AAT and the great rift that developed between Stromlo and the rest of Australian astronomy … It was very damaging; it was years before Stromlo was accepted back into the fold, and it saw the centre of optical astronomy shift considerably from Canberra to Sydney. (page 129).

But is this really true? It suggests that Eggen achieved little. Certainly, there was controversy over the hosting of the Anglo-Australian Observatory, and yes, optical astronomy did grow rapidly in Sydney, through developments at the various universities, but this had nothing to do with Eggen. However, Eggen's Directorship *was* marked by an impressive increase in the annual publications output of the Observatory; the acquisition of important new instrumentation; the growth of a pool of brilliant new staff members or Ph.D. students (including Mike Dopita, Ken Freeman, Harvey Butcher, Jeremy Mould, John Norris and Alex Rodgers) who would forge international reputations, and in several cases, eventually become Directors of the Observatory). In addition,

> Eggen's work on the motions, ages and compositions of stars in the Milky Way became a research theme for a generation of Stromlo astronomers. (page 134).

To my mind, these were Eggen's key achievements, and as for Gascoigne's claim that Eggen caused a rift in the Australian astronomical community that would take years to heal we need only note that when Don Mathewson took over the Directorship from Eggen in 1979 he was widely respected and accepted by optical *and* radio astronomers throughout Australia, as were the other leading astronomers at Stromlo. It is obvious that there was 'bad blood' between Eggen and Gascoigne, so we need to allow for an element of bias in Gascoigne's statements and his assessment. It is a great pity that we do not have Eggen's 'take' on all this, so we can learn why he chose to marginalize his one-time friend.

Chapter 8 ('an astronomical entrepreneur') covers Don Mathewson's directorship, and is of great interest to me. Don and I were both closely associated with the Chris Cross radio telescope at Fleurs, near Sydney (see Orchiston and Mathewson, 2009) and I knew him well during our days at Radiophysics in the 1960s, so in 1985 I accepted his invitation to take up a Visiting Fellowship at Mt Stromlo and Siding Spring Observatory and carry out research on the history of Australian astronomy. After serving as Acting Director following Eggen's departure in September 1977, Don took over as Director in April 1979, the first Australian since Duffield to lead the institution. Under his directorship the annual publications output and the number of graduate students increased substantially, while Mathewson's discovery of the Magellanic Stream was the highlight of his research career (see Mathewson, 2012). Other Stromlo astronomers also made important contributions to photoelectric photometry; studied the Hubble Constant, quasars, and planetary nebulae in the Magellanic Clouds, and conducted theoretical studies of Mira variables. This also was the first time that a number of Stromlo staff used space-based telescopes for their research programs. Mathewson's other major achievement was the 2.3-m Advanced Technology Telescope (ATT), a computer-controlled thin mirror telescope on an altazimuth mounting, which the popular Australian Prime Minister, Bob Hawke, opened at Siding Spring on 16 May 1984 (and because the Annual Meeting of the Astronomical Society of Australia was held at the time in nearby Coonabarabran, many of us from the Australian astronomical community were able to attend this grand event). This telescope was a great success, and it served as the model for later telescopes that were built around the world. Very recently the ATT was refurbished, so that it can continue to contribute to forefront astrophysics.

Stromlo under Alex Rodgers is the focus of Chapter 9 ('An instrumentalist and the MACHO project'). Rodgers became Stromlo's sixth Director in June 1987, having served as Acting Director from May 1986 when Don Mathewson retired. Like his predecessor he was born in Australia. Rodgers

> … was an exceptional instrumentalist and enjoyed nothing more than spending time in the Observatory's workshops, getting his hands dirty … He also was responsible for moving the Observatory into the electronic era by designing and constructing photon-counting arrays … In fact, he kept the Observatory's instrumentation up to date, thus enabling it to remain at the frontiers of international astronomy. (page 178).

Rodgers' major achievement was to refurbish the Great Melbourne Telescope so that it could be used for the MACHO Project: the search, using gravitational lensing, for evidence of the missing mass in our Galaxy. Other staff members carried out important research on star-forming regions, planetary nebulae in the Magellanic Clouds, and SN1987A. Rodgers' one major regret was that his concept of a locally-built 14-m telescope had to be abandoned, because Australian sites adequate to justify so large and expensive a telescope could not be found.

Chapter 10 ('Masters of the universe') discusses Jeremy Mould's directorship, from December 1993, when a number of different Stromlo staff made major discoveries and received national or international honours. In 1998 the Government provided funding for Australian astronomers to access 4.76% of observing time on the two Gemini Observatory 8.1-m telescopes, and Stromlo, working in partnership with other institutions, won contracts to design and construct instruments for the Gemini North telescope and ESO's Very Large Telescope. Thus,

> Mould's ideas about the feasibility of generating income from the commercialisation of astronomical instrumentation were being vindicated. (page 199).

Mould also brought Stromlo research to the public by opening a Visitor Centre on the mountain, designed in the best tradition of overseas science centres, and there was an impressive range of research to promote. Personally, Mould was primarily interested in the Hubble Constant, utilising Hubble Space Telescope data, and his team derived a figure of 72 ± 8 km s^{-1} Mpc^{-1}. A second major Stromlo cosmological project was led by Brian Schmidt. He and the 'High-Z Supernova Team' came up with an amazing result: that the expansion of the Universe was speeding up. Furthermore, by utilising data derived from supernovae and the cosmic microwave background, Schmidt et al. came up with figures of about 25% dark matter and 70% dark energy for the composition of the Universe. Stromlo's third major cosmological research project was the 2dF Galaxy Redshift Survey led by Matthew Colless and Durham University's Richard Ellis. This project explored the large-scale structure of the Universe, and "… produced more than 50 papers, of which more than 20 were in the highly cited category." (page 214). Colless and his colleagues also were able to derive a figure of 23% for the percentage of dark matter in the Universe, remarkably close to the value obtained by Schmidt. Two other notable Stromlo projects were carried out during Mould's directorship, one by John Norris and Mike Bessell on stars with low metallicities, and the other by Ken Freeman and Stromlo colleagues on the chemical evolution of globular clusters. As a result of this research, in 2001 six Stromlo astronomers (out of a total of 33 Australian astronomers) were selected by the Institute of Scientific Information as Citation Laureates. They were Mike Bessell, Matthew Colless, Mike Dopita, Ken Freeman, Jeremy Mould and Bruce Peterson. In addition, Ken Freeman was elected an F.R.S. in 1998 and the following year received the Dannie Heinemann Prize, while Brian Schmidt was the inaugural winner of Australia's Malcolm McIntosh Award for Achievement in the Physical Sciences.

Stromlo's eighth Director, American Penny Sackett, took over from Acting Director John Norriss on 22 July 2002. She was Stromlo's first (and thus far only) female Director, and Chapter 9 ('Bushfires and a new beginning') highlights her achievements. As the chapter title suggests, the most momentous event that occurred during her short directorship was the disastrous Canberra bushfire of 18–22 January 2003 which not only led to the loss of 4 lives but also the destruction of much of Mt Stromlo, surrounded as it was by pine trees. *Mt Stromlo Observatory: From Bush Observatory to the Nobel Prize* shows image after image of burning or burnt-out observatory buildings—a poignant reminder of the power of nature. All of the telescopes on the mountain were destroyed, as were the workshop and the library (where I had spent many hours carrying out my research), and the $5 million Near-infrared Integral Field Spectrograph, which was undergoing final testing before being shipped to the Gemini North Telescope in Hawaii. Fortunately, the Visitor Centre and the main building housing the astronomers' offices survived intact. As the authors say, a lesser person would have given up, but instead Penny Sackett focusing on rebuilding the Observatory. Despite on-going problems with the insurers, by the time she completed her term as Director in 2007, Stromlo had a new Advanced Instrumentation Technology Centre; a replacement Spectrograph had been constructed for the Gemini North Telescope and an Adaptive Optics Imager for the Gemini South Telescope; and construction of Brian Schmidt's 1.35-m Sky-mapper had been approved. But more important was Sackett's success in getting Stromlo formally involved in planning the Giant Magellan Telescope, which the authors regard as "… the best and furthest-reaching decision she made for the future of the Observatory and Australian astronomy." (page 243). Despite the devastating fire, the Stromlo research staff were remarkably productive during Sackett's directorship, producing >500 research papers on

> … solar and extrasolar planetary systems, stars and stellar populations, the Milky Way and galaxies, dark energy and dark matter, gamma-ray bursts, interstellar medium and galactic feedback, and adaptive optics. (page 244).

In 2002 Ken Freeman and Joss Bland-Hawthorn (from the Anglo-Australian Observatory) wrote a major review paper on how our Galaxy was formed for the *Annual Review of Astronomy and Astrophysics*, and in 2005 Mike Bessell prepared a paper on standard photometric systems for the same journal. In that same year, Brian Schmidt was awarded a prestigious Federation Fellowship and in 2006 he shared the Shaw Prize with two American colleagues.

It is sometimes hard to decide where the chronological cut-off date should be for any historical study, especially when one of the authors just happens to be a former Director of the Observatory in question. In the case of *Mt Stromlo Observatory* …, Chapter 12 is the last, and it spans the period 2007–2013 and Harvey Butcher's Directorship, where his "… approach to doing research, of developing new instrumental capabilities to make new observations possible, characterized … his career." (page 254). Butcher continued the direction charted by Penny Sackett, appointing new staff with international reputations, involving Stromlo in the Australian space industry, developing an adaptive optics facility and obtaining further Government funding for Stromlo's participation in the Giant Magellan Telescope. Cutting-edge research continued, and the annual number of published research papers increased. Several staff members reaped international honours, led by American-born Brian Schmidt who shared the 2011 Nobel Prize for Physics with two other American astronomers. In addition, in 2007 Schmidt and members of the High-Z Supernovae Research team shared the Gruber Prize for Cosmology. Schmidt also was elected an F.R.S. In 2012 Ken Freeman received the Prime Minister's Prize for Science. Also a F.R.S., in January 2013 he was awarded the Mathew Flinders Medal by the Australian Academy of Science and the Henry Norris Russell Lectureship by the American Astronomical Society. For further details of Butcher's directorship see Bhathal (2014).

The final chapter of the book is titled 'Brian Schmidt's Nobel Lecture 2011: accelerating expansion of the universe through observations of distant supernovae'. After a 1-page introduction, there is a reprint of the 25-page paper by Brian P. Schmidt with the above title that was published in the *Review of Modern Physics* on 13 August 2012.

The book ends with a 1-page listing of the successive 'Directors of Mount Stromlo Observatory', followed by a 10-page 'Timeline of major events', spanning 1905–2012, and finally a 10-page Index.

Mt Stromlo Observatory … is beautifully illustrated, boasting numerous images that have never been published before, many in colour. But although the book is well written, there are some obvious omissions or areas of over-simplification which should have been picked up by the assessors of the MS. For instance, while Cla Allen was indeed involved in galactic radio astronomy (page 80), the important contributions that he and his Stromlo colleague David Martyn made to solar radio astronomy (see Orchiston et al., 2006: 51–53) are ignored. Then, prior to the 50-in and 74-in telescopes becoming operational, the workhorses for the Observatory's research programs were the 30-in Reynolds reflector *and* the 'Catts Telescope'. Between 1952 and 1963

> … the Catts Telescope was first used at MSO in its original 20-in Cassegrainian configuration and from December 1959 as a refurbished 26-in Cassegrainian reflector at the Mount Bingar field station … [It] was used very effectively by ten MSO astronomers and visiting astronomers and by five different Ph.D. students for photometry or spectrophotometry of stars in our Galaxy and for photometry of clusters of southern extra-galactic nebulae. These investigations resulted in the publication of twenty-six research papers based *in toto* or in part on observations made with the Catts Telescope, and these were published mainly in *The Astronomical Journal*, *The Astrophysical Journal*, *Monthly Notices of the Royal Astronomical Society*, *The Observatory* and *Publications of the Astronomical Society of the Pacific*. (Orchiston, 2010: 251).

There are also numerous minor errors of fact. Figure 2.8 shows a traction engine not a 'tractor'. It is misleading (pages 39–40) to claim that Janssen and Lockyer alone discovered helium, when Pogson was the first to notice and comment on the anomalous yellow emission line, during the 1868 total solar eclipse (see Nath, 2013). Although used briefly for solar observations, the Collaroy radar station in Sydney (page 77) never was a CSIRO Division of Radiophysics field station (see Orchiston and Slee, 2005). The claim that R.H. Reynolds (the donor of the 30-in telescope) was the only amateur astronomer to serve as President of the Royal Astronomical Society (page 78) is certainly incorrect, as over the years many other amateur astronomers held this office, including Francis Bailey, George Bishop, Henry Colebrooke, Arthur Common, Sir John Herschel, Sir William Huggins, Edward Knobel, William Lassell, Dr John Lee, William Maw, T.E.R. Phillips, Sir James South and Lord Wrottesley. When Walter Stibbs moved to Scotland it was as the Napier Professor of Astronomy at the University of St. Andrews and not just as "… Director of the St. Andrews Observatory …" (page 79). And contrary to the claim on page 190, SN 1987A was independently discovered on the same night by Ian Sheldon (University of Toronto), *as well as* Oscar Duhalde (Las Campanas Observatory) and the world's leading visual observer of variable stars, amateur astronomer Albert Jones of New Zealand (see Marsden, 1987), and all should be assigned equal credit. On page 226 Sydney's Ruby Payne-Scott is listed as the world's first female radio astron-omer, but her career in radio astronomy was inspired by Dr Elizabeth Alexander, who carried out earlier research in New Zealand (for details see Orchiston, 2005). Fortunately, 'typos' are rare, although descendents of Heinz Gollnow would not enjoy seeing him listed as 'Gollonow' on page 109 (and in the Index).

One of the positive features of this book is the extensive use made throughout of sidebars to provide specific information without detracting from the flow of the main narrative. Some of these are biographical, others contain very specialised astronomical material, whilst yet others impart general information. Thus, there are sidebars on the 'Rise of astrophysics', 'Stark effect', 'The ionosphere and radio communications', 'McCarthyism and the intellectual community in the US', 'Supernova 1987A', 'WIMPS and MACHOs', 'Women astronomers in Australia' and the 'Butcher-Oemler effect', to name just a few. However, given his research interest in Australian astronomical history, it would seem that Bhathal missed several excellent opportunities. For instance, Father O'Connell is mentioned on page 84, without any indication of who he was or where he worked. He was Director of the Riverview Observatory in Sydney and it would have been nice to learn a little about this Jesuit research institution and its work on variable stars. Again, on page 163 we discover that an innovative feature of the 2.3-m Advanced Technology Telescope was that the whole observatory building rotated, not just the dome. Yet this was not an Australian 'first', for Henry Russell constructed the very same type of facility at Sydney Observatory back in 1880 (Orchiston and Bhathal, 1982), and associated with this observatory was a 15-in reflector with a mounting designed by Russell that is reminiscent of the horseshoe mounting that was used much later with the 200-in Palomar Telescope (Orchiston, 2000).

Although this book is well written and well illustrated, it is clear that the senior author could have been more thorough in his research as numerous errors of fact occur and some key references are missing. It is equally clear that the publishers did not maintain an adequate level of quality control during the printing process for my review copy suffers from having pages 132, 133, 136, 137, 140, 141, 144 and 145 overprinted with pages 90, 87, 86, 83, 98, 95, 94 and 91 respectively, making nearly half of the Eggen chapter totally unreadable! Without this defect, and with the numerous errors corrected, *Mt Stromlo Observatory* … would be good value at just AU$39.95.

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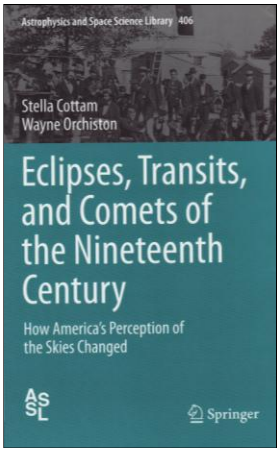
***Eclipses, Transits, and Comets of the Nineteenth Century: How America's Perceptions of the Skies Changed*, by Stella Cottam and Wayne Orchiston (Springer, 2015), pp. xii + 336, 239 illustrations. ISBN 978-3-319-08340-7 (hard cover), 160 × 240 mm, US$129.00.**



As we approach the total solar eclipse of 21 August 2017, whose totality will cross the cotinental United States from northwest to southeast and whose partial phases will be visible to the north through Canada to the Arctic and to the south through Central and northern South America, it is interesting and useful to ponder how best to get the public to participate in the event. Even today, I saw a discussion of worry about potential panic concerning eye safety—a panic that easily could be averted with proper public education and outreach in the days and months leading up to the eclipse.

The recent transits of Venus, in 2004 and 2012, did not lead to a darkening of the sky (since the dimming of the sunlight was only 0.1% of the total solar irradiance), but there was interest among the general public in those parts of the world from which the events were visible. Be-cause of Mercury's small apparent size, the 9 May 2016 transit of Mercury will be less detect-able (even from its zone of visibility, which in-cludes the Americas, Europe, and Africa), and we will have to wait until 2117 and 2125 for the next transits of Venus.

In a Ph.D. thesis completed through James Cook University in Australia, Stella Cottam described the nineteenth century public interest in America in major astronomical events, and she has now teamed with her former supervisor, Wayne Orchiston—who added additional material—to produce an interesting new book. They start with a discussion of interest shown in the Leonid Meteor Storm of 1833 (due back in about 2030) and the Great Comet of 1843 (with a Great Comet liable to appear at any time), and then move on to discuss the nineteenth century solar eclipses—especially those of 1868, famous for the discovery of helium, and the pair in 1869 and 1878 that were visible in the United States. They next discuss the 1874 and 1882 transits of Venus. For both eclipses and for transits, they discuss the then-current world-wide science, and scientists who were active in the field.

But interestingly, Cottam and Orchiston go beyond the scientific stories, however interesting they may be. They also discuss the treatment of these events in periodicals and newspapers of the time. Major sections discuss published reports, first of the eclipses and then of the transits. A short concluding section on public participation in research is a good forerunner to some potential projects for 2017.

This is a beautifully-produced book, with color images throughout, and the *Scientific American* map of the 1869 eclipse path shown on page 181 resembles the forthcoming eclipse path for 21 August 2017. The wide variety of images come from many sources, not just Wikipedia, and show the research skills of the authors.

This historical book by Cottam and Orchiston is fun to read and to look through. I can recommend it to all who like to know about eclipses, transits, or nineteenth century science in general, or who otherwise want something to tell them about the interactions of science with the public—or who just want an interesting book to read.

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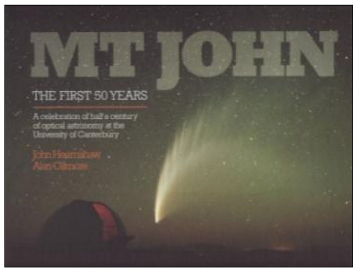
***Mt John – The First Fifty Years. A Celebration of Half a Century of Optical Astronomy at the University of Canterbury*, by John Hearnshaw and Alan Gilmore (Christchurch, Canterbury University Press, 2015), pp. 216, 188 illustrations. ISBN 978-1-927145-62-3 (hard cover), 310 × 240 mm, NZ$59.99.**



Mt John Observatory (henceforth MJO) is New Zealand's premier research observatory. Sited atop a ridge near the western shore of Lake Tekapo, in the South Island, with the snow-capped Southern Alps and New Zealand's highest peak, Mt Cook, off to the west, it is in a truly beautiful setting and must be one of the most charmingly-situated observatories in the world.

This book was written by two University of Canterbury astronomers, Emeritus Professor John Hearnshaw, who for years ran the Astronomy programs at the University, and Alan Gilmore, who until recently was the Superintendent of MJO. Both have had long and intimate associations with MJO, and both are 'key players' in New Zealand's small community of professional astronomers.

There are seven chapters, and the first is an Introduction, titled 'The founding of Mt John: The quest to explore the southern sky'. After briefly discussing early New Zealand astronomical history, Frank Bateson's site-testing activities in the South Island of New Zealand in 1961–1963 are recounted. Bateson was a leading New Zealand amateur astronomer, with a special passion for variable stars and Jupiter, and he had a vision of a national observatory where cutting edge astrophysical research could be undertaken. The University of Pennsylvania funded a site-testing program which led, eventually, to the selection in June 1963 of Mt John as the site for a new observatory operated jointly by the Universities of Canterbury and Pennsylvania. Later the University of Florida would join the collaboration.

Bateson was Astronomer-in-Charge of the 'Mt John University Observatory' (as it was originally known) from June 1963 until October 1969. Initial instruments were Bateson's own 8-in Grubb refractor and 16-in reflector; a triple astrograph provided by the University of Pennsylvania; and that University's historic 18-in Brashear refractor (which had to remain in its crate, the cost of a dome being prohibitive).

Chapter 2, titled 'The Bateson years: A survey of the southern sky', describes the construction of the early buildings at Mt John; installation of the telescopes and astrograph; the first major research project undertaken—with the 5-in astrograph—which resulted in the Canterbury Sky Atlas; the later Bamberg sky patrol; and the first IR survey of the southern sky. There was no Astronomy offered at the University of Canterbury in those days, so most MJO research was carried out by American astronomers and their graduate students. Leading the Americans was Professor Frank Bradshaw Wood, who

> ... had, from the start, been the most ardent supporter of Mount John University Observatory. Without his enthusiasm for a southern observing station attached to the University of Pennsylvania, and without the funding support that came directly from that university, it is certain that Mt John would never have eventuated. (page 43).

Bateson's departure from MJO also is discussed in detail in Chapter 2. I had always wondered why someone who dreamt of being an astronomer and finally succeeded, with a lovely house overlooking beautiful Lake Tekapo, would contemplate retirement when five years short of the mandatory retirement age of 65. Hearnshaw and Gilmore provide the answer: there was growing tension between Bateson and his American *and* New Zealand employers as they grew increasingly unhappy with his performance. In the end Bateson resigned on his 60th birthday, but Hearnshaw and Gilmore feel that New Zealand shortchanged itself on this occasion:

> The rift with Wood and other Pennsylvania astronomers ... and the cool relations that developed with McLellan, the head of Canterbury's Physics Department, considerably curtailed Bateson's effectiveness as astronomer-in-charge. There were differences of background and personality. Bateson was a businessman, not an academic, and he had a talent for public relations and for organisation. Academics saw him as egotistical and arrogant, and they were frightened of his apparent empire-building. In this respect they probably misjudged him, and in doing so missed out on an exceptional leader for the further development of Mt John into the 1970s.
>
> Probably no-one else could have set the founding of Mt John in motion in the way Bateson had done ... Wood and McLellan ... were both conservative risk-averse academics without Bateson's flair for public relations and garnering community support. It was a clash of personalities that led to tensions, and Bateson's ultimate fall from grace. (page 54).

Despite this prognosis, MJO flourished after Bateson's departure, partly because undergraduate and graduate astronomy programs finally were established at the University of Canterbury, and partly because of the arrival of two new telescopes, both 24-in (61-cm) reflectors ideally suited to photoelectric photometry of variable stars. Canterbury also awarded its first Ph.D. in 1979, to Gerry Gilmore, who would build an international reputation in England. These developments, and others, are outlined in Chapter 3, 'New telescopes, the study of southern variable stars and Mt John turns to spectroscopy'.

The mention of spectroscopy in the chapter title refers to the appointment in 1976 of John Hearnshaw to a new lectureship and his involvement in stellar spectroscopy. Little could he have imagined at the time that this would lead, eventually, to a full Chair and a 39-year association with the University of Canterbury and MJO. John has since become an authority on the design, construction and use of échelle spectrographs.

Fortunately, MJO's acquisition of important new instrumentation did not cease with the first échelle spectrograph. Chapter 4, 'The McLellan 1-m telescope: A new era of research into stellar spectroscopy and binary stars, and a new photographic sky patrol', begins by describing the 1-m Dall-Kirkham reflector, championed by John Hearnshaw. At the time this was the largest Dall-Kirkham in the world, and was built almost entirely in the University's own workshops. It was named the 'McLellan Telescope', and the official opening occurred at MJO on 11 July 1986. Subsequently, the échelle spectrograph was adapted for use on the new telescope. In the 1980s the Department of Physics at the University of Canterbury also gained two new astronomers, Drs Peter Cottrell and William Tobin, who would make important contributions to New Zealand astronomy. Meanwhile, the second author of the *Mt John* book, Alan Gilmore, together with his wife, Pam Kilmartin, began working at MJO in November

1980 and April 1981 respectively. Unlike other Canterbury staff and most of the graduate students—who carried out stellar astronomy—their main interest was in comets and minor planets.

Chapter 5 is titled 'Two new spectrographs for Mt John, a robotic telescope, more research on variable stars, comets and asteroids, and the search for extrasolar planets'. Hearnshaw and Gilmore regard the 1990s as "... Mt John's golden years." (page112), which saw the commissioning of two new spectrographs at MJO. The more important one was Hercules,

> ... a pioneering instrument that would become the world's first fibre-fed vacuum échelle spectrograph designed for precise Doppler-shift measurements on brighter stars, as well as detailed analysis of fundamental stellar properties, including chemical composition. (page 116).

Like the 1-m telescope, Hercules (which stands for High Efficiency and Resolution Canterbury University Large Echelle Spectrograph) was another locally-designed and built innovative instrument, and it would serve New Zealand astronomy well by providing data for Canterbury staff and a succession of graduate students. Two of the most interesting projects, employing Hercules, relate to asteroseismology and the search for extrasolar planets. But not all of Chapter 5 is devoted to instrumentation and stellar astronomy, for Alan Gilmore provides several pages about the MJO minor planet program as well as a page on 'Life on Mt John: A personal perspective from Alan and Pam'.

In Chapter 6 ('The MOA Project at Mt John') the authors introduce a very different type of extrasolar planet search strategy that also is pursued at MJO, and this is the use of gravitational lensing. The MOA Project (MOA = Microlensing Observations in Astrophysics) was launched in 1995 as a Japanese-New Zealand collaboration, with the New Zealand astronomers from Auckland University, Carter Observatory, Victoria University of Wellington and the University of Canterbury (where John Hearnshaw was the sole participant). The 61-cm Optical Craftsman Telescope at MJO was dedicated to the Project and was automated, some optical modifications were necessary, and the Japanese collaborators provided a very large digital CCD camera. While a number of microlensing events were recorded it was only in July 2003 that irrefutable evidence was obtained of an extrasolar planet (named MOA-2003-BLG-53Lb). As Hearnshaw and Gilmore observe,

> This was the first ever planet found by the new microlensing technique and the results were beyond doubt. Nine years of hard work by the MOA team had finally come to fruition. (page 141).

Meanwhile, the Japanese decided to ramp up their support for the MOA Project by providing a larger dedicated telescope, and on 1 December 2004 the 1.8-m altazimuth-mounted MOA Telescope, with its 80 million pixel CCD camera, was officially opened at MJO.

An exciting discovery by the MOA team is the presence of large numbers of extrasolar planets that are not associated with any known stars. Meanwhile, research also continues on variable stars discovered during the MOA Project.

Finally, it is important to point out that in addition to the MOA Project, two University of Canterbury astronomers are involved in PLANET, another successful extrasolar planet search program that uses microlensing. Thus, extrasolar planets are an important component of the overall research strategy of the Canterbury astronomers.

The final, profusely-illustrated Chapter, on 'Mt John reaches out to the public' turns from astronomical research to astronomical education and popularisation. The University of Canterbury organises Aurora Schools in Astronomy for senior secondary school students, which include popular visits to MJO. The University also arranges several popular MJO visits each year for alumni. However, two other recent developments have succeeded in bringing astronomy to much larger audiences. Responding to an explosive public interest in astro-tourism, Earth & Sky Ltd. began running very popular day-time and night-time tours of Mt John and MJO in 2004, and they later set up an astro-cafe with stunning views across Lake Tekapo. Now the company is planning to erect a Visitor Centre at Lake Tekapo village along with a dome to house the historic 18-in Brashear refractor, which (finally) will be used for public viewing. The other initiative was the successful creation in 2012 of the McKenzie Basin—where MJO is located—as a recognised UNESCO International Dark Sky Reserve. This led, in turn, to an international conference in 2012, and in 2013 to the first 'Starlight Festival', which drew an audience of 300 and helped create a greater awareness of MJO and the research carried out there.

Rounding out this very attractive, large-format book with numerous stunning non-astronomical coloured photographs, are appendices listing University of Canterbury Astronomy staff and astronomy graduate students, plus students from other universities who observed at MJO or used MJO data; 16 pages of notes and references; a Glossary; a Bibliography; and an Index.

Mt John ... provides a visual feast and is a wonderful read. It is reasonably priced, and I thoroughly recommend it for anyone interested in New Zealand astronomy.

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