JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807

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The annual subscription rates for Volume 9 (2006) are:

AU$77:00 for institutions
AU$44:00 for individuals

COVER PHOTOGRAPH

Bruce Slee (1924–) is shown examining the chart records of the Mills Cross radio telescope in 1955. The Mills Cross was an innovative high resolution array, the first of three cross-type radio telescopes erected at the CSIRO's Division of Radiophysics Fleurs field station near Sydney. This is the second in the series of *JAH*^{2} issues celebrating Bruce Slee's sixty years in astronomy. For an overview of his research see pages 3-10 in the previous issue of this journal, while one aspect of his research portfolio is discussed on pages 97-106 in this issue.

Journal of Astronomical History and Heritage, 8(2), 75-86 (2005).

RADIO ASTRONOMY AT STANFORD

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Abstract: Many astronomical topics were addressed by students and staff of the Stanford Radio Astronomy Institute over the course of decades, and some of the memorable milestones can be discussed here at length. These are antenna design and construction, the sunspot number series, astronomical tomography, the cosmic microwave background radiation, nulling interferometry for peering into circumstellar environments, celestial mechanics of the early Earth satellites, the extraterrestrial connection, dynamic spectra of exospheric phenomena, the versatile Hartley transform and Centaurus A.

In addition to the text references, a complete list of solar publications related to the microwave spectroheliograph is appended. Further detail, and non-solar publications, are available in the annual reports published in the *Astronomical Journal* and *Bulletin American Astronomical Society* from 1961 to1980, especially the final report.

Keywords: Stanford University, microwave radio astronomy, sunspot investigations, extraterrestrial life.

1 INTRODUCTION

The CSIR Radiophysics Laboratory was built on the grounds of Sydney University, Australia, in 1938 for the purpose of developing radar for use in the Pacific. By 1946, when radar had won World War II, the Laboratory had a superabundance of talented radar specialists, all of whom were thinking about their future. There were not enough resources for the innovative proposals on the table, and many of the creative people departed as reduction to a sustainable size took place (Sullivan, 2005). Of those who continued in radio astronomy elsewhere, W.N. 'Chris' Christiansen ultimately went to the Electrical Engineering Department at the University of Sydney, B.Y. Mills to the Physics Department at the same University, J.G. Bolton and G.J. Stanley to Caltech, J.A. Warburton to the University of Nevada, F.J. Kerr to the University of Maryland, and J.L. Pawsey, with whom I co-authored the first book on radio astronomy (Pawsey and Bracewell, 1955), was appointed Director of the National Radio Astronomy Observatory, Charlottesville. I was spared painful aspects of some of these separations; I studied in Cambridge until 1950, moving from centimetre wavelengths to tens of kilometres, and upon returning to Radiophysics made a relatively peaceful transfer to Stanford University in 1955, whilst on leave.

2 THE STANFORD MICROWAVE SPECTROHELIOGRAPH

In 1954 I spent the year at Berkeley as a visiting Assistant Professor of Astronomy at the invitation of Professor Otto Struve (who was then Head of the Department), and gave a two-semester course on radio astronomy. Struve requested a proposal for a new instrument for radio astronomy; I suggested a microwave spectroheliograph, and he submitted the plan to Lawrence Livermore Laboratory for a cost estimate.

At the same time, I mailed the plan to Joseph L. Pawsey, the senior co-author of our book, *Radio Astronomy*, proposing to build this radio telescope in Sydney. It comprised NS and EW arms in a cross configuration, each containing sixteen solid metal 10-ft parabolic 'dishes' spaced at 25-ft intervals. It was designed to operate at a wavelength of 9.2 cm, with a pencil beam of 3.1 arcminutes.

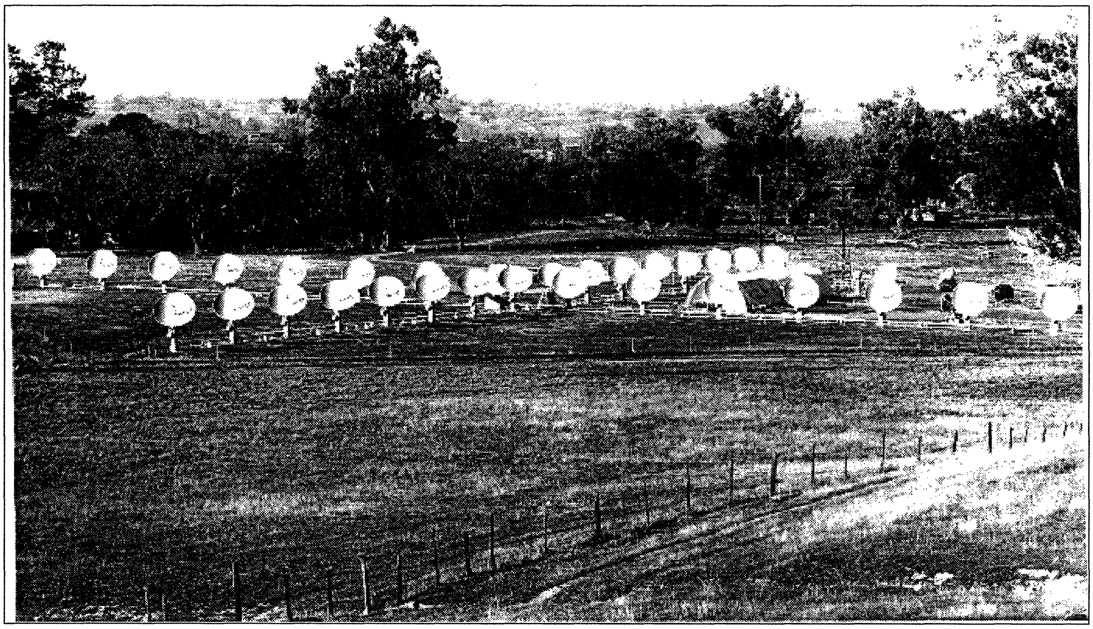

Figure 1: The 9.2 cm spectroheliograph.

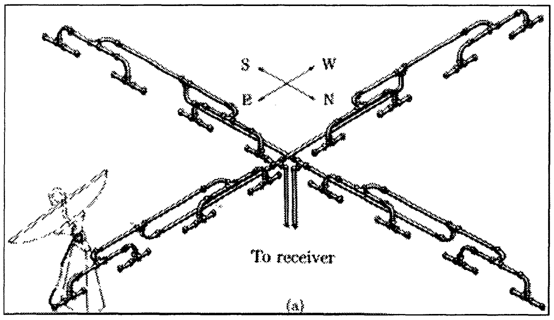

Figure 2a: Waveguide array.

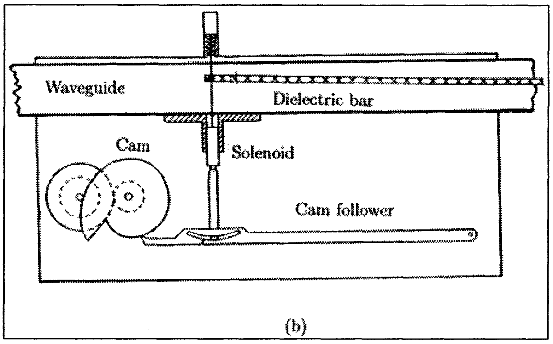

Figure 2b: Phase-shifter.

The plan was not acted on as Christiansen, veteran Radiophysics researcher with industrial experience, planned to do much the same. Because of financial uncertainties, there was no suggestion that I should collaborate with Chris, my respected elder.

The Berkeley document was the first written description of the microwave spectroheliograph concept, but the design was obvious to those familiar with the newly-conceived Mills Cross (Mills et al., 1958) and Christiansen's existing grating arrays (e.g. Christiansen and Warburton, 1953; Davies, 2005). Stanford University agreed to construct the array (Figure 1), and it became operational in April 1960.

The first description in print (Bracewell, 1957) was followed by a detailed account of the Stanford instrument (Bracewell and Swarup, 1961). Figure 2a shows the S-band waveguides connecting the EW and NS arrays to the receiver and Figure 2b shows one of the phase-shifters in the NS arm. Each arm terminated at a waveguide flange in the control room, where the two signals were multiplied together and demodulated.

Between row scans it was necessary to readjust the phase length to each of the NS antennas in accordance with the date and time of start (nominally noon). A phase-shifter was designed in the form of a slender bar of polystyrene approximately one metre long which was inserted in the waveguide and provided with tapered ends at a separation suitable for reducing unwanted reflections to undetectability. The net phase shift was altered at approximately two-minute intervals by skewing the bar in small steps with respect to the waveguide electric field. The number of steps, depending on the Sun's rate of change of zenith distance in accordance with time and date, was determined by an analogue computer, a rotating brass cylinder with pinholes distributed along a helix. As each pinhole passed over a photodetector a pulse was sent to a cam-activated solenoid (Figure 2b).

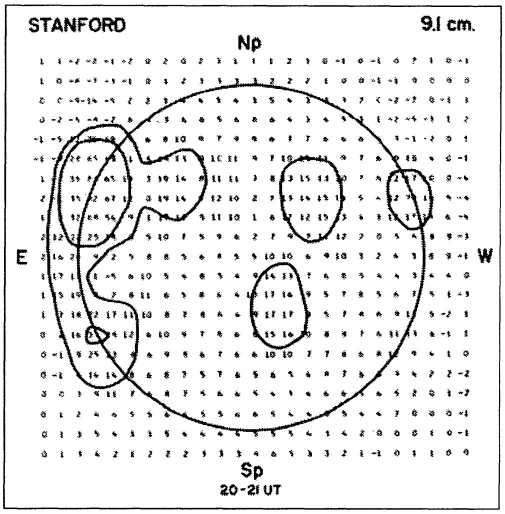

Figure 3a: Sun map of 1969 January 3.

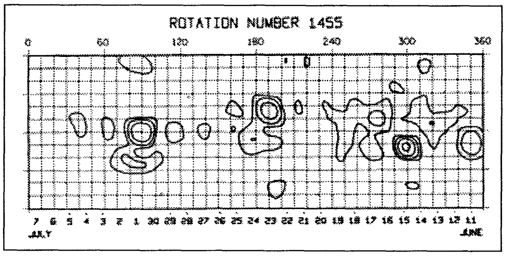

Figure 3b: Brightness map for one solar rotation.

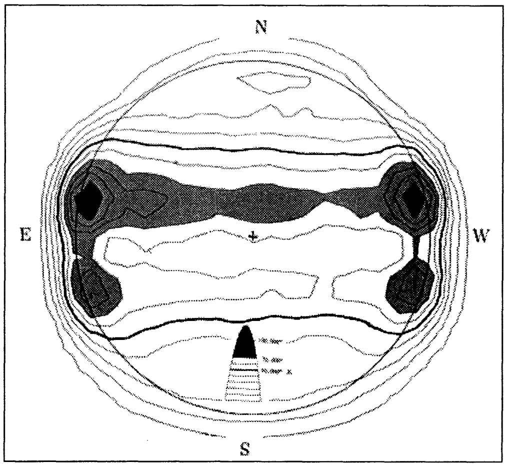

Figure 3c: Average of the 360 maps for 1969.

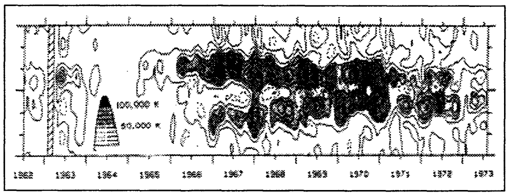

Figure 3d: Butterfly diagram.

The waveguide path to each antenna feed horn was kept constant within one millimeter. The waveguide itself was painted white, shaded from direct sunlight and rain, and tightly sealed; nevertheless the phase length to individual antenna feeds was found to vary from month to month, largely as a result of activity of spiders and birds. To measure these shifts a novel scheme was developed that became the forerunner for adjustment of interferometer arrays elsewhere. At each feed horn a very small fluorescent tube developed by Govind Swarup was inserted across the waveguide. A signal injected into the NS waveguide terminal in the control room would undergo successive subdivisions at the seven tee junctions and radiate into space. But if one discharge tube was switched on, it caused almost total reflection from its feed horn. A slotted waveguide section between the signal generator and the transmission waveguide terminal indicated, for each feed horn in turn, the location of a standing wave minimum and the amount of the necessary adjustment, if any. Phase compensation was carried out with calibrated half-wavelength slivers of copper inserted on the waveguide floor at a junction.

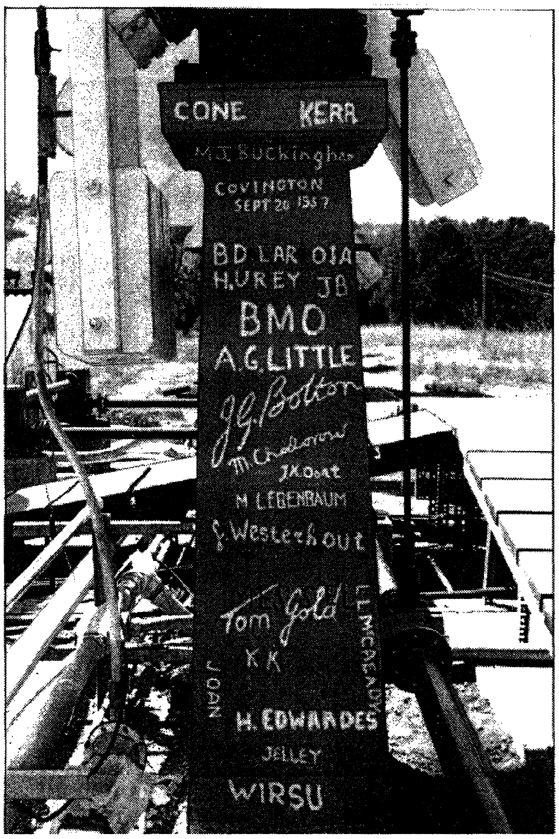

Figure 4: Pier East 1s with signatures of F.J. Kerr (Australia and Maryland), M. Buckingham (Australia and Carolina), A. Covington (Canada), B.D. Laroia (India), Harold Urey (U.S.), Barney Oliver (U.S.), A.G. Little (Australia, Stanford), J.G. Bolton (Australia., Caltech), M. Chodorow (Stanford), J.K. Oort (Netherlands), M. Lebenbaum (U.S.), G. Westerhout (Netherlands, Maryland), H. Messel (Australia and Canada), Tommy Gold (Vienna, U.K., Harvard, Cornell), L.L. McCready (Australia), Joan Freeman, (Australia and U.K.), J.V. Jelly (U.K.), and H.N. Edwardes (Australia), out of a total of fifty-seven on this one pier.

After demodulation the resulting signal was sent to an electric typewriter that directly printed the day's solar map, row by row, in double-digit format, as shown for 1969 January 3 in Figure 3a. Simultaneously, a five-hole paper tape was generated and fed into a teletypewriter for immediate transmission to military users and to the Space Agency for further distribution. Monthly charts of brightness (Figure 3b) plotted as a function of heliographic latitude and date, a presentation used by Meudon and Mt. Wilson Observatories, were published periodically (NASA, 1975). Werner Graf did much ingenious data-handling to produce annual average maps (Figure 3c), a novel and revealing presentation, while the butterfly diagram (Figure 3d) shows intriguing relationships between one hemisphere and the other. Comparable data at L-band from Christiansen's Cross at Fleurs near Sydney (Christiansen and Mathewson, 1958; Orchiston, 2004) were published by the *Quarterly Bulletin of Solar Activity*.

Eleven years of S-band Sun mapping, faithfully pursued by Joel Deuter and Jim Rutherford in the years from 1962 to 1973 inclusive produced 157, 280, 329, 350, 354, 359, 361, 360, 358, 364, 363, and 243 maps, respectively.

The microwave spectroheliograph was astronomically productive in the field of solar physics, as indicated by the plethora of references listed in Section 17 at the end of this paper, but operation over the years also generated a significant fraction of publications in the fields of antenna practice, data reduction, and imaging. For example, by switching the EW arm against a two-element interferometer constructed so as to double the EW length, a fan beam of width one arcminute was demonstrated (Bracewell, 1957). This milestone in antenna technique, directly dependent on precision phase adjustment, represented the first achievement of radio-wavelength angular resolution comparable to that of the human eye using light.

Over the decades, nearly two hundred international astronomers have visited the site and incised their names with hammer and chisel on the spectroheliograph piers (e.g. see Figure 4).

3 RESTORATION

Restoration of observations, aimed at correcting for the loss of angular resolution associated with the finite beamwidth of an antenna, had been of interest since J.S. Hey's original discovery of Cygnus A in 1946. The method of successive substitutions (Bracewell and Roberts, 1954) provided a clear theoretical description of the possibilities, showing among other things, that the 'true' distribution of source brightness could never be derived from the observed distribution alone. Resolution could be improved a little, for example by applying a positivity constraint, or by judicious extrapolation of the spectrum of the data. Experiments in the *laboratory* can present a known true distribution to an antenna under test, but in observational astronomy it proved to be distressing to present a sky map that had been restored after being observed, and to read later that a radio telescope with higher resolution falsified the published details. Since those times, authors have been very cautious about restoration. The possibilities are limited by two factors. To start with, Fourier theory shows that a given antenna ignores celestial spatial frequencies beyond a limit set by the size of the antenna aperture dimension in wavelengths. Once the detail in the finer Fourier components has been lost, it cannot be recovered, unless there is other information from elsewhere. How far one can use the antenna properties in enhancing the Fourier components that, as recorded, have been reduced by calculable amounts, is set by the spatial noise level. The noise magnitude, and its dependence on time and direction, is not easy to assess. In principle, a transit observation of a structured but weak source should start long before the actual transit and continue until long after to obtain a record from which the character of the noise may be ascertainable. This was seldom done by impatient observers; observations of lunar occultations and solar eclipses offer examples. Noise arises from the receiving equipment, spatial fluctuations in brightness of the sky, passing airplanes, and other annoyances. At one time it was seriously thought (in Cambridge) that certain solar bursts observed by Ruby Payne-Scott (in Sydney) came from passing planes.

A key paper (Bracewell, 1958) recorded the culmination of studies up to that time, and has remained a classic. A modern imaging application for a computer these days may have a 'deblurring' button. The more times it is pushed the sharper the map becomes. There is more to restoration than can be encompassed by buttons. Even so, the application implies that where one stops is a matter of judgment based on experience; that is so. The distinction between 'restoration' and 'reconstruction' dates to those days.

The spectral sensitivity function introduced in the same issue of *Proceedings of the Institution of Radio Engineers* represented a significant step forward from the (real) optical concept of modulation transfer function (MTF). This original optical concept has been superseded in optics, where appropriate, by the (complex) optical transfer function (OTF), a new name equivalent to the spectral sensitivity function. Today the simple term 'transfer function' has prevailed in both astronomy and optics.

4 DERECTIFYING THE SUNSPOT NUMBER SERIES

Although one thinks of the solar cycle as occupying 11.1 ± 1.55 years, magnetic observations at the Mt. Wilson Observatory in 1918 showed that alternate cycles revealed alternating magnetic polarities. So the solar oscillator *period* was about 22 years, with a spread in cycle length characterised by a certain Q. In other words, the oscillation was not monochromatic, but had a certain bandwidth.

It would make sense to redraw the graph of sunspot number R versus t (Figure 5 a) so as to emphasise the 22-year character; for example one might alter the sign of R between successive solar maxima. Such a procedure would eliminate rectification artefacts from the sunspot number spectrum. The sunspot number does not descend to zero at sunspot minimum; however, during the minimum, the spots of the new cycle are in a higher latitude than, and have opposite magnetic polarity to, spots of the old cycle. The Greenwich photoheliograph results distinguish between the signs to be given to spots during the minimum and allow a zero epoch to be determined.

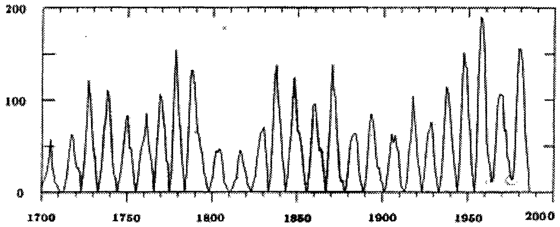

Figure 5a: The sunspot number R.

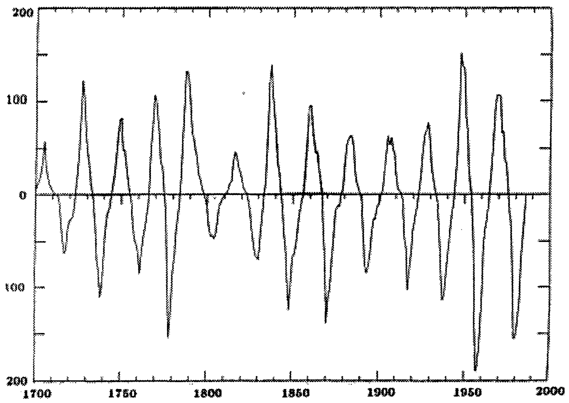

Figure 5b: The derectified number $R_\pm$.

The derectified sunspot number $R_\pm$ (Figure 5b) reveals two new things: the Q of the 22-year cycle is 11.5, which is higher than the value 7.2 for the 11-year cycle and indicates that we are on the right physical track. Also, the curious alternation in height of the 11-year maxima (zigzag effect) reveals itself as an additive variation of long duration though not demonstrably periodic.

A more appropriate 'physical' number, $\mathcal{R}$, was sought by averaging segments of $R_\pm$ that straddle the zero crossings. This average segment shows a curious dip, which disappears if $R_\pm$ is related to a supposed $\mathcal{R}$ by $R_\pm \approx |\mathcal{R}|^{3/2}$ sgn $\mathcal{R}$. In support of this three-halves law, which produces a more nearly linear passage through zero, is the fact of further spectral simplification (Bracewell, 1988). The curious third harmonic in the sunspot series spectrum can be similarly disposed of; it comes from the peaks of R being sharp, the more so as R_{max} is greater.

There is another thing about the shape of the sunspot cycle. Climbing from a minimum to the following maximum may take less time than for the descent. This asymmetry is more pronounced the greater the maximum. In fact, sunspot number prediction as performed by M. Waldmeier, using the initial rate of climb to predict the date and height of the coming maximum, was never matched by statisticians. The asymmetry could possibly be due to a buoyancy effect in the solar interior not requiring non-sinusoidal behaviour of the fundamental oscillator. If indeed the surface appearance is produced by rising ribbons of magnetic flux toward the sunspot zones then the equator-ward drift could be due to interior refraction that brings the earliest manifestation of subsurface magnetic field to the higher latitudes (Bracewell, 1999).

5 RESEARCH SUPPORT

Financial support for radio astronomy at Stanford was provided from the beginning by the Air Force Office of Scientific Research which, following the lead of the Office of Naval Research, was implementing a plan urged by Vannevar Bush (author of a textbook in Electrical Engineering Communications at Sydney University) to support research in universities with military money, pending the establishment of a National Science Foundation. Prior to World War II, agriculture and some medicine were the only recipients of Government support for research. To ensure a future supply of radar-level engineers, university research was now to be funded, successfully, out of the generous military budget. After several years, Senator Mansfield slipped an amendment into the budget requiring that each grant or contract awarded should in future specify a military mission. After that, things went downhill until ultimately NSF, in financial circumstances reminiscent of the experience at the Radiophysics Laboratory in Sydney, had to focus on the NRAO, and cast loose several universities that had significant projects in planning.

6 SPUTNIK-ERA CELESTIAL MECHANICS

A telephone call came one evening in October 1957 from the *New York Times* asking if it was true that the Soviets had a Sputnik circling the Earth and sending out radio signals at 20.005 megacycles. This was the first I had heard of it. My colleagues, V.R. Eshleman, A.M. Peterson and O.G. Villard, were dining at our house with their wives. The men all rushed out to a field shack and we did pick up the beeps. After that, sources in Washington, D.C., circulated times of passage overhead to newspapers in the San Francisco Bay Area but they were not correct. Newton, in his *Principia Mathematica*, *Book III*, *System of the World*, had published a diagram showing the launch of an artificial satellite and worked out the periodic time as depending on height, but he had no knowledge of solar-terrestrial influences on the density of the upper atmosphere. Figure 6 is an example of correct daily charts that were published locally. An increase in atmospheric density caused by incoming solar ultraviolet speeds up a low satellite significantly. Knowledge of times of passage for a few previous passes overhead made accurate prediction possible.

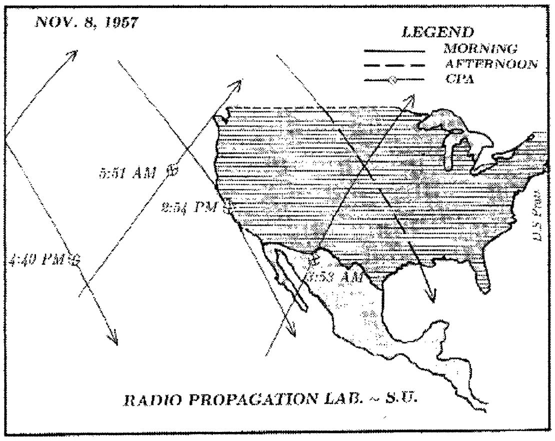

Figure 6: Predicted times, paths and closest points of approach (CPA) of Sputnik II over the San Francisco Bay area (Daily Palo Alto Times, 7 November 1957).

In 1959 the Explorer I satellite was launched by the Jet Propulsion Laboratory while it was in rotation about its long vertical axis on the launch pad. The idea was to preserve its direction in space, as is done by rifling in firearms. But on later passes overhead it was tumbling instead of spinning as planned, and then began slithering like a ski whirling on ice. The rocket scientists had overlooked the principle of conservation of angular momentum (Bracewell and Garriott, 1958). Garriott was at that time a student, but later, as an astronaut, he was filmed floating in zero gravity as he released a can of soft drink, rotating about its long axis. The slow conversion from spinning to precession to tumbling was fascinating. One can toss a full can spinning about its long axis into the air from the ground and see the same sequence of events occurring, but rather rapidly. An informative lesson is taught by getting a student group to see how high they can toss a spinning can and then catch it. They can toss it pretty high, but why it is difficult to catch presents food for thought. For the derivation of these results see Bracewell (1959).

7 THE MINIMUM REDUNDANCY ARRAY

As production of solar maps seven days a week became routine, we considered and published several follow-up projects. A giant 320-foot centimetre-wave cylinder was discussed with antenna construction firms, (one of them so competent as to find out the dollar amount of our proposal to NSF). I found negotiating to be an educational experience. So the cylinder design was abandoned in favor of a minimum redundancy array of five equatorially-mounted 60-foot dishes for 2.8 cm wavelength (Bracewell et al., 1973). The innovative mount was designed using commercial I-beams. Later I noticed that the Dwingeloo people had arrived at the same optimum. The dishes themselves are centred on a heavy steel octagonal prism made from welded channels on a rotatable gunmount from US Navy surplus. The large precision declination gear proved to be machinable locally in a temperature-controlled shop, but the cost of opening up the cutting room was prohibitive. In general we found that the cost of doing things ourselves was about one-fifth of the commercial price. Figures 7 and 8 show the home-grown product. The necessary precision was achieved without gear teeth, using wire rope wound on a smooth surface with a selsyn indicating, in the control room, the latched position. The hour-angle gear, which is in motion, is different. A steel wheel was lifted onto the equatorial mount and teeth were cut by a torch as the wheel was rotated. This low-brow procedure compensates for the slight deflection of the mount as hour-angle changes. Much mechanical and structural engineering went into the design—and my indebtedness to the Sydney University Civil and Mechanical Engineering Departments shows.

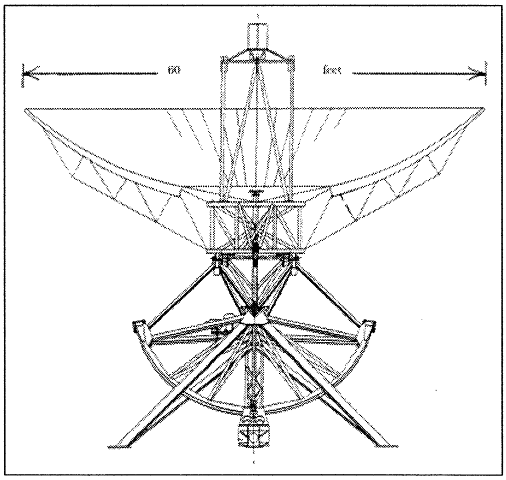

Figure 7: Schematic diagram of an equatorially mounted 60-foot reflector.

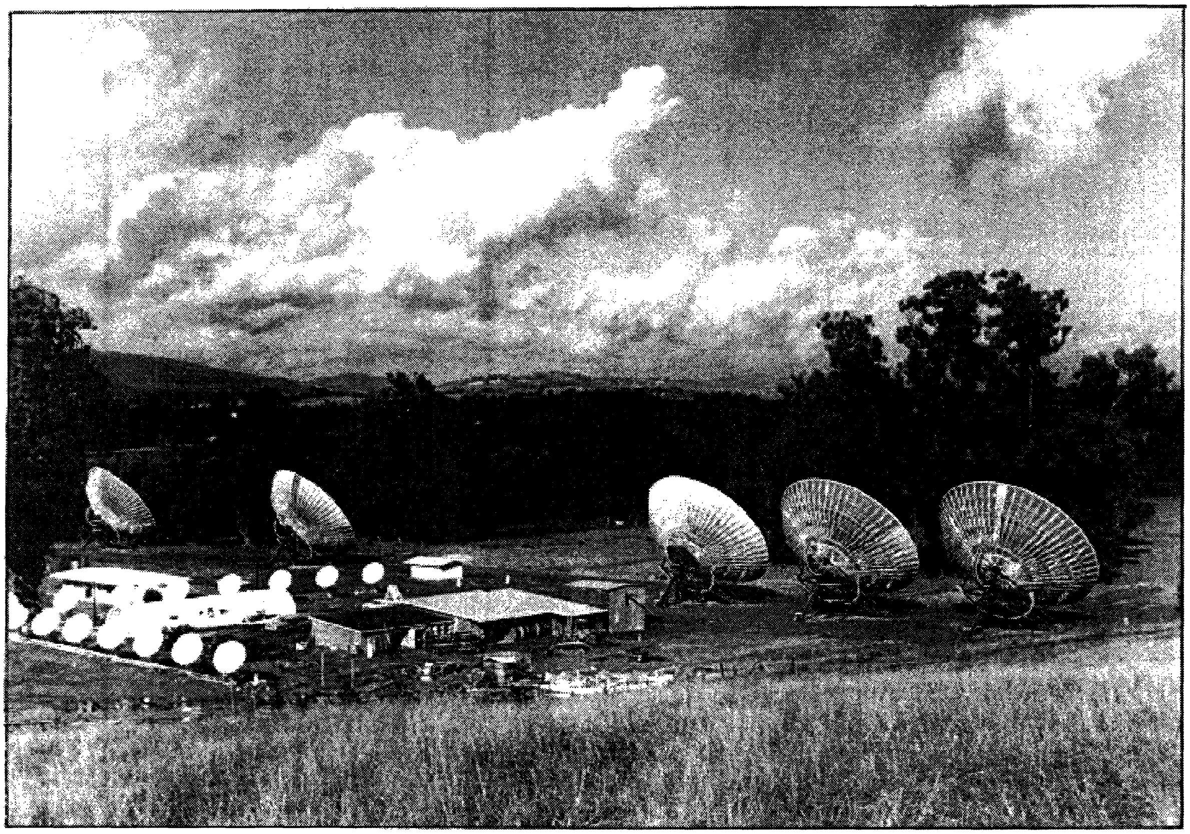

Figure 8: The minimum redundancy array of 60-foot dishes.

The steel hub supported 56 paraboloidal aluminium petals pressed from 4 × 24ft sheet. When bolted onto a curved fixture shaped as a $6^3/_7$ degree segment of the paraboloid to be assembled, the sheet's protruding wings were bent upward by about 120° and riveted into the rigidifying, tubular space frame. After the petals were attached to the hub a transit mounted on axis was used by E.K. 'Ned' Conklin to adjust their fit to their neighbours.

Investigations conducted with the 60-foot array are indicated in the reference list. With a 20-arcsecond beam, a variety of observing projects could be attacked. Of particular interest was the announcement of the cosmic background radiation by Penzias and Wilson (1966), which inspired our group to conduct research in this new field.

8 THE ROTATION SYNTHESIS ALGORITHM (TOMOGRAPHY)

A striking step forward in the field of data reduction is furnished by the steps leading to the algorithm for reconstruction of an image from fan-beam scans. Christiansen had obtained fan beam scans of the Sun at 21 cm wavelength as the Sun swept through the beams at advancing position angles hour by hour. If there is not much detail in an image, just a few angles can give significant information. In an oft-quoted example from radiology, an X-ray image may reveal that a piece of birdshot is lodged in your head, but not exactly where. An image taken in just one more direction tells where it is. In computed tomography as practiced in radiology today, 180 scans are made at 1° intervals. Christiansen, however, could produce new information about the L-band Sun with just a few directions of scan. He also introduced a Fourier transform technique to obtain positional information about the hot plage areas (Christiansen and Warburton, 1955). Professor Govind Swarup, FRS, will remember the painstaking manual integration procedure that was carried out on a large drawing board to implement the scheme. Later Swarup came to Stanford as a major contributor to the success of the microwave spectroheliograph, was appointed Assistant Professor in Electrical Engineering on receiving his Ph.D., and returned to India where his first radio telescope won a spot on an Indian postage stamp. He subsequently went on to further success with the Giant Metre-wave Radio Telescope.

The theory of reconstruction (Bracewell, 1956) solved a data reduction problem of radio astronomy which, in general, involves restoration. It was shown that, by dividing the problem in two parts, the reconstruction component was fully soluble mathematically but that the restoration problem was not. A later development (Bracewell and Riddle, 1967) was a simple space-domain algorithm for reconstruction from line integrals. This introduced the reconstruction algorithm used later for computed tomography in medical diagnosis.

Allan Cormack, a South African physicist who, by coincidence, was at Cambridge at the same time as myself, shared the Nobel Prize for Physiology or Medicine with Godfrey Newbold Hounsley in 1979 for presenting an inversion formula for the Radon transform. His solution (Cormack, 1963) was mathematically elegant but never used for computation (see The

1979 Nobel Prize, 1979). In the fifties, hospital X-ray departments employed a physicist from the local university to consult on X-ray safety. In this capacity, at the Groote Schuur Hospital, Cormack had placed metal cylinders on the central platform of an optical diffractometer as used in elementary physics labs, and taken sets of X-ray pictures from different angles, as the set-up was rotated about a vertical axis. That set his mind working on the possibility of mathematical computation of the absorption distribution in a plane. This would improve on a chest X-ray that shows both the ribs in front of, and the ribs behind, the organ of interest.

The inversion theory of 1956 was noted in various review references (e.g. Bates and McDonnell, 1986; Brooks and Di Chiro, 1975, 1976; Deans, 1983; Rosenfeld and Kak, 1982), but the Bracewell and Riddle 1967 paper introduced the technique of modified back-projection, which entered current use in radiology. This paper was heavily cited in sixty different journals, and it became my most cited paper ever!

The word tomography was already in use by radiologists to describe a procedure in which an X-ray source and a detector simultaneously move in opposite directions, above and below a prone patient. A plane of interest, containing say the spine, could be emphasized, while the volumes above and below were smeared. So tomography (the Greek term, *τομος*, means 'slice') was a familiar term. It led to the terms 'computer-assisted tomography' (CAT scan) and 'computed tomography' (CT scan). Plain back-projection was independently described by Vainshtein (1970) but had the defect that the point response went infinite.

9 THE COSMIC BACKGROUND RADIATION

When the detection of this hitherto unobserved (but predicted) radiation was announced by Penzias and Wilson (1966) it was characterised as isotropic. This reminded me of the cosmic rays, which, when discovered, were reported as coming uniformly from all over the sky—but they proved to exhibit directional detail. So we should look for anisotropy.

At that time we had built one 60-foot dish that was then lying on its back waiting to be lifted onto an equatorial mount. A pair of feed horns was installed, one pointing up to the sky in general and the other pointing down into the reflector and receiving from the zenith with a narrow beam. By attention to symmetry in the necessary tee junction a sophisticated switchable feed system was designed in collaboration with Conklin. For further reliability the two horns were made rotatable between up and down. By switching between the two horns one could detect hour-angle dependence of radiation received from the zenith in the zone passing over the narrow beam. Sure enough, a faint periodic variation of amplitude 0.0016 degrees K was detected (Conklin, 1969).

Conklin was first to record the dipole component of the cosmic background radiation, and to determine the right ascension of the Sun's absolute way through the primeval radiation. As an achievement before the five-element array was erected, that was a famous milestone. Walter Sullivan reported it on the front page of the *New York Times* of 18 June 1969. Relative to receiver noise, which is many orders of magnitude larger, the sensitivity reached was remarkable. The cosmic background dipole had been revealed (Figure 9).

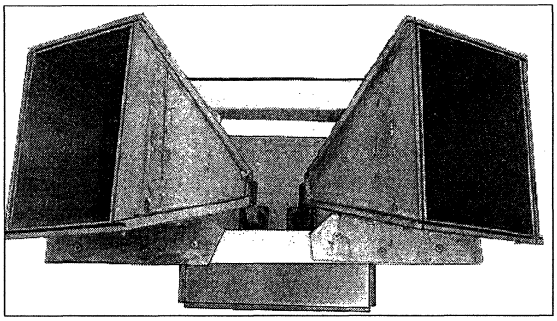

Figure 9: The energy that flowed through these horns, and first revealed the milliKelvin anisotropy of the cosmic background radiation, was one-fifth of an erg.

We then looked for spatial fluctuations on fine angular scales and set a limit of 0.005 degrees K for beamwidths greater than 10 arcminutes (Bracewell and Conklin, 1967). This upper limit held for some years and became a basis for theories of the Universe by cosmologists. Today, at even lower levels, complex spatial fluctuations have been mapped for the whole sky by satellite.

Some years passed during which Conklin's Ph.D. thesis work was dismissed as being due to interference. By 1977, eight years later, the work had been repeated (a) at Princeton using a balloon (Corey and Wilkinson, 1976) and (b) at Berkeley using the Kuiper Airborne Observatory (Smoot, Gorenstein, and Muller, 1977), with more advanced technology. It was cheering to see that our right ascension for the direction of absolute motion of the Sun relative to the cosmic background was bracketed by the new observations, and agreed with each of the new values (11h–12h) better than they did with one another (see Table 1)!

Table 1: Early glimpses of the Sun's absolute motion.

Year	R.A.	Velocity (km/s)	Source
1969	$11^h 20^m$	308 ± 93	Stanford
1976	12^h	270 ± 70	Princeton
1977	$11^h 00^m$	390 ± 60	Berkeley
2000	$11^h 11^m$	370 ± 2	Various

Discovery of the Sun's absolute motion through the cosmic background radiation was certainly a milestone; it started with an unfinished dish and the design of small but ingenious microwave instrumentation. Conklin did not depend on a big dish to complete his work; instead he developed portable equipment, which he took to 12,500 feet on top of White Mountain, California.

During these experimental developments the question arose as to the radiation temperature that would be seen in different directions inside a blackbody enclosure of temperature, T, if the observer was in motion. According to two internal reports (Photon view ..., 1968; Relativistic observer ..., 1968), the temperature in the forward direction would appear higher than the equilibrium temperature, T, due to three classical effects: stellar aberration, the Doppler effect, and the Lorentz Transformation. For an observer moving with velocity, v, the temperature in the direction of motion would appear to be T(1+v/c), while in the reverse direction it would appear correspondingly diminished. After this second internal report was distributed, a paper appeared (Condon and Harwit, 1968) discussing the same question but arriving at a different answer—the spectrum would no longer be that of a black body. The first Stanford report was dusted off, submitted to Journal 'A', and rejected by a referee who reported to the editor that the paper would be more suitable for Journal 'B'. So I changed course and the piece appeared in *Nature* (Bracewell and Conklin, 1968), where the correct result was given together with the generalisation

$$T_{rel} = T\,(1 + (v/c)\cos\theta)/\sqrt{(1-(v/c)^2)} \qquad (1)$$

for an observer moving at relativistic velocity in any direction θ. The same answer, obtained by quantum theorists proved to have been queued for Journal B.

Thus the brief foray into experimental and theoretical cosmology certainly made a mark. The validity of Conklin's data was later acknowledged by both R.W. Wilson (1979) and P.J.E. Peebles (1993).

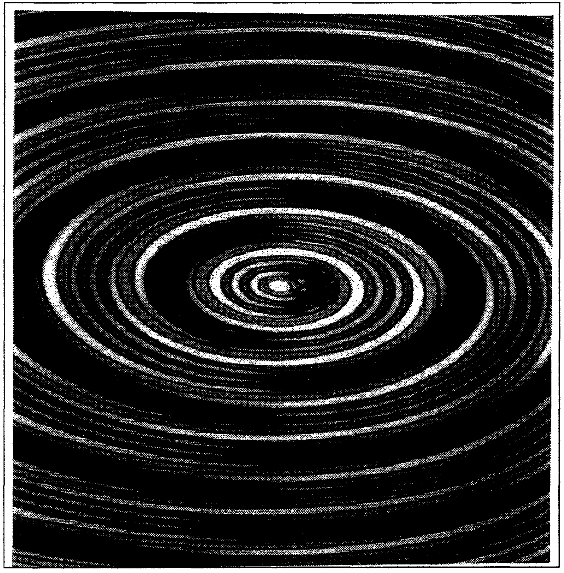

Figure 10: The Hartley diffraction of a spiral slit, a representation that, unlike optical diffraction patterns or antenna patterns, contains all the phase information.

10 NULLING INTERFEROMETRY

As the 60-foot dishes were being brought into action, the 1971 NASA-Ames Summer Workshop (Project Cyclops) was organised by B.M. 'Barney' Oliver which focused attention on the detection of planets around nearby stars. An orbital infrared nulling interferometer was proposed (Bracewell, 1978) that would cancel out the relatively weak radiation from a star while remaining sensitive to the self-emission of a circling planet. It *was* whimsically designed to fit into the bay of the as-yet unlaunched Space Shuttle. With the passage of time, the nulling principle was adopted for the Terrestrial Planet Finder mission, and I might yet see it fly. Meanwhile, the idea was tested on the Multiple Mirror Telescope before it was dismantled, using two 1.8m mirrors spaced five metres apart, and was shown to work (Hinz et al., 1998), even through Earth's atmosphere. What is more, a previously unknown infrared cloud was seen as the radiation from Betelgeuse was nulled out.

11 EXTRATERRESTRIAL THOUGHT

Prompted by mention that aliens wishing to attract our attention would use the universal hydrogen-line wavelength (Cocconi and Morrison, 1959), I thought about extraterrestrial intelligence, wrote a number of papers (e.g. Bracewell, 1960) and in 1974 published *The Galactic Club* (at the urging of the Stanford Alumni Association). The experience of the Mediterranean peoples, the pre-Copernicans, and the inhabitants of Zhong Guo (= Middle Kingdom China) suggested that the human race is not likely to be unique; neither China nor the Mediterranean turned out to be at the middle of the world, and Earth did not turn out to be the centre of the Universe. But man is unique on Earth, which casts doubt on the hypothesis of mediocrity, and allows that man's destiny may be to populate the Galaxy with human intelligence.

This proposal did not meet with a warm reception by action-oriented seekers for alien intelligence who, however, should be encouraged, even as we bear in mind that the driving concept, viz. mediocrity, is bracketed on one side by the uniqueness concept and on the other by the non-steady-state possibility of a galactic club. As opined in *Isaac Azimov's Science Fiction Magazine*: "I am inclined to think that favorable conditions for development of intelligent life are *not* abundant, suitable planets are *not* common, and that man may indeed be unique or quasi-unique. The best way to find out is to *do* something, such as searching for nonsolar planets; speculation will not tell us." (Bracewell, 1978).

12 THE HARTLEY TRANSFORM

Much of the modern theory of image formation in astronomy and in other fields, notably crystallography, involves Fourier's concept of spectral analysis. When the 'Cooley-Tukey algorithm' was announced the signal processing community was most enthusiastic. The momentum was retained but the enthusiasm was damped when it was realised that the technique was in use in other fields. That is why we say 'Fast Fourier Transform' today. The history then turned out to be deeper than expected. Friedrich Gauss had used the FFT principle, subdivision of N data into smaller sets depending on the factors of N, *before* Fourier presented his paper for the mathematics prize topic of 1811. Gauss wrote (in Latin) "Try it you'll like it."

When the fast Hartley algorithm was announced in 1984 there was reluctance to believe that something remained to be discovered that halved the computing time. The factor of two improvement results from the two-fold redundancy of the Fourier transform of real data: each complex transform value is duplicated by the appearance of its complex conjugate. The Hartley transform of a real function, being itself real, does not waste computing time on redundant values. Diffraction patterns, as familiar in optics, photography, antenna practice and X-ray crystallography, present the squared modulus, or intensity, of the complex electromagnetic field. One never sees a two-dimensional complex Fourier transform of an image in print; the phase is always suppressed. The Hartley transform of an image can be printed on a grey scale and retains the phase information, as exhibited on the front cover of *Proceedings of the Institute of Electrical and Electronic Engineers* for March 1984 (Figure 10). That issue cites 271 papers generated by the original announcement of the Hartley algorithm, but prejudice lingered. The Fourier transform was said to be optically physical, while the Hartley transform had no physical counterpart. That view was demolished by production of an optical, photographable plane in the laboratory by John Villasenor in 1987, and shortly after, in 1988, in an anechoic room, for the far field of a microwave antenna. Oddly, it did not occur to critics that a *complex* electromagnetic field is a product of the mathematical mind, not of *Nature*; Fourier himself expressed his series in real sines and cosines. The mentally-conceived complex exponential later proved popular, for example in alternating-current theory, because it proved amenable to simple algebraic manipulation.

13 DYNAMIC SPECTRA AND THE CHIRPLET

In 1946 Herman Gabor published a way of presenting a time-dependent signal in a way that had wider physical applicability than the fully equivalent Fourier spectrum. For example, the Fourier transform of a Beethoven symphony contains everything acoustical that is in the original performance. Even one pizzicato note from a single violin string is there. However, the ear of a listener to music does not pass the waveform to the brain; analogue preprocessing conveys a sensation of pitch dependency to the consciousness. The ear does adaptive spectral analysis. When it receives the sound wave from a plucked string, it broadens its bandwidth, Δf, and reduces its time resolution, Δt. When it hears a sustained tone, it narrows its bandwidth and relaxes its time resolution. The resulting perception may be called a dynamic spectrum, which can be presented by grey-scale modulation on a time-frequency plane. Gabor noted the property that $\Delta f \Delta t$ cannot be less than 1/2, which looks related to Heisenberg's uncertainty principle, except that no quanta are involved, only classical physics. Gabor's concept was to divide the time-frequency plane into minimum-area rectangles, representing 'elementary signals', whose aspect ratio could be chosen to suit the time signal. The idea was applied to presentation of bird calls, human speech, and whistler research. A whistler is a sound-frequency electromagnetic wave of (mostly) descending pitch that results from the passage of an impulse from a lightning flash, nearby or in the antipodes, that is dispersed on passage through the Van Allen Belt (as Donald Carpenter's exosphere is now known). But Gabor overlooked another elementary signal, also of area 1/2, which, though centred at a particular time and frequency, was not of fixed frequency throughout its duration. This new fundamental building block, the 'chirplet' (Mihovilović and Bracewell, 1991; 1992) proves to be rewardingly revealing of detail in natural ionospheric phenomena, seismograms, and other complicated signals.

14 CENTAURUS A

Centaurus A, one of the four original discrete radio sources named by John Bolton, Gordon Stanley and Bruce Slee (1949) using a cliff interferometer at Dover Heights, was examined by Twiss, Carter and Little in 1960. They found two components of equal strength and width separated by 5 arcminutes, as far as their resolution permitted. Alec Little then came to Stanford from the Radiophysics Laboratory in Sydney, where I had known him since he was a boy. We confirmed the E-W separation, and obtained distinct widths and strengths of the two components, used one arm of the microwave spectroheliograph. We then discussed the possibility of obtaining high resolution in declination. The point of this would be to see whether the two components, clearly on opposite sides of the galaxy NGC 5128, lay along, or perpendicular to, the dark band crossing the galaxy. This would have implications for the origin of the highly-extended background previously known from lower frequency observations at lower resolution. The subsequent developments were exciting. I went to the new 210-foot Parkes Radio Telescope in Australia to settle this question, becoming the first visiting observer, as recorded on page 1 of the Visitors' Book. For this fascinating story, which combines technical observational factors as well as social ones, see Bracewell (2002). The outcome, including the discovery of strong polarisation (see Figure 11), was certainly a milestone in the work of the Stanford group.

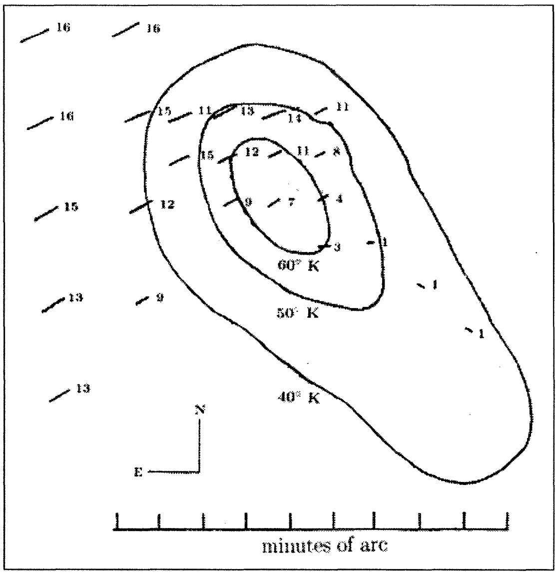

Figure 11: Preliminary contour map of Centaurus-A obtained with the Parkes Radio Telescope at 10 cm in 1962, which confirmed the existence of two source components, aligned NE-SW, perpendicular to the dark band crossing the galaxy. Polarization vectors are also shown; the NE component exhibits 15% plane polarization at a position angle of 115° (after Bracewell, 2002, 109-110).

15 CONCLUDING REMARKS

Work on the digital solar maps was contributed by new arrivals, especially Werner Graf from Basel and Zvonko Fazarinc from Ljubliana. Other newly-arrived graduate students, Steve Wernecke, John Grebenkemper, and Mark Stull, became involved in the design, construction and operation of the array of five 60-foot dishes. The heavy construction work was handled by old-timers, C.C. Lee, Carl Crisp and others.

Design of the 60-foot dishes was approached by a mixture of theory of elasticity and empirical trial.

Stress, strain, pressure, ultimate strength of materials, and Hooke's Law were not known until recently and yet colossal ships, canals, aqueducts, temples, bridges and domes were built in Greco-Roman times without such theoretical knowledge. When the performance under wind load of curved plates such as the fifty-six comprising one dish was needed, we cantilevered a segment from a concrete column and loaded it with sand bags until it broke. In the area of failure we put more rivets. Drive gears, chains, sprockets, stowing arrangements, and feed supports were all developed by cautious testing to insure adequacy against calculated wind load. In thirty years none of the dishes was blown off its mount or suffered structural damage of any kind. At the time, I knew nothing of county rules, and the architect in the Planning Office did not bother to tell me. When I went to him for information on the presumably well-known load-bearing capacity of the acres of deep campus adobe, on which all the campus buildings had been erected, he described how a soils consultant would pound a crowbar into the ground and tell me. Kent Price simply adopted the handbook value for load-bearing capacity of marsh, and the foundations have held up the massive steel mounts to our complete satisfaction. During this time, Wally Scott, an engineer borrowed from SLAC, exercised a restraining, conservative hand. Chi Chrun Lee attended to innumerable structural details the way it would be done in China, and he once startled us by making a roller bearing by hand—a machine part that I thought had to be ordered from Philadelphia. Carl Crisp could weld anything, up to enormous sizes. He welded up a semicircular hour-angle drive wheel, mounted it on the prepared bearings, and rotated it back and forth past a welding torch to achieve the millimeter precision and strict circular shape required. Many other competent technicians worked happily on the project for limited periods.

During the interval after the spectroheliograph ceased work and when the five-element array was under construction, observational work was carried out at other observatories. In 1967, T. Krishnan and K.R. Lang used the 150-foot antenna of the Stanford Radar Astronomy Center to observe occultations. A.R. Thompson and R.S. Colvin looked (successfully) for neutral hydrogen in planetary nebulae and, with M.P. Hughes, obtained spectra of 100 other sources. The interim period was also one of activity on theory of interferometry. In 1972 L.R. D'Addario and M.R. Stull studied Cygnus X-3, and G.S. Downs and A.R. Thompson worked on polarisation in Cassiopeia A. In 1973 K.M. Price and M.A. Stull worked on Centaurus A. Stull went to Arecibo to re-examine, at high resolution, 430 sources from the Ohio State catalogue and also used Fred Haddock's 85-foot dish at the University of Michigan to observe thirty-two sources. By 1974, observations with the five-element array were well under way. M. Felli and G. Tofani, observers from Arcetri Observatory, were working with D'Addario. The final Annual Report published in the *Bulletin of the American Astronomical Society* in 1980, summarises the life of the Institute.

As 2005 unfolds a new life is dawning in which data from microsatellites measuring phenomena ranging from upper atmospheric to seismic can be downloaded. The antenna structures and their controls permit upgrading to higher frequencies, greater bandwidths, high data rates and faster-than-sidereal tracking.

16 GENERAL REFERENCES

Bates, R.H.T., and McDonnell, M.J., 1986. *Image Restoration and Reconstruction.* Oxford, Clarendon Press.

Bolton, J.G., Stanley, G.J., and Slee, O.B. ,1949. Positions of three discrete sources of galactic radio-frequency radiation. *Nature*, 164, 101-102.

Bracewell, R.N., 1956. Strip integration in radio astronomy. *Australian Journal of Physics*, 9, 198-217.

Bracewell, R.N., 1957. Antenna problems in radio astronomy. *Institution of Radio Engineers National Convention Record*, 5, 68-71.

Bracewell, R.N. 1958. Restoration in the presence of errors. *Proceedings of the Institution of Radio Engineers*, 46, 106-111.

Bracewell, R.N., 1959. Satellite rotation. *Advances in Astronautical Sciences*, 4, 317-328.

Bracewell, R.N., 1960. Communications from superior galactic communities. *Nature*, 186, 670-671.

Bracewell, R.N., 1978a. Detecting nonsolar planets by spinning infrared interferometer, *Nature*, 274, 780-781.

Bracewell, R.N., 1978b. On man's role in the Galaxy. *Isaac Azimov's Science Fiction Magazine*, 2, 142-148.

Bracewell, R.N., 1984. The fast Hartley transform. *Proceedings of the Institute of Electrical and Electronic Engineers*, 72, 1010-1018.

Bracewell, R.N., 1988. Three-halves law in sunspot cycle shape. *Monthly Notices of the Royal Astronomical Society*, 230, 535-550.

Bracewell, R.N., 1999. The solar cycle: a central-source wave theory. *Proceedings of the Astronomical Society of Australia*, 8, 145-147.

Bracewell, R.N., 2002. The discovery of strong extragalactic polarisation using the Parkes Radio Telescope. *Journal of Astronomical History and Heritage*, 5, 107-114.

Bracewell, R.N., and Conklin, E.K., 1967. Limits on small scale variations in the cosmic background radiation. *Nature,* 216, 777-779.

Bracewell, R.N., and Conklin, E.K., 1968. An observer moving in the 3° radiation field. *Nature*, 219, 1343-1344.

Bracewell, R.N., and Garriott, O., 1958. Rotation of artificial Earth satellites. *Nature*, 82, 760-762.

Bracewell. R.N., and Riddle, A.C., 1967. Inversion of fan beam scans in radio astronomy. *Astrophysical Journal*, 150, 427-434.

Bracewell, R.N, and Roberts, J.A., 1954. Aerial smoothing in radio astronomy. *Australian Journal of Physics*, 7, 615-640.

Bracewell, R.N., and Swarup, G., 1961. The Stanford microwave spectroheliograph antenna, a microsteradian pencil beam antenna. *IRE Transactions on Antennas Propagation*, AP-9, 22-30.

Bracewell, R.N., and Williams, G., 1986. Hilbert transform analysis of the Elatina varve record of solar activity. *Monthly Notices of the Royal Astronomical Society*, 223, 457-468.

Bracewell, R.N., Buneman, O., Hao, H., and Villasenor, J., 1986. The two-dimensional Hartley transform. *Proceedings of the Institute of Electrical and Electronic Engineers*, 74, 1283-1284.

Bracewell, R.N., Colvin, R.S., D'Addario, L.R., Grebenkemper, C.J., Price, K.M., and Thompson, A.R., 1973. The Stanford five-element radio telescope. *Proceedings of the Institute of Electrical and Electronic Engineers*, 61, 1249-1257 (Special issue on radio and radar astronomy).

Brooks, R.A., and Di Chiro, G., 1975. Theory of image reconstruction in computed tomography. *Radiology*, 117, 561-572.

Brooks, R.A., and Di Chiro, G., 1976. Principles of computer assisted tomography (C.A.T.) in radiography and radioisotopic imaging. *Physics in Medicine and Biology*, 21, 689-732.

Christiansen, W.N., and Mathewson, D.S., 1958. Scanning the Sun with a highly directional array. *Proceedings of the Institution of Radio Engineers*, 46, 127-131.

Christiansen, W.N., and Warburton, J.A., 1953. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part I. A new highly directional aerial system. *Australian Journal of Physics*, 6, 190-202.

Christiansen, W.N., and Warburton, J.A., 1955. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part III. The quiet Sun—two dimensional observations. *Australian Journal of Physics*, 8, 474-486.

Cocconi, G., and Morrison, P., 1959. Searching for interstellar communications. *Nature*, 184, 844-846.

Condon, J.J., and Harwit, M., 1967. Means of measuring the Earth's velocity through the 3° radiation field. *Physical Review Letters*, 20, 1309-1310.

Conklin, E.K., 1969. Velocity of the Earth with respect to the cosmic background radiation. *Nature*, 222, 971-972.

Conklin, E.K., and Bracewell, R.N., 1967a. Isotropy of cosmic background radiation at 10,690 MHz. *Physical Review Letters*, 18, 614.

Conklin, E.K. and Bracewell, R.N., 1967b. Limits on small scale variations in the cosmic background radiation. *Nature*, 216, 777-779.

Corey, B.E., and Wilkinson, D.T., 1976. A measurement of the cosmic background anisotropy at 19 GHz. *Bulletin of the American Astronomical Society*, 8, 351.

Cormack, M.A., 1963. Representation of a function by its line integrals, with some radiological implications. *Journal of Applied Mathematics*, 34, 2722 and 35, 2908.

Davies, R.D., 2005. A history of the Potts Hill radio astronomy field station. *Journal of Astronomical History and Heritage*, 8, 87-96.

Deans, S.R., 1983. *The Radon Transform and Some of its Applications*. New York, Wiley-Interscience.

Hinz, P.M. et al., 1998. Imaging circumstellar environments with a nulling interferometer. *Nature*, 395, 251-253.

Mihovilović, D., and Bracewell, R.N., 1991. Adaptive chirplet representation of signals on the time-frequency plane. *Electronics Letters*, 27, 1159-1161.

Mihovilović, D., and Bracewell, R.N., 1992. Whistler analysis in the time-frequency plane using chirplets. *Journal of Geophysical Research and Space Physics*, 97, 17,139-17,204.

Mills, B.Y., Little, A.G., Sheridan, K.V., and Slee, O.B., 1958. A high resolution radio telescope for use at 3.5m. *Proceedings of the Institution of Radio Engineers*, 46, 67-84.

NASA, 1975. Synoptic maps of solar 9.1 cm microwave emission from June 1962 to August 1973. World Data Center for Solar-Terrestrial Physics, Report UAG-44.

Orchiston, W., 2004. The rise and fall of the Chris Cross: a pioneering Australian radio telescope. In Orchiston, W., Stephenson, R., Debarbat, S., and Nha, I-S. (eds.). *Astronomical Instruments and Archives from the Asia-Pacific Region*. Seoul, IAU Commission 41. Pp. 157-162.

Pawsey, J.L., and Bracewell, R.N., 1955. *Radio Astronomy*. Oxford, Clarendon Press.

Peebles, P.J.E., 1993. *Principles of Physical Cosmology*. Princeton, Princeton University Press.

Penzias, A., and Wilson, R.W., 1966. Determination of the microwave spectrum of Galactic radiation. *Astrophysical Journal*, 46, 666-669 .

Photon view of observer moving in the 3° K radiation field. Stanford, Electrical Engineering Department, Glint No. 277 (1968).

Relativistic observer in radiation field. Stanford, Electrical Engineering Department, Glint No. 279 (1968).

Rosenfeld, A., and Kak, A.C., 1982. *Digital Image Processing. Volume 1*. New York, Academic Press.

Smoot, G.F., Gorenstein, O.O., and Miller, R.A., 1977. Detection of anisotropy in the cosmic background radiation. *Physical Review Letters*, 39, 898.

Sullivan, W.T., 2005. The beginnings of Australian radio astronomy. *Journal of Astronomical History and Heritage*, 8, 11-32.

The 1979 Nobel Prize in physiology or medicine. *Science*, 206, 1060-1062 (1979).

Twiss, R.Q., Carter, A.W.L., and Little, A.G., 1960. Brightness distribution over some radio sources at 1427 Mc/s. *The Observatory*, 80, 153-159.

Vainshtein, B.K., 1970. Finding the structure of objects from projections. *Kristallografiya*, 15, 781-787.

Villasenor, J., and Bracewell, R.N., 1987. Optical phase obtained by analogue Hartley transformation. *Nature*, 330, 735-737.

Villasenor, J., and Bracewell, R.N., 1988. Lenseless microwave imaging using the Hartley transform. *Nature*, 335, 617-619.

Wilson, R.W., 1979. The cosmic background radiation. Nobel Prize lecture, 8 December 1978. *Science*, 205, 866-874.

17 SOLAR PAPERS

Asper, H.K., Bracewell, R.N., Deuter, J., Krishnan, T., Picken, J., and Rose, S., 1964. High resolution observations of the radio Sun at 9.1 centimeters on July 20, 1963. *Journal of Geophysical Research*, 69, 1805-1807.

Bracewell, R.N., 1954a. Maximum of the Planck energy spectrum. *Nature*, 174, 563.

Bracewell, R.N., 1954b. Using cosmic radio waves to study solar flares. *The Observatory*, 74, 155-157.

Bracewell, R.N., 1955. The Sky at 17 Meters. *Astronomical Society of the Pacific Leaflet*, No. 317.

Bracewell, R.N., 1968. The Sun. In Messel, H., and Butler, S.T. (eds.). *Man in Inner and Outer Space*. Sydney, Shake-speare Head Press. Chapters 1 to 5, pp. 7-66.

Bracewell, R.N., 1979. Electricity from sunlight. In Messel, H. (ed.). *Energy for Survival*. Sydney, Pergamon. Pp. 263-281.

Bracewell, R.N., 1986a. Review of "Solar Flare Prediction" by C. Sawyer, J.W. Warwick, and J.T. Dennett. *Applied Optics*, 25, 3609.

Bracewell, R.N., 1986b. Simulating the sunspot cycle. *Nature*, 323, 516-519.

Bracewell, R.N., 1988a. The impact of varves on solar physics. *Solar Physics*, 117, 261-267.

Bracewell, R.N., 1988b. Spectral analysis of the Elatina series. *Solar Physics*, 116, 179-194.

Bracewell, R.N., 1988c. Three-halves law in sunspot cycle shape. *Monthly Notices of the Royal Astronomical Society*, 230, 535-550.

Bracewell, R.N., 1988d. Varves and solar physics. *Quarterly Journal of the Royal Astronomical Society*, 29, 119-128. (Associated discussion in *The Observatory*, 108.)

Bracewell, R.N., 1988e. What causes the sunspot cycle. *Australian Physicist*, 25, 294-295.

Bracewell, R.N., 1989. The solar cycle: a central-source wave theory. *Proceedings of the Astronomical Society of Australia*, 8, 145-147.

Bracewell, R.N., and Bain, W.C., 1952. Theory of formation of an ionospheric layer below *E* Layer based on eclipse and solar flare effects at 16 kc/sec. *Journal of Atmospheric and Terrestrial Physics*, 2, 226-235.

Bracewell, R.N., and Deuter, J.H., 1967. The 9.1 cm spectroheliogram of May 20, 1966. *Journal of Geophysical Research*, 72, 37-38.

Bracewell, R.N., and Graf, W., 1981. Solar quiescent prominences. *Nature*, 290, 758-759.

Bracewell, R.N., and Graf W., 1985. Sunspot number series envelope and phase. *Australian Journal of Physics* (Giovanelli Commemorative Issue), 38, 1009-1025.

Bracewell, R.N., and Preston, G.W., 1956. Radio reflection and refraction phenomena in the high solar corona. *Astrophysical Journal*, 123, 14-29.

Bracewell, R.N., and Straker, T.W., 1949. The study of flares by means of very long waves. *Monthly Notices of the Royal Astronomical Society*, 109, 28-45.

Bracewell, R.N., and Swarup, G., 1961. The Stanford Microwave Spectroheliograph antenna, a microsteradian pencil beam antenna. *IRE Transactions on Antennas and Propagation*, AP-9, 22-30.

Bracewell, R.N., and Wernecke, S.J., 1975. Image reconstruction over a finite field of view. *Journal of the Optical Society of America*, 65, 1342-1346

Bracewell, R.N., Eshleman, V.R., and Hollweg, J.V., 1969. The occulting disk of the Sun at radio wavelengths. *Astrophysical Journal*, 155, 367-368.

Deuter, J.H., and Bracewell, R.N., 1971. The microwave spectroheliograms of March 6-10, 1970. In Lincoln, J.V., and Bucknam, D.B. (eds.). *Data on Solar-Geophysical Activity Associated with the Major Geomagnetic Storm of March 8, 1970.* Boulder, National Oceanic and Atmospheric Administration. Pp. 64-67.

Deuter, J.H., and Bracewell, R.N., 1972. The microwave Sun at the time of the cosmic ray increase of September 1, 1971. *Upper Atmosphere Geophysics Report UAG-24*, Part I, 325-326.

Graf, W., and Bracewell, R.N., 1973a. The height of 9.1 cm solar emission from altitude shift. *Solar Physics*, 28, 425-434.

Graf, W., and Bracewell, R.N., 1973b. Latitude and solar-cycle dependence of the height of 9.1 cm radio emission. *Solar Physics*, 33, 75-85.

Graf, W., and Bracewell, R.N., 1975a. Solar radio emission at 9.1 cm and sector boundaries. *Solar Physics*, 44, 195-204.

Graf, W., and Bracewell, R.N., 1975b. *Synoptic Maps of Solar 9.1 cm Microwave Emission from June 1962 to August 1973.* Boulder, National Oceanic and Atmospheric Admin -istration (UAG Report No. 44).

Graf, W., Bracewell, R.N., Deuter, J.H., and Rutherford, J.S., 1971. The Sun as a test source for boresight calibration of microwave antennas. *Institute of Electrical and Electronic Engineers Transactions on Antennas and Propagation*, AP-19, 606-612.

Straker, T.W., and Bracewell, R.N., 1949. A Sudden Phase Anomaly, 1949, February 11. *The Observatory*, 69, 69-70.

18 MICROWAVE PAPERS

Bracewell, R.N., 1947a. Charts for resonant frequencies of cavities. *Proceedings of the Institute of Radio Engineers*, 35, 830-841.

Bracewell, R.N., 1947b. *The Theory and Application of Certain Special Types of Ultra-high Frequency Transmission Lines*. Master of Engineering Thesis, University of Sydney. Pp. 54 + figures.

Bracewell, R.N., 1953a. A microwave computing problem. *Proceedings of the Physical Society of London*, B66, 987-988. 1953.

Bracewell, R.N., 1953b. A new instrument in radio astronomy. *The Observatory*, 73, 200-201.

Bracewell, R.N., 1954a. Microwave transmission and cavity resonator theory. In Bowen, E.G. (ed.). *Textbook of Radar.* Cambridge, Cambridge University Press (Second Edition). Pp. 110-160.

Bracewell, R.N. 1954b. A new transducer diagram. *Proceedings of the Institute of Radio Engineers*, 42, pp. 1519-1521.

Bracewell, R.N., 1954c. Step discontinuities in disc transmission lines. *Proceedings of the Institute of Radio Engineers*, 42, 1453-1547.

Bracewell, R.N., 1962a. How large can a microwave antenna be? *The Microwave Journal*, 5, 57-61.

Bracewell, R.N., 1962b. Radio astronomy techniques. *Handbuch der Physik*. 54, 42-129.

Bracewell, R.N., 1968. The microwave sky. In Arm, David L. (ed.). *Vistas in Science*. Albuquerque, University of New Mexico Press. Pp. 78-93.

Bracewell, R.N., and Swarup, G., 1961. The Stanford Microwave Spectroheliograph antenna, a microsteradian pencil beam antenna. *IRE Transactions on Antennas and Propagation*, AP-9, 22-30.

Deuter, J.H., and Bracewell, R.N., 1971. The microwave spectroheliograms of March 6-10, 1970. In Lincoln, J.V., and Bucknam, D.B. (eds.). *Data on Solar-Geophysical Activity Associated with the Major Geomagnetic Storm of March 8, 1970.* Boulder, National Oceanic and Atmospheric Administration. Pp. 64-67.

Deuter, J.H., and Bracewell, R.N., 1972. The microwave Sun at the time of the cosmic ray increase of September 1, 1971. *Upper Atmosphere Geophysics Report UAG-24*, Part I, 325-326.

Graf, W., and Bracewell, R.N., 1975. *Synoptic Maps of Solar 9.1 cm Microwave Emission from June 1962 to August 1973.* Boulder, National Oceanic and Atmospheric Administration (UAG Report No. 44).

Graf, W., Bracewell, R.N., Deuter, J.H., and Rutherford, J.S., 1971. The Sun as a test source for boresight calibration of microwave antennas. *Institute of Electrical and Electronic Engineers Transactions on Antennas and Propagation*, AP-19, 606-612.

Villasenor, J.D., and Bracewell, R.N., 1988. Lenseless micro-swave imaging using the Hartley Transform. *Nature*, 335, 617-619.

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Journal of Astronomical History and Heritage, 8(2), 87-96 (2005).

A HISTORY OF THE POTTS HILL RADIO ASTRONOMY FIELD STATION

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Abstract: A description is given of the research activities at the Potts Hill field station of the CSIRO Division of Radiophysics in the period 1946 to 1958. The approach is set in the context of the group structure of the radio astronomy research of the Division and of the links between the groups, particularly those links which involved Potts Hill. Significant research on the structure of the Sun and the Galaxy as well as the discovery of 21-cm H-line and its mapping in the southern sky was achieved in the 12-year lifetime of the field station. Personal recollections are given of research activity during its most active phase in 1951-1953.

Keywords: Sun, Galaxy, radio astronomy, research group structure

1 INTRODUCTION

This article attempts an overview of the activities at one of the field stations of the Division of Radiophysics of the Commonwealth Scientific Industrial Organisation (CSIRO) in the period 1951-1953 viewed from a time fifty years later. It has been interesting to take one's mind back to a formative period in my own career and examine some of the factors at work within research groups. But at the same time, one is assessing the situation from the perspective some fifty years on of having been the Director of another Laboratory which had a similar ethos.

It is helpful to clarify some nomenclature at this point. The Council for Scientific and Industrial Research (CSIR) which was responsible for the Radiophysics Laboratory that conducted WW2 radar research was reconstituted as the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in 1949. The Laboratory then became the Division of Radiophysics. However old names die hard. Even today the radio astronomy group is referred to in conversation or in the historical literature as the Radiophysics Lab, Radiophysics, the Lab or just RP.

One of the features of the radio astronomy activity in the Radiophysics Division was a strong group structure under the over-arching guidance of J.L. Pawsey (Figure 1). Groups soon developed under the vigorous leadership of J.G. Bolton, W.N. Christiansen, B.Y. Mills and J.P. Wild, all of whom achieved prominence in their specific fields of radio astronomy (Sullivan, 2005). Three of these became Fellows of the Royal Society, along with Pawsey and E.G. Bowen, Chief of the Division. Although the groups worked at different field stations (see Figure 2). There was good contact between them at the two-weekly science meetings held back at the Radiophysics Lab; in addition, I remember playing in the weekly matches of the Radiophysics cricket team, which both Bolton and Wild were captain of at various times. This group structure was similar to that operated by A.C.B. Lovell at the Jodrell Bank Experimental Station (as Jodrell Bank Observatory was then known), the main difference being that many of the latter group members were younger, being research students in Manchester University. Another similarity was the role of cricket: Lovell was captain of the local village cricket team which included several of us from Jodrell Bank.

Figure 1: Joseph Lade Pawsey, leader of the radio astronomy group at the Division of Radiophysics (courtesy ATNF Historic Photographic Archive: B7454-2).

In September 1953 I moved to an assistant lectureship in the Physics Department of Manchester University, began research at Jodrell Bank with Bernard Lovell, and started to build up the H-line group. In 1963 I spent a sabbatical year at Radiophysics at the invitation of John Bolton, where I worked with Frank Gardner on measuring the polarization of radio sources and mapping the Faraday rotation across the sky with the recently-completed 210-ft Parkes Radio Telescope. By this time the group structures had changed markedly: Christiansen and Mills had both moved to Sydney University, while Bolton was the Director of the Parkes Observatory, which he operated with great efficiency as a national and international facility.

This paper reviews the history of radio astronomy research at the Potts Hill field station (location 16 in Figure 2). Section 2 sets Potts Hill in the context of the other research groups and field stations. There was a significant movement of operations between the various field stations, as documented by Orchiston and Slee (2005a). Section 3 attempts to identify all of the main research projects that took place at Potts Hill, which was one of the Sydney field stations that was most accessible from the Radiophysics Lab. It should be noted that since many of the publications from this period are not explicit about the location of the equipment used, there may be some uncertainty about some of the attributions to Potts Hill. Finally, in Section 4 I present a snapshot of my experiences at Potts Hill between 1951 and 1953.

2 THE EMERGENCE OF RESEARCH GROUPS WITHIN THE RADIOPHYSICS DIVISION

It is interesting to trace the way in which the various research groups grew out of the World War II activities of the Radiophysics Laboratory of CSIR located in the grounds of the University of Sydney. In 1939 the Radiophysics Lab was established with the purpose of supporting military forces in the Pacific area with research into the basic principles of radar and developing new systems for the wartime conditions in the Pacific. Throughout, there was close liaison with London. Furthermore, a number of the senior staff had worked in the UK before the war, including the first Chief of the Division, Dr. D.F. Martyn, Dr. J.L. (Joe) Pawsey (who had worked on developing television) and Dr. J.H. (Jack) Piddington, who built the first radar set in Australia, in 1938.

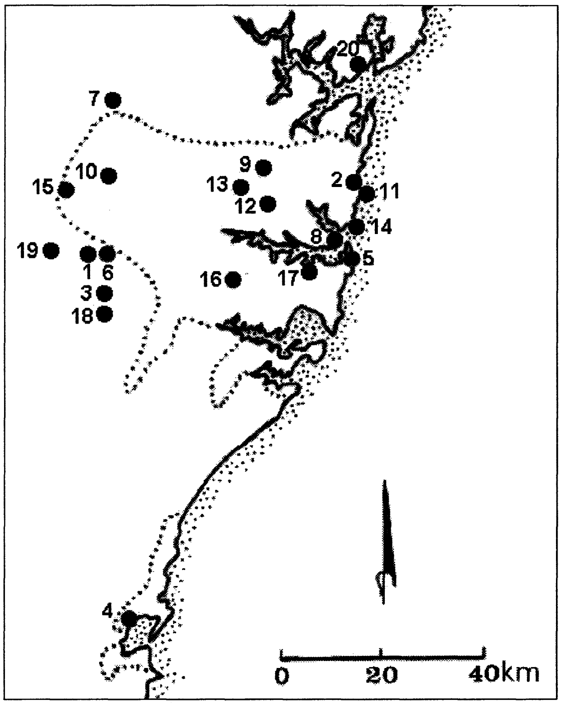

Figure 2: Map of the Sydney-Wollongong regions (dotted lines) showing locations, Radiophysics Lab field stations and remote sites used for radio astronomy, 1945-1963. Key: 1 = Badgerys Creek, 2 = Collaroy, 3 = Cumberland Park, 4 = Dapto, 5 = Dover Heights, 6 = Fleurs, 7 = Freeman's Reach, 8 = Georges Heights, 9 = Hornsby Valley, 10 = Llandilo, 11 = Long Reef, 12 = Marsfield (ATNF Headquarters), 13 = Murraybank, 14 = North Head, 15 = Penrith, 16 = Potts Hill, 17 = Radiophysics Laboratory (Sydney University grounds), 18 = Rossmore, 19 = Wallacia, 20 = West Head (after Orchiston and Slee, 2005a: 121).

One of the first successes of the Radiophysics Lab team was the development of a shore defence radar system which was installed at Dover Heights adjacent to the entrance to Sydney Harbour. An aircraft warning system with a range of 100 km was also located at this site by 1940.

When Dr. E.G. (Taffy) Bowen was confirmed as Chief of the CSIR Division of Radiophysics in 1946 he was given a free hand to pursue a research programme based on the expertise developed by the Radiophysics Lab during WW2 and directed to underpinning the growing Australian industries. He was also permitted to undertake 'blue skies' research as it would be called today. The scientific programme which emerged focussed on rain physics, under Bowen's direction, and radio astronomy, which was directed by Pawsey.

The radio astronomy group was in a prime position internationally since expertise and equipment from the war years had been retained, whereas elsewhere in the world the groups had to reform in universities or government laboratories. At Radiophysics, Pawsey oversaw the formation of various radio astronomy teams with designated leaders, and aerial systems were established at a number of different field stations and remote sites around Sydney and near Wollongong (see Figure 2). Activities at the leading field stations are summarized below.

2.1 Dover Heights (1945-1954)

During the war a number of identifications were made of radio emission coming from the Sun, notably by J.S. Hey of the UK Army Operational Research Group, G.C. Southworth at the Bell Telephone Laboratories, and Elizabeth Alexander of the New Zealand Radio Development Laboratory. The first follow-up observations of the Sun by Radiophysics Lab staff were mainly inspired by Alexander's work (see Orchiston, 2005), and were made in October 1945 by Pawsey, R.V. (Ruby) Payne-Scott and L.L. (Lindsay) McCready (1946) using an RAAF radar antenna and 200 MHz receiver system sited on an escarpment overlooking the sea at Collaroy to the north of the Sydney Harbour Heads (location 2 in Figure 2). This was the first use of the sea-interferometer for astronomy, although the concept was well-known to wartime radar operators. In order to obtain better angular resolution the group moved to the higher cliff site at Dover Heights just south of the Sydney Harbour Heads (location 5 in Figure 2) from which they were able to better identify the active areas on the Sun's disk (McCready, Pawsey and Payne-Scott, 1947). These observations established the Dover Heights field station (see Bolton, 1982; Slee, 1994; Stanley, 1992).

J.G. (John) Bolton, a war-time naval radar officer, joined the Radiophysics Lab in 1946, and under Pawsey's guidance he and G.J. (Gordon) Stanley set about extending the frequency range of the Dover Heights sea-interferometer. Success came immediately in the form of a detection of the Cygnus radio source first identified by Hey with wartime radar receivers (Bolton and Stanley, 1948). This soon led on to the discovery of six new sources whose positions and upper limits to their sizes were determined (Bolton, Stanley and Slee, 1949). Sea-interferometry at Dover Heights continued into the 1950s and ultimately produced a catalogue of 104 discrete sources at 100 MHz (Bolton, Stanley and Slee, 1954).

In 1952 John Bolton, Gordon Stanley and O.B. (Bruce) Slee extended the diameter of a former telescope they had dug in the sandy soil to 80 ft and converted the surface for operation at 408 MHz (for details see Orchiston and Slee, 2002b). This transit instrument was used to make a survey of the sky around the zenith covering the declination range −17° to −49° (McGee, Slee and Stanley, 1955). Radio astronomy at this site was closed down in 1954 following John Bolton's transfer to rain physics research for two years and his subsequent move to the USA where he established the radio astronomy group at the California Institute of Technology in 1955 (Kellermann et al., 2005; Stanley, 1994).

2.2 Potts Hill (1948-1963)

This was the second substantial field station established by the Radiophysics Lab away from the RF interference of central Sydney (location 16 in Figure 2). Located on flat wooded land surrounding one of the two Potts Hill reservoirs of the Sydney water system (Figure 3), it was a 30-minute drive (~10 miles) from the Laboratory. A wide range of investigations was conducted at this site under the guidance of several different group leaders. These projects will be described in detail in Section 3.

2.3 Hornsby Valley (1946-1955)

The Hornsby Valley field station was situated in an isolated valley in the hilly terrain some 10 miles north of the Radiophysics Lab (Orchiston and Slee, 2005b), and is pinpointed by location 9 in Figure 2. It was an ideal site for making low-frequency observations at night, when RFI was at a minimum. In late 1947 the site was used by F.J. (Frank) Kerr and colleagues (Kerr, Shain and Higgins, 1949) to accommodate the rhombic receiving aerial for some of the earliest radar studies of the Moon's surface. The transmitter for these experiments was the Radio Australia station at Shepparton, Victoria, operating at 17.84 and 21.54 MHz and with a power of ~60 kW.

Towards the end of 1947, Ruby Payne-Scott transferred from Dover Heights to Hornsby Valley, where she continued her solar work using 60, 65 and 85 MHz Yagi antennas and an 18.3 MHz broadside array (see Payne-Scott, 1949).

The major radio telescope subsequently built at Hornsby Valley was the 6 × 5 dipole aerial array operated by C.A. (Alex) Shain and C.S. (Charlie) Higgins (1954) at 18.3 MHz. Armed with a 17° beamwidth, they were able to map the Galactic background and identify thirty-seven discrete sources. Following the discovery of Jupiter metre-wave burst radiation by Burke and Franklin in 1955, Shain (1956) subsequently examined the Hornsby Valley records taken in 1950 and 1951 and was able to identify many examples of Jovian emission.

A successor instrument was constructed at 9.15 MHz with a beamwidth of ~30°. Galactic emission could be mapped at times of low ionospheric activity, and a brightness temperature spectral index of –2.8 was determined between 9.15 and 100 MHz—the lowest frequency range of any spectral index at the time. Shain moved his low frequency activities to the larger and flatter Fleurs site in 1955.

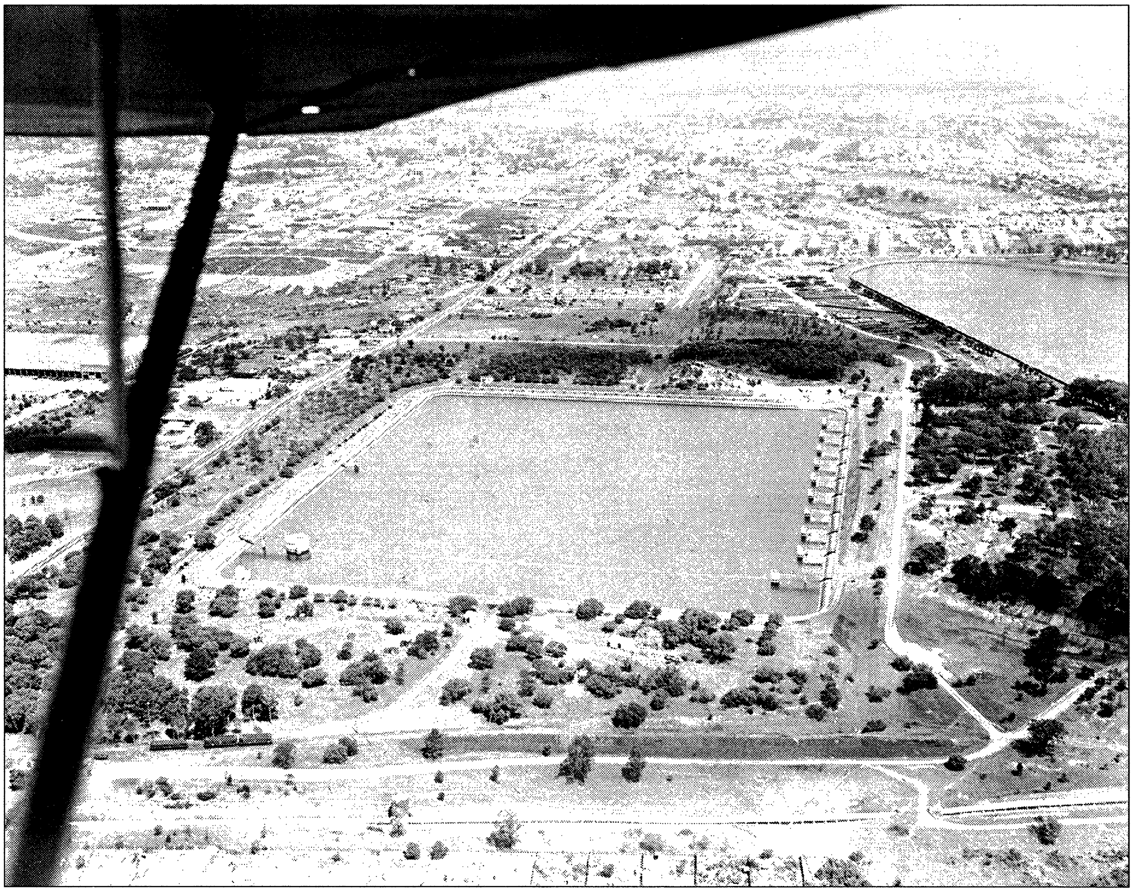

Figure 3: Aerial photograph, looking south, of the eastern reservoir at Potts Hill. Eventually, radio telescopes and associated huts were located along the southern and eastern margins of the reservoir, and across the extended area of flat land in the foreground, to the north of the reservoir (courtesy ATNF Historic Photographic Archive: B3253-1).

2.4 Dapto (1952-1963)

Dapto, some 50 miles south of Sydney, was chosen as the site sufficiently clear of radio frequency interference to enable a serious spectral survey of solar emission to be undertaken. An exploratory development of a radio spectrograph was made by J.P. (Paul) Wild and Lindsay McCready (1950) at a site near Penrith at the foot of the Blue Mountains (location 15 in Figure 2). This first radio spectrograph covered a frequency range of 70-130 MHz. Observations between February and June 1949 showed that there was a potentially rich harvest to be gained from this technique on a better site.

The move south to Dapto (location 4 in Figure 2) was made in 1951, with more advanced equipment and an improved observing strategy. A frequency range of 40-240 MHz was scanned using three octave-band equatorially-driven rhombic aerials (Wild, Murray and Rowe, 1954). Data were logged photographically about once per second. It was immediately deduced that the fundamental frequency amongst the harmonics seen was the natural plasma frequency of the corona at the position of the source. This result opened up the exciting possibility of deriving the position, velocity and size of the emitting source.

A broad programme of research on the time variations of the active Sun continued throughout the 1950s and early 1960s. The realization of the importance of being able to directly measure the location of the active regions as they moved through the corona led to the proposal to build an array with adequate resolution. This became the Culgoora Radioheliograph, which was constructed near Narrabri, 250 km NW of Sydney, in 1967. It consisted of ninety-six 13-m aerials in a circular configuration.

2.5 Fleurs (1953-1963)

At the end of 1949, B.Y. (Bernie) Mills with his colleagues set up interferometry in open farmland at Badgerys Creek near Wallacia, 20 miles west of Sydney (location 1 in Figure 2). Initially there were three 20 × 30-ft broadside aerials on E-W baselines of 60, 270 and 330m, which were used to survey the sky from $\delta = -90°$ to $+50°$ at a frequency of 101 MHz (Mills, 1952). Mills constructed a log N – log S plot from the 77 discrete sources from his survey. His results from this work were at variance with those of Ryle's group in Cambridge, and thus began a long-running dispute between the two groups (see Mills, 1984; Sullivan, 1990).

The next major development took in 1954, when A.G. (Alec) Little oversaw the construction of new form of array which came to be known as the 'Mills Cross', based on a prototype fabricated by Mills, Little and Sheridan at Potts Hill in 1952-1953 (see Section 3.4 below). The new antenna was built at Fleurs (location 6 in Figure 2), a disused wartime airstrip near Badgerys Creek (Orchiston and Slee, 2002a). It took the form of a cross-shaped array with arms 1,500 ft long comprising 250 dipoles operating at a frequency of 85.5 MHz with a half-power beamwidth of 49 arcmin; the declination range covered was –80° to +10° (Mills, 1955). This large radio telescope was operated until the early 1960s, and produced the first detailed basic radio data for the southern sky at a long wavelength (3.5m).

Meanwhile, Alex Shain expanded his low frequency research by moving to Fleurs and constructing a 19.7 MHz array of the Mills Cross type. The arms were 3,400 ft E-W and 3,625 ft N-S, which produced a resolution of 1.4° (Shain, 1958). The 'Shain Cross', as it became known, was operated for several years by Alex Shain, Charlie Higgins, M.M. (Max) Komasaroff and Bruce Slee, and was closed in 1964, four years after Shain's untimely death.

Figure 4: The 16 x 18-ft paraboloid on a polar mount. Jim Hindman, on the top of the ladder, was involved in both solar and H-line observations (courtesy ATNF Historic Photographic Archive: B2649-2).

In 1956 W.N. (Chris) Christiansen moved his solar operations from Potts Hill to Fleurs where he built a sensitive cross-type array. The 'Chris Cross', as it became known, had 320-m arms, each consisting of thirty-two 6-m diameter paraboloids. It operated at a wavelength of 21 cm with a resolution of 3 arcmin, and the first results were produced in 1957 (Christiansen, Mathewson, and Pawsey, 1957). This instrument worked successfully for many years producing high resolution radio maps of the Sun before it was 'remorphed' as the Fleurs Synthesis Telescope (see Orchiston, 2004b).

3 RESEARCH ACTIVITIES AT POTTS HILL (1948-1963)

In this section I describe the most important research projects that were pursued at this radio-quiet, easily accessible field station.

3.1 Early Work – Up to ~1950

According to Orchiston and Slee (2005a: 134), "The first radio telescopes at Potts Hill were situated at the northern end of the reservoir and comprised a single Yagi antenna (used by Little to observe the Sun at 62 MHz), and a 3.05 metre (10-ft) diameter dish (which was employed by Piddington and Minnett to survey radiation from the region of the Galactic Centre at 1,210 MHz)."

In the second half of 1948 a 16 × 18-ft ex-radar paraboloid that had originally been used for solar work by F.J. (Fred) Lehany and D.E. (Don) Yabsley (1949) at the short-lived Georges Heights field station (Orchiston 2004a) was relocated to Potts Hill (Figure 4). The original crude support was replaced by an equatorial mounting, and this radio telescope was one of the principal instruments at Potts Hill in the early days, operating at 200, 600 and 1,200 MHz.

Christiansen, Yabsley and Mills (1949) used this antenna to follow the partial solar eclipse of 1 November 1948 at 600 MHz, while simultaneous observations were made with 10-ft aerials taken to Rockbank near Melbourne (Orchiston, 2004c) and Strahan in Tasmania. The high angular resolution provided by the occulting edge of the Moon during the eclipse showed that ~80% of the solar emission came from beyond the solar limb, and moreover, the 600 MHz Sun was found to be limb-brightened.

J.J. (Jack) Piddington and H.C. (Harry) Minnett (1952) subsequently used the 16 × 18-ft paraboloid at 1,210 MHz in their study of the Cygnus-A and Cygnus-X regions with a 3° beam.

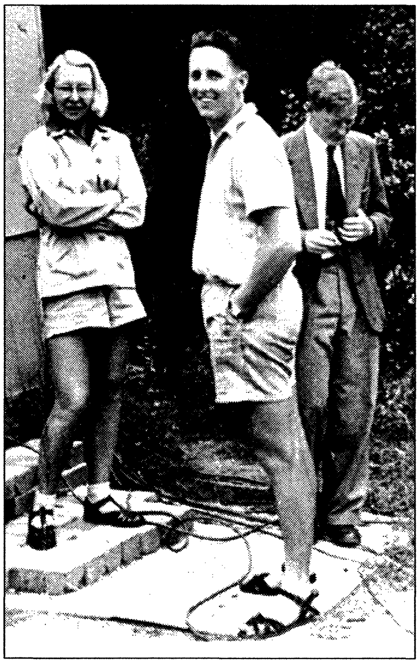

Figure 5: Ruby Payne-Scott, Alec Little and Chris Christiansen outside the solar trailer in about 1949 (courtesy W.T. Sullivan).

Ruby Payne-Scott (Figure 5), who made important contributions to the theory of the sea-interferometer in her pioneering solar observations with Pawsey and McCready, moved her solar work to Potts Hill towards the end of 1948. In order to investigate the two types of solar activity identified at Hornsby Valley, she worked with Alec Little (Figure 5) during 1949-1951 to systematically study the positions and movement of solar bursts at 97 MHz. They used a two-element E-W interferometer of baseline 790 ft, sensitive to polarization. Their position interferometer, the first of its type in the world, was located along the southern side of the reservoir (see Payne-Scott and Little, 1951; 1952). These papers by Ruby Payne-Scott appear to be her last published scientific work before she was forced by the then-existing regulations to resign from CSIRO employment in 1951 immediately preceding the birth of her first child.

During evenings Payne-Scott and Little did not require the solar position interferometer, so Bernie Mills and A.B. Thomas (1951) were able to use it to study the variable discrete source in Cygnus. They confirmed that the strong source scintillations exhibited by Cygnus-A originated in the F-region.

3.2 The Solar Grating Interferometer

Chris Christiansen, the leader of the Potts Hill solar group, began his researches there with the 16 × 18-ft ex-radar paraboloid. Working with J.V. (Jim) Hindman, he made long-term observations of the integrated emission from the Sun at 600 and 1,200 MHz and separated the sunspot-correlated emission from the steady emission (Christiansen and Hindman, 1951). With colleagues, he used the paraboloid to follow the time-variation of the radio emission from two large solar disturbances (Christiansen et al., 1951).

In 1950 he was given permission to build an array which could produce daily high resolution strip scans of the Sun at low cost. The array operated at a wavelength of 21 cm and consisted of thirty-two 6-ft paraboloids on a 700-ft E-W baseline adjacent to the southern wall of the reservoir (see Figure 6). Each aerial was connected via a branching network providing equal path lengths to the correlator (Christiansen and Warburton, 1953). A drift scan of the 3 arcmin-wide lobe pattern across the Sun could be made every 15 minutes by moving the paraboloids forward in appropriate steps. The first observations were made in 1952 by Christiansen and J.A. (Joe) Warburton, and they showed the positions of radio emission above current or recent sunspots and a clear limb-brightening of the quiet Sun.

Figure 6: Chris Christiansen and the first solar grating array (courtesy ATNF Historic Photographic Archive: B2976-1).

Figure 7: The solar grating arrays in 1953, looking south-west. The E-W arm consisted of thirty-two 6-ft paraboloids while the N-S arm had sixteen 10-ft paraboloids. Aperture synthesis was achieved by combining the Fourier components from each arm (courtesy ATNF Historic Photographic Archive: B3475-1).

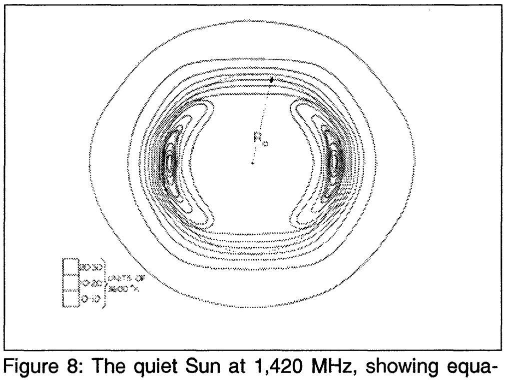

Figure 8: The quiet Sun at 1,420 MHz, showing equatorial limb-brightening (courtesy ATNF Historic Photographic Archive: B3480).

Following the successful operation of the E-W grating interferometer an orthogonal N-S arm was constructed along the eastern wall of the reservoir in order to determine the two-dimensional brightness distribution across the Sun. The N-S arm consisted of sixteen 10-ft wire mesh steerable paraboloids on a 700-ft baseline, as shown in Figure 7. A two-dimensional synthesis map of the Sun each day could be made by combining the Fourier components of the E-W and N-S arrays while tracking the Sun throughout the day. The Fourier processing was done by hand and was a lengthy operation (Christiansen and Warburton, 1955). Nevertheless, the 3 arcmin resolution maps provided unique information about the quiet and active Sun at a decimetre wavelength (Figure 8). Observations with the grating interferometer will be discussed further in Section 4. This work was transferred to Fleurs in 1956 (see Section 2.5).

In 1954, the E-W grating array was converted to operation at a wavelength of 60 cm (500 MHz) by Govind Swarup and R. Parthasarathy (1955; 1958), providing 8.2 arcmin resolution. They found no evidence for limb-brightening at this frequency. The active regions were of higher temperature and were at greater heights than at 21-cm wavelength.

3.3 21-cm Hydrogen Line Observations

Following a cable to Pawsey in March 1951 from Frank Kerr (who was visiting Harvard University at the time), Christiansen and Hindman embarked on a crash programme to confirm the detection of 21-cm wavelength emission from neutral hydrogen made by Ewen and Purcell. Within six weeks they had built a narrow-band receiver system for the 16 × 18-ft paraboloid and made the first hydrogen line observations of the southern sky. The aerial is shown in close-up in Figure 4. In the meantime, Dutch astronomers J.H. Oort and C.A. Muller had also completed observations with an ex-WW2 German Wurtzburg telescope at Kootwijk. The results from all three groups were published jointly in the 1 September 1951 issue of *Nature* (Volume 168, pages 356-358).

After the initial confirmatory measurements, Christiansen and Hindman (1952) proceeded to make a preliminary hydrogen-line survey of the southern sky covering the declination range −66° to +50° at an angular resolution of 2.3°. The Galactic Plane in the centre and anticentre regions was clearly delineated. I find it interesting to note that their map showed the existence of the Gould Belt system which extragalactic astronomers know as the 'zone of avoidance'. A more extensive mapping of the Gould Belt system was one of my earliest 21-cm projects at Jodrell Bank (Davies, 1960). When these observations with the 16 × 18-ft radio telescope were completed, Christiansen returned to his heavy commitments with the solar grating interferometer.

Upon his return to Australia in 1951 Frank Kerr (1984) took up the challenge of making a detailed study of the southern sky which matched and could be integrated with a corresponding neutral hydrogen survey of the northern sky by the Dutch. A 36-ft paraboloid (Figure 9) restricted to motion in the meridian, took the place of the 16 × 18-ft dish for this new work. Using a multichannel receiver, successive drift scans were used to build up the H-line spectra at an angular resolution of 1.5°. The first observations were of the Magellanic Clouds (Kerr, Hindman and Robinson, 1954). Working with Gerard de Vaucouleurs, Kerr measured the rotation curves of the two Clouds and determined their total masses and hydrogen contents (Kerr and de Vaucouleurs, 1955; 1956).

The southern Milky Way survey was completed in 1956. This was combined with the Dutch northern survey to produce an iconic map of the HI distribution in the Galaxy and a definitive rotation curve (Oort, Kerr and Westerhout, 1958). Kerr and colleagues then transferred their H-line studies to the new 210-ft Parkes Radio Telescope in 1962.

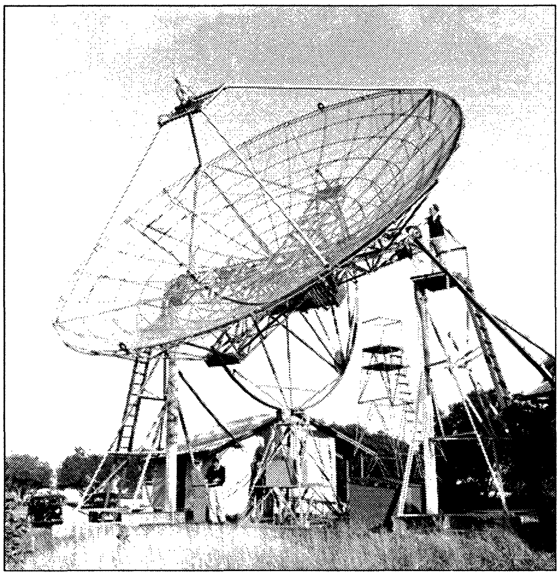

Figure 9: The 36-ft paraboloid, a meridian instrument used primarily for H-line studies. Also shown is the associated receiver hut (courtesy ATNF Historic Photographic Archive: B3679-1).

Although dedicated to H-line work, the Potts Hill 36-ft dish was occasionally employed for other projects. For example, Piddington and G.H. (Gil) Trent (1956) used it to survey the southern sky at 600 MHz. At this frequency the beamwidth was 3°.

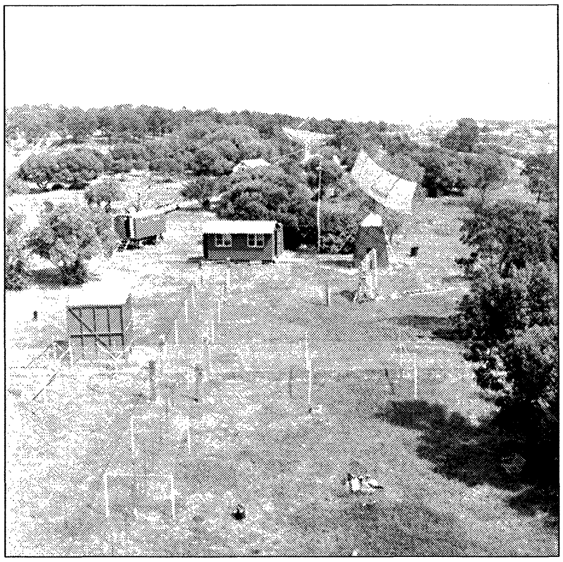

Figure 10: This Potts Hill photograph was taken in 1952. In the foreground is the 120 x 120-ft Mills Cross prototype which was under test. Adjacent to it is the 16 x 18-ft paraboloid that was used for solar, Galactic and HI observations. Beyond these two radio telescopes and near the centre of the photograph is the 36-ft H-line transit dish (courtesy ATNF Historic Photographic Archive: B3171-4).

3.4 The Mills Cross Prototype

Chris Christiansen (1984: 122) tells the story that one day in 1953 Bernie Mills came to Potts Hill to see the two grating interferometers. In discussions between the two it was agreed if the two arms were located about a common centre the outputs could be multiplied to give high resolving power in two dimensions. By next morning Mills had devised the detailed design of the Mills Cross antenna. He foresaw a resolution of about 1° at 100 MHz.

In order to prove to the powers-that-be that his idea would really work in practice a pilot model, shown in Figure 10, was built at Potts Hill by Alec Little and K.V. (Kevin) Sheridan. It had two arms, each 120 ft long consisting of dipoles operating at 97 MHz. Switching between in-phase and anti-phase correlations of the two arms gave a clean beam of 8° width; no central (common) dipole was required. The aerial system gave the first detection of the Magellanic Cloud. The prototype lived up to expectations (Mills and Little, 1953) and cleared the path for the construction at Fleurs of a full-scale 'Mills Cross' with a beamwidth of 49 arcmin (see Section 2.5).

4 THE RADIOPHYSICS LAB 1951-1953: A PERSONAL VIEW

4.1 Introduction

During the period January 1951 to August 1953 I was a Research Officer in the Radiophysics Division of CSIRO working on solar radio astronomy principally with Chris Christiansen and Jack Piddington but under the general oversight of Joe Pawsey. I had just completed my degree in Physics at the University of Adelaide where L.G.H. (Leonard) Huxley had recently been made Head of Department. During WW2 Huxley had worked on the development of radar and had written a textbook on waveguides with which we undergraduates had become closely familiar. Through this radar connection I found my way to the Radiophysics Lab. (Sir Leonard) Huxley subsequently became the Vice-Chancellor of the Australian National University.

I was one of three—Joe Warburton, myself and A.N. Other (whom, I am given to understand, only stayed a few months)—who were the first intake of raw graduates into the Radiophysics Lab. Joe Pawsey prepared our initiation into the research environment with characteristic wisdom. Initially we each spent several days at the various field stations. In the next months, as we settled into our various research groups, we were encouraged to develop our electronic skills by building IF amplifiers at the Lab. At this time, Joe Pawsey was fascinated by the relation between the radio and optical activity of the Sun. He had recently acquired breath-taking movies from the McMath-Hulbert Observatory at the University of Michigan which showed eruptive prominence activity above the solar limb. He advised me to view this film every day for the next week to really embed in my mind the structure of the Sun's atmosphere. This was later to be significant in my first publication. Every two weeks the various radio astronomy groups met in the Lab to discuss their research work, and these meetings provided me with an overview of activities, particularly so when I was appointed secretary and had to write up the minutes!

Throughout my time at the Radiophysics Lab I was attached to Chris Christiansen's group and travelled daily with Alec Little, Jim Hindman and Chris in a Lab vehicle to Potts Hill where the E-W arm of the grating array was being constructed. Looking back over this period it is clear that I must have spent some fraction of my time at the Lab, where Joe Pawsey encouraged me to make an assessment of the large body of solar burst data which the Radiophysics staff had accumulated since 1945. This work directly led to a collaboration with Jack Piddington, who had been thinking about the origin of the solar corona.

4.2 Analysis of the Radiophysics Lab Solar Burst Data

By the time I arrived at the Radiophysics Lab in January 1951, Joe Pawsey had seen the scientific value of collating the large body of burst information as a function of frequency. In order to do this it was necessary to tabulate the material from times when *continuous* records had been taken, which was not the case for all the equipments. C.W. (Clay) Allen at the Mount Stromlo Observatory had been running a 200 MHz solar monitor for many years and was keen for me to use his data as he was about to move to the Perren Chair in University College, London. I spent several weeks at Mount Stromlo extracting the solar burst data.

Data covering the period from January 1950 to June 1951 were available at six frequencies between 60, and 10,000 MHz. The analysis (Davies 1954) included a comparison with solar flare and sunspot data as well as terrestrial records. The latter included ionospheric fade-outs at 18 MHz supplied by Alex Shain, as well as magnetic crochets from Toolangi Magnetic Observatory in Victoria.

4.3 Collaboration with J.H. Piddington – The Origin of the Solar Corona

With his pre-WW2 radar experience and involvement in ionospheric research in the UK (e.g. Appleton and Piddington, 1938), J.H. (Jack) Piddington was well-placed to tackle the interpretation of radio emission from the Sun and the Milky Way when the radio astronomy group was formed in the Radiophysics Lab. Although he was happy to discuss shared scientific interests in the ionosphere and solar physics with Mount Stromlo's D.F. Martyn, he did not form a close association with the Radiophysics theory group, which consisted of K.C. Westfold, S.F. Smerd and J.A. Roberts. He worked most comfortably on his own, researching his chosen set of problems. In retrospect, I feel that his many scientific contributions were not given the credit they deserved.

Joe Pawsey suggested that I work with Piddington on making further analyses of the extensive Radiophysics Lab solar radio data which were relevant to the origin of the solar corona. At the time it proved difficult to separate the sunspot-correlated emission from the basic component identified as the 'quiet Sun' which could be thought of as originating in the solar corona. Our work, using observations between 600 and 10,000 MHz which referred to thermal gas, indicated that the 'sunspot' emission continued for one, and often two, solar rotations after the sunspots themselves had disappeared. Previous estimates were shown to be a factor of 2-3 too high because of this effect. A picture was painted of this hot gas from immediately above the active sunspot area rising and merging with surrounding cooler gas to become the corona, which could be replaced by this process in a few days (Piddington and Davies, 1953a; 1953b). It was suggested that energy was transferred from the sunspot to the corona by Alfvén waves. This interest in the role of magnetic fields in the astronomical environment occupied much of Piddington's effort after this time.

4.4 Working with W.N. Christiansen

During the first six months that I worked with Chris Christiansen at Potts Hill he was heavily occupied, along with Jim Hindman, in confirming the Harvard detection of Galactic HI and the subsequent survey of a substantial area of the southern Galactic plane. The design of the E-W solar grating interferometer had been completed and construction had begun when I arrived. My first job, along with Joe Warburton, was to align the wooden posts which were to support the thirty-two 6-ft paraboloids. It was ironic that the last job that I did with my brothers before leaving the family farm was to dig post holes for fencing around one of the paddocks. There were two differences however between the two situations. First, the post holes in Naracoorte (South Australia) were in limestone, while those in Potts Hill were in a softer alluvial clay. Secondly, instead of aligning the posts by eye—as we did on the farm—at Potts Hill we used a theodolite. At that time we did not know that Ph.D. meant 'Post-hole Digger'!

While still helping with construction of the grating interferometer in 1951 I was also responsible for operating a spectrohelioscope which gave an H-alpha image of the Sun. This instrument had been installed at Potts Hill by the solar physicist R.G. (Ron) Giovanelli from the Physics Division of CSIRO (which shared the building with us on the Sydney University campus). The purpose of this instrument was to locate activity on the Sun for comparison with the maps generated by the array. The array came into operation in early 1952, and on clear days I made maps of the features of the H-alpha Sun and used Stonyhurst discs to present the data. The features included sunspots, bright plages, and prominences (which were visible in emission on the limb, or in absorption as dark filaments on the disk). It turned out that the most interesting result of this early work was the association of the 21 cm emission with the plage areas which emerged before sunspots and continued for up to one rotation after the spots had disappeared. Furthermore it was found that the prominences lasted even longer. This result had been hinted at in early eclipse observations.

It was clear from these high resolution (3 arcmin) measurements that the plage was the critical feature of the optical Sun, and that it was associated with the overlying radio emission (see Figure 11). All of these features were invariably associated with a localized magnetic field (Christiansen, Warburton and Davies, 1957).

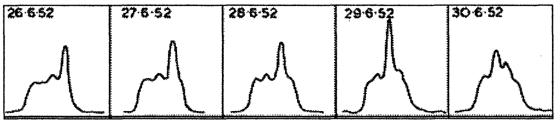

Figure 11: 1,420 MHz E-W strip scans of the Sun showing enhanced emission associated with radio plages (adapted from ATNF Historic Photographic Archive: B2849-1).

While observing the Sun with the spectrohelioscope on the afternoon of 26 February 1953 I noticed a large prominence on the NE limb. At 0450 UT it suddenly erupted to a height of 3-4 arcmin. The radio records at 62, 98 and 200 MHz showed a simultaneous burst. However, an even larger burst occurred at 0630 UT, and this was associated with material streaming back towards the Sun (Davies, 1953). Such eruptive prominences are not infrequent, although not all gave strong radio emission. This was my first 'solo' scientific paper, which was published in *Nature* while I was on board ship between Australia and England.

5 ACKNOWLEDGEMENTS

I thank Ron Ekers, Dick McGee and Jessica Chapman for help in obtaining material for this article, and particularly Wayne Orchiston for reading and commenting on the original manuscript. Woody Sullivan generously gave permission to use the image reproduced in Figure 5.

6 REFERENCES

Appleton, E.V., and Piddington, J.H., 1938. The reflexion coefficients of ionospheric regions. *Proceedings of the Royal Society*, A164, 467-476.

Bolton, J.G., 1982. Radio astronomy at Dover Heights. *Proceedings of the Astronomical Society of Australia*, 4, 349-358.

Bolton, J.G., and Stanley, G.J., 1948. Observations of the variable source of cosmic radio frequency radiation in the constellation of Cygnus. *Australian Journal of Scientific Research*, A1, 58-69.

Bolton, J.G., Stanley, G.J., and Slee, O.B., 1949. Positions of three discrete sources of galactic radio-frequency radiation. *Nature*, 164, 101-102.

Bolton, J.G., Stanley, G.J., and Slee, O.B., 1954. Galactic radiation at radio frequencies. VIII: Discrete sources at 100 Mc/s between declinations +50° and –50°.*Australian Journal of Physics*, 7, 110-129.

Christiansen, W.N., 1984. The first decade of solar radio astronomy in Australia. In Sullivan, 113-131.

Christiansen, W.N., and Hindman, J.V., 1951. A long-period change in radio-frequency radiation from the 'Quiet Sun' at decimeter wave-lengths. *Nature*, 167, 635-637.

Christiansen, W.N., and Hindman, J.V., 1952. A preliminary survey of 1420 Mc/s. line emission from Galactic hydrogen. *Australian Journal of Scientific Research*, A5, 437-455.

Christiansen, W.N., and Warburton, J.A., 1953. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part I. A new highly directional aerial system. *Australian Journal of Physics*, 6, 190-202.

Christiansen, W.N., and Warburton, J.A., 1955. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part III. The Quiet Sun—two-dimensional observations. *Australian Journal of Physics*, 8, 474-486.

Christiansen, W.N., Mathewson, D.S., and Pawsey, J.L., 1957. Radio pictures of the Sun. *Nature*, 180, 944-946.

Christiansen, W.N., Warburton, J.A., and Davies, R.D., 1957. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part IV. The slowly varying component. *Australian Journal of Physics*, 10, 491-514.

Christiansen, W.N., Yabsley, D.E., and Mills, B.Y., 1949. Measurements of solar radiation at a wavelength of 50 centimetres during the eclipse of November 1, 1948. *Australian Journal of Scientific Research*, A2, 506-523.

Christiansen, W.N., Hindman, J.V., Little, A.G., Payne-Scott, R., Yabsley, D.E., and Allen, C.W., 1951. Radio observations of two large solar disturbances. *Australian Journal of Scientific Research*, A4, 51-61.

Davies, R.D., 1953. Radio observations at the time of an ascending solar prominence. *Nature*, 172, 446-447.

Davies, R.D., 1954. An analysis of bursts of solar radio emission and their association with solar and terrestrial phenomena. *Monthly Notices of the Royal Astronomical Society*, 114, 74-92.

Davies, R.D., 1960. A study of neutral hydrogen in the solar neighbourhood of the Milky Way. *Monthly Notices of the Royal Astronomical Society*, 120, 483-497.

Kellermann, K.I., Orchiston, W., and Slee, B., 2005. Gordon James Stanley and the early development of radio astronomy in Australia and the USA. *Publications of the Astronomical Society of Australia*, 22, 1-11.

Kerr, F.J., 1984. Early days in radio and radar astronomy in Australia. In Sullivan, 133-145.

Kerr, F.J., and De Vaucouleurs, G., 1955. Rotation and other motions of the Magellanic Clouds from radio observations. *Australian Journal of Physics*, 8, 508-521.

Kerr, F.J., and De Vaucouleurs, G., 1956. The masses of the Magellanic Clouds from radio observations. *Australian Journal of Physics*, 9, 90-111.

Kerr, F.J., Hindman, J.V., and Robinson, B.J., 1954. Observations of the 21 cm line from the Magellanic Clouds. *Australian Journal of Physics*, 7, 297-314.

Kerr, F.J., Shain, C.A., and Higgins, C.S., 1949. Moon echoes and penetration of the ionosphere. *Nature*, 163, 310-313.

Lehany, F.J., and Yabsley, D.E., 1949. Solar radiation at 1200 Mc/s., 600 Mc/s., and 200 Mc/s. *Australian Journal of Scientific Research*, A2, 48-62.

McCready, L.L., Pawsey, J.L., and Payne-Scott, R., 1947. Solar radiation at radio frequencies and its relation to sunspots. *Proceedings of the Royal Society*, A190, 357-375.

McGee, R.X., Slee, O.B., and Stanley, G.J., 1955. Galactic survey at 400 Mc/s between declinations –17° and –49°. *Australian Journal of Physics*, 8, 347-367.

Mills, B.Y., 1952. The distribution of discrete sources of cosmic radio radiation. *Australian Journal of Scientific Research*, A5, 266-287.

Mills, B.Y., 1955. The observation and interpretation of radio emission from some bright galaxies. *Australian Journal of Physics*, 8, 368-389.

Mills, B.Y., 1984. Radio sources and the log N – log S controversy. In Sullivan, 147-165.

Mills, B.Y., and Little, A.G., 1953. A high-resolution aerial system of a new type. *Australian Journal of Physics*, 6, 272-278.

Mills, B.Y., and Thomas, A.B., 1951. Observations of the source of radio-frequency radiation in the constellation of Cygnus. *Australian Journal of Scientific Research*, A4, 158-171.

Oort, J.H., Kerr, F.J., and Westerhout, G., 1958. The Galactic system as a spiral nebula. *Monthly Notices of the Royal Astronomical Society*, 18, 379-389.

Orchiston, W., 2004a. Radio astronomy at the short-lived Georges Heights field station. *ATNF News*, 52, 8-9.

Orchiston, W., 2004b. The rise and fall of the Chris Cross: a pioneering Australian radio telescope. In Orchiston, W., Stephenson, R., Débarbat, S., and Nha, I.-S. (eds.). *Astronomical Instruments and Archives From the Asia-Pacific Region*. Seoul, IAU Commission 41. Pp. 157-162.

Orchiston, W., 2004c. The 1948 solar eclipse and the genesis of radio astronomy in Victoria. Journal of Astronomical History and Heritage, 7, 118-121

Orchiston, W., 2005. Dr Elizabeth Alexander: first female radio astronomer. In Orchiston, W. (ed.). *The New Astronomy: Opening the Electromagnetic Window and Expanding our View of Planet Earth*. Dordrecht, Springer. Pp.71-92.

Orchiston, W., and Slee, B. 2002a. The flowering of Fleurs: an interesting interlude in Australian radio astronomy. *ATNF News*, 47, 12-15.

Orchiston, W., and Slee, B. 2002b. Ingenuity and initative in Australian radio astronomy: the Dover Heights hole-in-the-ground antenna. *Journal of Astronomical History and Heritage*, 5, 21-34.

Orchiston, W., and Slee, B. 2005a. The Radiophysics field stations and the early development of radio astronomy. In Orchiston, W. (ed.). *The New Astronomy: Opening the Electromagnetic Window and Expanding our View of Planet Earth*. Dordrecht, Springer. Pp. 119-168.

Orchiston, W., and Slee, B. 2005b. Shame about Shain! Early Australian radio astronomy at Hornsby Valley. *ATNF News*, 55, 14-16.

Pawsey, J.L., Payne-Scott, R., and McCready, L.L., 1946. Radio-frequency energy from the Sun. *Nature*, 157, 158-159.

Payne-Scott, R., 1949. The noise-like character of solar radiation at metre wavelengths. *Australian Journal of Scientific Research*, A2, 228-231.

Payne-Scott, R., and Little, A.G., 1951. The position and movement on the solar disk of sources of radiation at a frequency of 97 Mc/s. II. Noise storms. *Australian Journal of Scientific Research*, A4, 508-525.

Payne-Scott, R., and Little, A.G., 1952. The position and movement on the solar disk of sources of radiation at a frequency of 97 Mc/s. III. Outbursts. *Australian Journal of Scientific Research*, A5, 32-46.

Piddington, J.H., and Davies, R.D., 1953a. Origin of the solar corona. *Nature*, 171, 692-693.

Piddington, J.H., and Davies, R.D., 1953b. Thermal emission from the Sun and the source of coronal heating. *Monthly Notices of the Royal Astronomical Society*, 113, 582-596.

Piddington, J.H., and Minnett, H.C., 1952. Radio-frequency radiation from the constellation of Cygnus. *Australian Journal of Scientific Research*, A5, 17-31.

Piddington, J.H., and Trent, G.H., 1956. A survey of cosmic radio emission at 600 Mc/s. *Australian Journal of Physics*, 9, 481-493.

Shain, C.A., 1956. 18.3 Mc/s radiation from Jupiter. *Australian Journal of Physics*, 9, 61-73.

Shain, C.A., 1958. The radio emission from Centaurus-A and Fornax-A. *Australian Journal of Physics*, 11, 517-529.

Shain, C.A., and Higgins, C.S., 1954. Observations of the general background and discrete sources of 18.3 Mc/s cosmic noise. *Australian Journal of Physics*, 7, 130-149.

Slee, O.B., 1994. Some memories of the Dover Heights field station, 1946-1954. *Australian Journal of Physics*, 47, 517-534.

Stanley, G.J., 1994. Recollections of John G. Bolton at Dover Heights and Caltech. *Australian Journal of Physics*, 47, 507-516.

Sullivan, W.T. (ed.), 1984. *The Early Years of Radio Astronomy*. Cambridge, Cambridge University Press.

Sullivan, W.T., 1990. The entry of radio astronomy into cosmology: radio stars and Martin Ryle's 2C survey. In Bertotti, R., Balbinot, R., Bergia, S., and Messina, A. (eds.). *Modern Cosmology in Retrospect*. Cambridge, Cambridge University Press. Pp. 309-330.

Sullivan, W.T., 2005. The beginnings of Australian radio astronomy. *Journal of Astronomical History and Heritage*, 8, 11-32.

Swarup, G., and Parthasarathy, R., 1955. Solar brightness distribution at a wavelength of 60 centimetres. I. The quiet Sun. *Australian Journal of Physics*, 8, 487-497.

Swarup, G., and Parthasarathy, R., 1958. Solar brightness distribution at a wavelength of 60 centimetres. II. Localized radio bright regions. *Australian Journal of Physics*, 11, 338-349.

Wild, J.P., and McCready, L.L., 1950. Observations of the spectrum of high-intensity solar radiation at metre wavelengths. Part I. The apparatus and spectral types of solar bursts observed. *Australian Journal of Scientific Research*, A3, 387-398.

Wild, J.P., Murray, J.D., and Rowe, W.C., 1954. Harmonics in the spectra of solar radio disturbances. *Australian Journal of Physics*, 7, 439-459.

Rod Davies is Emeritus Professor of Radio Astronomy at the University of Manchester, U.K. From 1988 to 1997 he was Director of the Jodrell Bank Observatory. After early research on solar radio astronomy at the Radiophysics Division of CSIRO he moved to Jodrell Bank and established the hydrogen line group to exploit the potential of the 250-ft radio telescope. The group made extensive studies of H-line emission from galaxies in the local universe, which included the first high-resolution mapping of the Andromeda Nebula and investigations of the peculiar velocity of the Local Group galaxies. His more recent work involves the Cosmic Microwave Background; he established the CMB station at Izana Observatory, Tenerife, in collaboration with colleagues at the Instituto de Astrofisica de Canarias.

He is currently working with colleagues on scientific programmes to be undertaken with the Planck CMB Satellite, which will be launched in 2007.

He is a former Secretary and President of the Royal Astronomical Society and was Chairman of the Local Organising Committee of the 24th General Assembly of the IAU held in Manchester during August 2000. He is a Fellow of the Royal Society.

Journal of Astronomical History and Heritage, 8(2), 97-106 (2005).

EARLY AUSTRALIAN MEASUREMENTS OF ANGULAR STRUCTURE IN DISCRETE RADIO SOURCES

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Abstract: These angular diameter measurements of the discrete sources were the first to result in estimates of their brightness temperatures, and, together with concurrent measurements of their radio spectra, showed that the sources were non-thermal in physical nature. Identification with optical galaxies and a supernova remnant were able to fix their distances and thus their linear dimensions and total power outputs, the latter being so great that the generating mechanism remained obscure for some years. Nearer the Earth, interferometer measurements of scattered emission from discrete sources passing behind the Sun's extended corona outlined the large volume of interplanetary space that contained electron-density turbulence of sufficient strength to scatter their radiations and so increase their apparent angular diameters. The ultimate manifestation of coronal scattering was the discovery in 1963-1964 that the decametric radio bursts from Jupiter were, in fact, caused by the drifting of a scattered diffraction pattern across the receiving antennas at the speed of the solar wind.

Keywords: source size measurements, discrete sources, coronal scattering, Jovian bursts, interferometry, Fleurs-Wallacia Interferometer, barley sugar arrays, Dover Heights, Badgerys Creek, Fleurs.

1 INTRODUCTION

The measurement of the angular size of a discrete radio source, together with its intensity at the Earth, give arguably the most important information about its intrinsic properties. Even if its distance is unknown, one can deduce a quantity called its brightness temperature, which is a measure of the energy emitted from each square centimetre of the object's surface; this gives an important clue to the kind of physical processes that are responsible for the radio emission. If, in addition, one knows its distance, usually as a result of identifying the radio source with a star or galaxy, one can compute the actual total radio power emitted by the source and measure its linear dimensions. Other parameters such as the radio spectrum (i.e. how the source intensity at the Earth changes with radio frequency) and its polarization give important auxiliary information, but here we shall not be concerned with those quantities.

Australian radio astronomers began estimating angular sizes, or at least their upper limits, in mid-1947 when the first extra-solar discrete source, Cygnus-A, was isolated from the cosmic noise background (Bolton and Stanley, 1948). For the next eighteen years similar observations were made at a variety of field stations operated by the Division of Radiophysics (later transformed into the Australia Telescope National Facility). In this paper I attempt to summarize those measurements and outline some of the physical source parameters that were deduced. In the late 1940s and early 1950s similar measurements were commenced in England and later in the USA, and these results have tended to be emphasized in the literature, but there is little doubt that the Australian experiments (one of which has never been published) did have an important stimulatory effect on furthering the worldwide scope of angular size measurements.

2 THE FIRST MEASUREMENTS AT DOVER HEIGHTS

Cygnus-A was detected in June 1947 by a 100 MHz sea interferometer located at the CSIRO's Division of Radiophysics field station at Dover Heights (for field station localities, see the map on page 88). Figure 1 shows the simple Yagi antennas that were used by John Bolton and Gordon Stanley. Although these antennas could be rotated in altitude and azimuth in order to point at a desired spot in the sky, for sea-interferometry they were both swung down so that they were aligned parallel to the horizon. These antennas were located on top of a WW2 ex-radar station block house some 74 m above sea level.

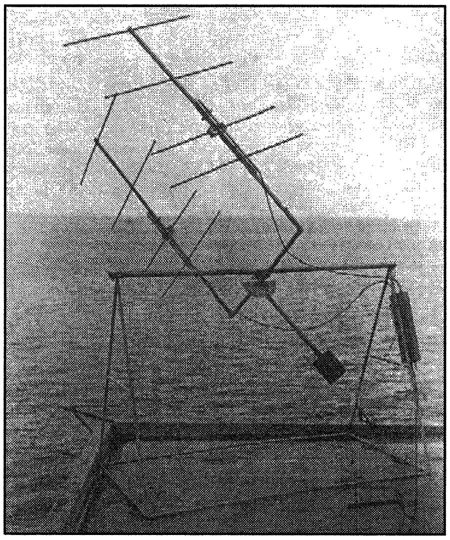

Figure 1: The 100 MHz twin-Yagi used at Dover heights in June 1947 to observe the first discrete cosmic radio source, Cygnus-A.

The principle of the sea interferometer is described in detail by Bolton and Slee (1953), but a simple explanation assisted by Figure 2 will suffice here. The upper trace shows a set of interference fringes that were formed as Cygnus-A suddenly rose above the horizon, while the lower set of fringes were made by the rising Sun. The sinusoidal fringe pattern is due to interference between the direct rays from the source and rays reflected off the sea, which is almost a perfect reflector at metre radio wavelengths. As the radio source rises the rays alternately add and subtract (due to the changing difference in path length), resulting in maxima and minima in the pattern. The angular spacing between the fringes depends on the height of the antenna above sea level; the greater the height the smaller the spacing.

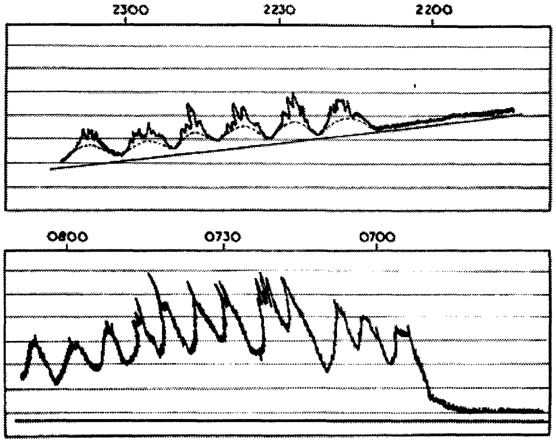

Figure 2: Chart recordings of Cygnus-A rising at Dover Heights (upper trace), and the rising Sun (lower trace).

How does this interferometer estimate the angular size of the source? If you can imagine a point source, i.e. one with angular size much smaller than the fringe spacing, you will see that it will sit entirely within one fringe and produce a pattern with maxima twice the intensity of that produced from the same antenna in free space. In the minima, the direct and reflected rays will exactly cancel leaving zero intensity. If the angular diameter of the source starts to approach the fringe spacing, some points on the source will produce rays that neither add nor cancel completely, resulting in the fringe maxima decreasing and the fringe minima increasing in intensity. Eventually, as the source diameter equals or exceeds the fringe spacing, the fringe pattern will disappear, leaving a constant elevated level equal to that recorded if the antenna were in free space.

The ratio of observed maximum to minimum fringe amplitude compared with the ratio one expects from a point source gives a measure of the angular diameter of the source. Of course, there are various complicating factors that introduce errors in this estimated ratio; two of the most important are evident in the upper trace of Figure 2, in which the maxima display intensity variations due to ionospheric scintillations (twinkling), making it difficult to measure maximum amplitude; the fringes are also often superposed on a slowly varying cosmic background level, which needs to be extrapolated to estimate the height of the minima. In the case of Cygnus-A, we estimated that the source diameter in the direction perpendicular to the horizon was <8 arcmin. The effect of angular size on the minimum fringe amplitude is clearly illustrated in the lower fringe pattern of the rising Sun, using the same antenna at Dover Heights at 100 MHz. Here the angular diameter of the radio Sun is ~0.6° and the fringe spacing was 1.1°. The intensity variations on the fringe maxima here are due to small solar bursts.

In 1947 and 1948 three new sources, Taurus-A, Virgo-A and Centaurus-A, were also detected with the same antenna, but using a much more stable receiver (Bolton, Stanley & Slee, 1949). These three sources were found to be an order of magnitude weaker than Cygnus-A, so that the various complications mentioned above did not permit accurate estimates of angular size other than to state that the mere existence of a clear fringe pattern indicated that their angular diameters were less than say 20 arcmin. Although the sea interferometer was a valuable instrument for detecting sources, it soon became clear that its inherent imperfections would not permit more accurate angular diameter measurements.

3 IMPROVED MEASUREMENTS AT BADGERYS CREEK

In 1952 Bernard Mills erected three 101 MHz broadside arrays at Badgerys Creek, about 45 km west of Sydney. These were Michelson-type interferometers, with three baselines in an E-W direction, and each antenna could be tilted in elevation. One of these antennas can be seen in Figure 3. In a subsequent survey of the southern sky, followed by more accurate position measurements of six of the strongest sources, Mills was able to record many of the sources already isolated at Dover Heights and confirm the optical identifications of three of the strongest sources already proposed by Bolton, Stanley and Slee (1949). At this stage, the Cygnus source remained an enigma (Mills, 1952a; 1952b). However, although Mills utilized baselines up to 300 m in length, he was not able to resolve these sources properly and could only place upper limits of about 10 arcmins on their angular diameters.

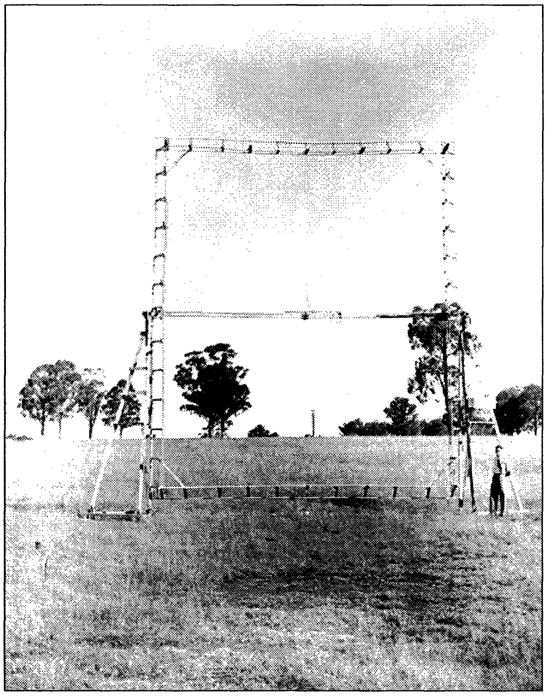

Figure 3: One of the three 101 MHz broadside arrays constructed at Badgerys Creek in 1951. They formed three interferometers with different baselines.

Mills' solution to this problem was to construct a mobile 2-Yagi 101 MHz antenna, from which the source emission was transmitted via a radio link to Badgerys Creek to be combined with the output of one of the broadside arrays. The remote equipment is shown in Figure 4. In order to maintain coherence between the two sites, the remote 101 MHz signal was converted to a higher frequency by beating it with the output of an oscillator of suitable frequency and then both signals were transmitted to Badgerys Creek, where the source signal was down-converted coherently to 101 MHz. During the observations, interferometer fringes for the four strongest sources were obtained for several spacings out to a maximum of 10 km, usually in an E-W direction. These preliminary observations reported by Mills (1952a) were made at the same time that similar measurements of Cygnus-A and Cassiopea-A were under way at Jodrell Bank in England.

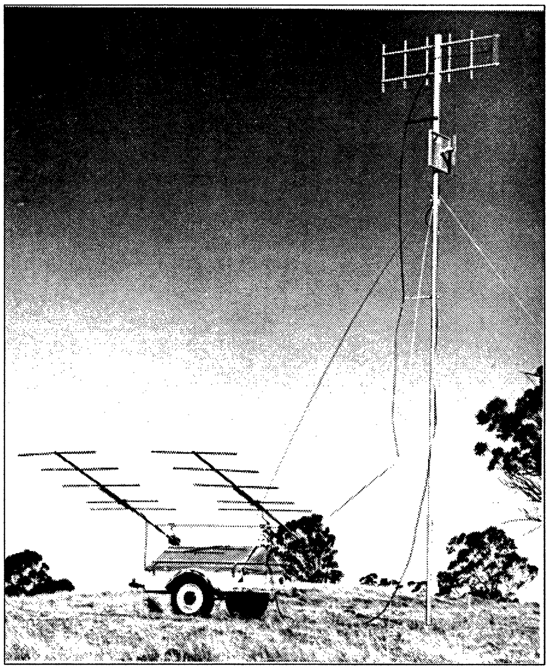

Figure 4: The mobile 101 MHz twin-Yagi antenna with its radio link used for long baseline interferometry at Badgerys Creek in 1952-1953.

The principle of angular diameter measurement with a 2-element interferometer is exactly the same as that for the sea interferometer with the need to measure the peak-peak amplitude of the fringes as a function of the interferometer spacing. At the closest spacing one can assume that the source is unresolved, resulting in a reference 'fringe visibility' of unity. As the spacing increases, the fringe amplitude decreases until eventually the fringe visibility drops to near zero.

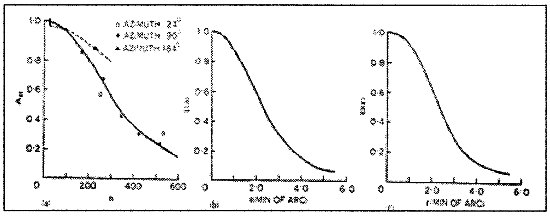

Figure 5: Fringe visibility measurements of Virgo-A from the long baseline interferometer (left-hand curve), and the deduced brightness distribution (right-hand curve).

Figure 5a illustrates fringe visibility measurements for Virgo-A (Mills, 1953) with baselines extending out to 600 λ (wavelengths), or 1.8 km. In order to interpret Figure 5a in terms of the angular diameter from these rather limited data, one must assume a model of how the radio brightness varies across the source. A Gaussian brightness distribution seems a feasible model, and has the advantage of simplifying the mathematics involved in converting the fringe visibility distribution of Figure 5a to the corresponding brightness distribution of Figure 5c. These measurements yielded effective E-W diameters of 4.0, 4.6 and 5.0 arcmin for Taurus-A, Virgo-A and Centaurus-A, while the angular diameter of Cygnus-A was found to be much smaller than 0.75 arcmin.

These relatively large values of angular diameter were the first to show that discrete sources were not necessarily star-like, and were consistent with the angular diameters of the optical objects with which they had been identified (i.e. two galaxies and an historical supernova remnant). It now became possible to estimate their radio brightness temperatures, total emitted powers and linear dimensions, and thus begin to think about probable mechanisms for the radio emission.

4 THE FLEURS–WALLACIA INTERFEROMETER

The Mills Cross was an innovative radio telescope built in 1953-1954 at Fleurs, about 50 km west of Sydney. It consisted of 460 metre-long N-S and E-W arms, each containing 250 dipole elements backed by a wire mesh reflector. By suitably combining the outputs of the two arrays a pencil beam of 49 arcmin resolution at 85.5 MHz could be swung to the required declination and the equipment operated as a transit telescope. Photographs of the crossed arrays, receiver and an example its chart-recorder output are provided by Orchiston (2004). During the main survey for discrete radio sources from 1954 to 1956, ~2,000 radio sources with flux densities above 2 Jy were detected and published in the Mills-Slee-Hill (MHS) Catalogue, but the resolution of the Cross was insufficient to resolve most of them for measurements of angular diameter.

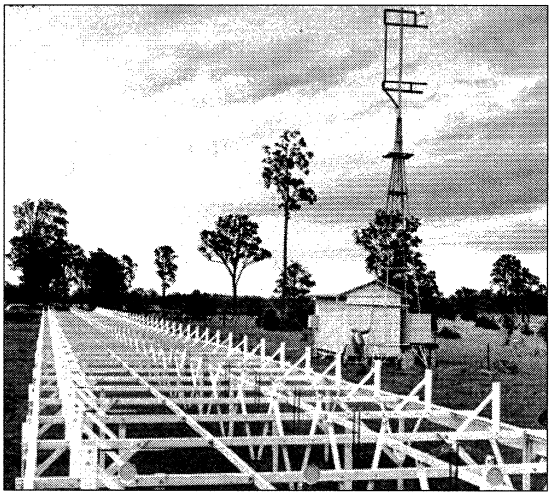

Figure 6: The 85.5 MHz Wallacia array was modelled on the N-S arm of the Mills Cross, and formed part of the Fleurs-Wallacia Interferometer. Adjacent to the equipment hut is the microwave link used to transmit the source signals to Fleurs.

To partially rectify this deficiency it was decided to build a special interferometer with a fixed 10.2 km E-W baseline by replicating a section of the N-S arm of the Mills Cross at Wallacia (see Figure 6), from where the source signals could be coherently transmitted by radio link (as described above in Section 3) to form a long baseline interferometer with the output of the E-W arm of the Cross. A schematic diagram of the interferometer can be seen in Figure 7.

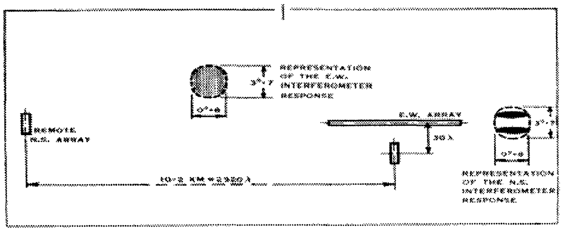

Figure 7: A schematic diagram of the Fleurs-Wallacia Interferometer. See the text, section 4, for further details.

Like all practical interferometers, a zero baseline fringe visibility was established by using a section of the N-S arm of the Cross that was identical to the newly–built array at Wallacia, great care being taken to ensure that these two arrays had very similar gains and phasing arrangements to swing their beams to the same positions in the meridian plane. As explained by Goddard et al. (1960), a determined effort was made to provide auxiliary equipment to stabilize the receiver gains, slow the fringes so that they could be recorded on a chart and to insert lengths of delay line into one or the other signal paths to preserve coherence between the source signals.

Figure 8 illustrates the chart-recorded output from this dual interferometer with the zero baseline (actually 30 λ) interferometer fringes at the top, and the 10.2 km (2,907 λ) fringes at the bottom, providing a fringe spacing of 1.2 arcmin at the zenith. The fringe visibility is simply the ratio of the maximum amplitudes in the lower and upper traces, providing one point on the E-W brightness distribution across the source. As explained in Section 3, one can compute an angular diameter from this meagre information by assuming that the source has a Gaussian brightness distribution. The left hand patterns show an unresolved quasar, while the almost completely resolved radio galaxy, Hydra-A, gave the patterns on the right. The equipment provided usable values of angular diameter from ~10 to 60 arcsec for about 1,000 sources in the MSH Catalogue.

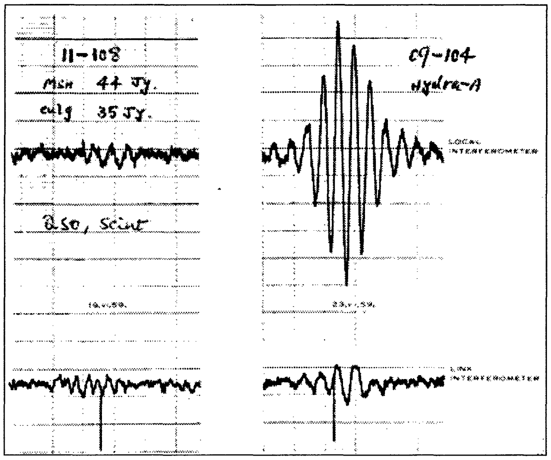

Figure 8: A sample of fringes from the Fleurs-Wallacia Interferometer. The quasar on the left is unresolved, while the radio galaxy on the right is almost completely resolved. The upper trace for each source shows the fringes from a very short reference baseline.

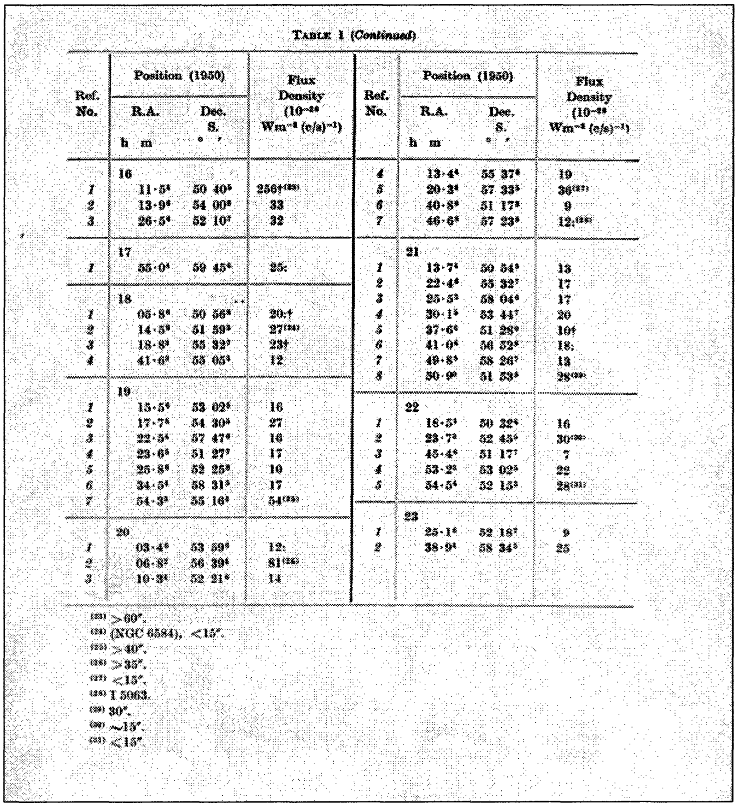

TABLE 1 (Continued)

Ref. No.	Position (1950) R.A. h m	Position (1950) Dec. S. ° ′	Flux Density (10^{-26} Wm^{-2} (c/s)$^{-1}$)
	16		
1	11·5^{4}	50 40^{5}	256†$^{(23)}$
2	13·9^{4}	54 00^{9}	33
3	26·5^{4}	52 10^{7}	32
	17		
1	55·0^{4}	59 45^{6}	25:
	18		
1	06·8^{6}	50 56^{8}	20:†
2	14·5^{9}	51 59^{3}	27$^{(24)}$
3	18·8^{3}	55 32^{7}	23†
4	41·6^{3}	53 05^{4}	12
	19		
1	15·5^{6}	53 02^{8}	16
2	17·7^{8}	54 30^{5}	27
3	22·5^{4}	57 47^{6}	16
4	23·6^{5}	51 27^{7}	17
5	25·8^{6}	52 25^{8}	10
6	34·5^{4}	58 31^{5}	17
7	54·3^{3}	55 16^{4}	54$^{(25)}$
	20		
1	03·4^{8}	53 59^{6}	12:
2	06·8^{2}	56 39^{4}	81$^{(26)}$
3	10·3^{4}	52 21^{6}	14
4	13·4^{4}	55 37^{6}	19
5	20·3^{4}	57 33^{5}	36$^{(27)}$
6	40·8^{6}	51 17^{8}	9
7	46·6^{8}	57 23^{6}	12:$^{(28)}$
	21		
1	13·7^{4}	50 54^{6}	13
2	22·4^{4}	55 32^{7}	17
3	25·5^{3}	58 04^{6}	17
4	30·1^{5}	53 44^{7}	20
5	37·6^{8}	51 28^{6}	10†
6	41·0^{4}	56 52^{8}	18:
7	49·8^{5}	58 26^{7}	13
8	50·9^{9}	51 53^{4}	28$^{(29)}$
	22		
1	16·5^{4}	50 32^{4}	16
2	23·7^{3}	52 45^{6}	30$^{(30)}$
3	45·4^{6}	51 17^{7}	7
4	53·2^{3}	53 02^{5}	22
5	54·5^{4}	52 15^{3}	28$^{(31)}$
	23		
1	25·1^{6}	52 18^{7}	9
2	38·9^{4}	58 34^{5}	25

(23) >60″.
(24) (NGC 6584), <15″.
(25) >40″.
(26) >35″.
(27) <15″.
(28) I 5063.
(29) 30″.
(30) ~15″.
(31) <15″.

Figure 9: A page of the MSH Catalogue with footnotes showing the angular diameters measured with the Fleurs-Wallacia Interferometer.

The results of this survey were never published as a complete catalogue, but appeared in footnotes to the last two editions of the MSH Catalogue or were used in special investigations of smaller groups of sources. A page of the third edition of the MSH Catalogue can be seen in Figure 9. The angular diameter measurements from this interferometer showed clearly that most of the sources with 85.5 MHz flux densities >20 Jy were at least partially resolved, except that the quasars among them had angular diameters of <10 arcsec. This result, together with concurrent similar measurements at Jodrell Bank, showed that quasars possessed brightness temperatures at least three orders of magnitude higher than those of the sources that were resolved in Mills' experiment at Badgerys Creek.

5 CORONAL SCATTERING OBSERVED WITH THE FLEURS-WALLACIA INTERFEROMETER

Independent discoveries by Hewish (1956) and Slee (1956) of the scattering of radiation from the source Taurus-A as it passed close to the Sun stimulated further research by Slee (1959) at Fleurs using an interferometer consisting of the N-S arm of the Mills Cross and a pair of helical antennas only 63 λ (220 m) to the east of the centre of the Cross. For the three days of closest approach to the Sun, the amplitude of interference fringes from Taurus-A dropped to practically zero, suggesting that electron density fluctuations of relatively small scale size in the far-outer corona scattered the 85.5 MHz radiation and increased its apparent angular diameter to such an extent that the source was completely resolved. Such information permitted estimates of both the scale size of the scattering irregularities and their electron density, and suggested a method of probing the solar corona out to even larger distances from the Sun.

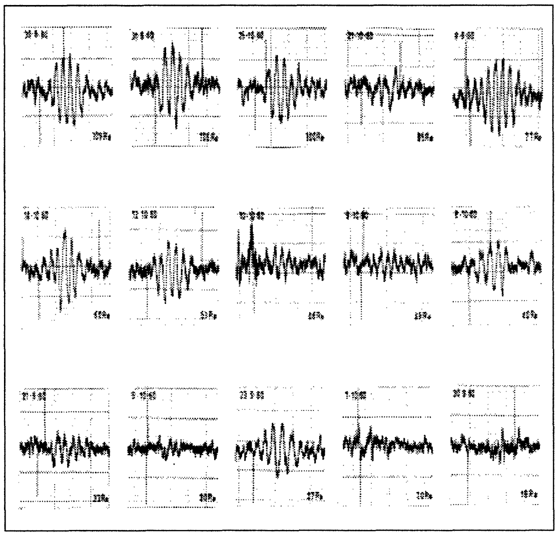

Figure 10: Fringes from the quasar 3C 273, recorded by the Fleurs-Wallacia Interferometer as the source passed the Sun at various angular separations. Each record was obtained during the transit time of the source through the 50 arcmin beam of the E-W arm of the Cross.

From June to October 1960, after completing the survey described in Section 4, the Fleurs-Wallacia Interferometer was used to measure the scattering suffered by thirteen small-diameter radio sources as they passed the Sun at a variety of angular separations of closest approach. The daily sets of fringes from the quasar 3C 273 with the 10.2 km spaced interferometer are shown in Figure 10, which omits the reference fringe patterns seen in Figure 8. This figure illustrates the effectiveness of a long baseline interferometer to resolve out the potentially-confusing effects of a source of large angular diameter such as the Sun, and permit the relatively weak fringes of the discrete sources under study to show through with minimum disruption. It is clear from Figure 10 that the amplitude of the fringe pattern is systematically reduced, sometimes to zero, when 3C 273 is within 50 solar radii.

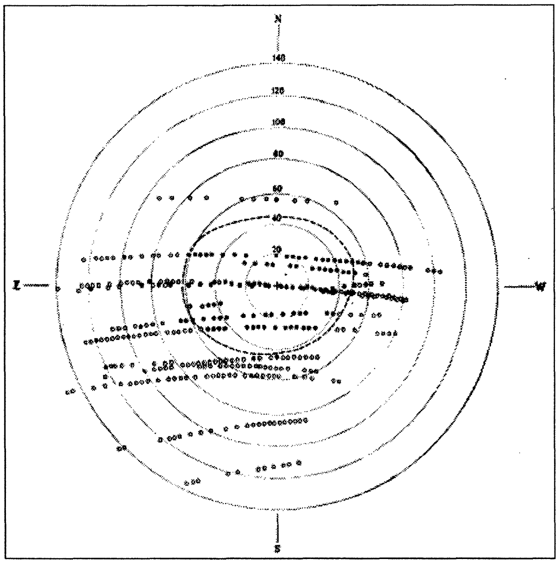

Figure 11: An outline of the Sun's scattering corona at 85.5 MHz, formed by recording daily transits of thirteen sources as they passed the Sun at varying angular distances. The filled circles denote transits with significantly-reduced fringe amplitudes.

A summary of the results for all thirteen sources can be seen in Figure 11, which indicates that in 1960 the Sun's 85.5 MHz scattering corona, as defined by the filled circles, could be traced out to 60 solar radii in the Sun's equatorial region, but only to about 40 solar radii in the polar direction. There were one or two occasions when detectable angular broadening was recorded out to 100 solar radii in the equatorial region. This study was the first to show the real extent of the scattering corona, and to suggest that, because the angular scattering increases as the square of the wavelength, it should be possible to trace the corona out beyond the Earth's orbit if a low-enough frequency could be employed. This subject was revisited in the Jovian interferometry that is described below in Section 7.

6 INTERFEROMETRY WITH A BARLEY-SUGAR ARRAY

It had been possible to estimate rough angular diameters or at least their upper limits in the Fleurs-Wallacia experiment, but the next ambitious project centred on Fleurs as the home site was intended to survey sources in the MSH Catalogue with four baselines ranging between 1800 and 9200 λ. It was hoped to obtain more details of angular structure, e.g. the presence of double sources, and to improve the angular resolution by almost a factor of three. Even if some sources were still unresolved, the reduced upper limits to angular diameter would be very useful in estimating the high brightness temperatures and small linear sizes of quasars and the active nuclei of galaxies.

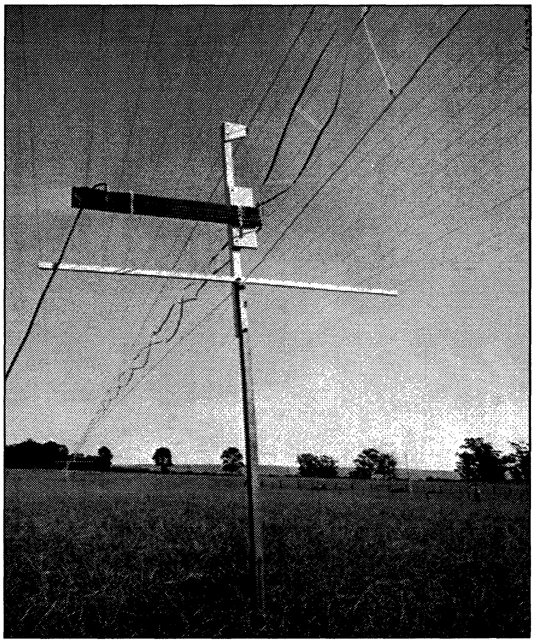

Figure 12: One of the four barley-sugar antennas used in the N-S long baseline interferometer. More details are given in the text of Section 6.

The success of the experiment depended upon constructing a portable antenna of relatively large collecting area, which could be erected and dismantled within a few days for use at the four selected remote sites. The adopted design (Scheuer et al., 1963) consisted of a twisted, very leaky, open-wire transmission line known colloquially as a 'barley sugar', which was aligned E-W above an open-wire reflector. One of these barley-sugar antennas is shown in Figure 12. Four such antennas were placed parallel to each other to form a diffraction grating, which produced four beams spaced at intervals of 10 arcmin along the N-S meridian; each of these beams had a width of 50 arcmin E-W and 2.5 degrees N-S. The beam of each barley-sugar, 50° in the N-S direction, approximated the N-S beamwidth of the E-W arm of the Fleurs Cross, and was tilted with respect to the zenith, the direction of tilt being controlled by the sense of twist of the leaky feeder. Thus the observing at each remote site was divided into two sessions so that the barley-sugar beams could be swung to cover the whole declination range of the MSH survey. A similar operation was needed to swing the beam of the E-W arm of the Mills Cross. The four barley-sugar antennas were connected in phase to an 85.5 MHz receiver whose output was transmitted to Fleurs by a radio link.

The signal from the remote site was multiplied with the output from the E-W arm of the Mills Cross, as shown schematically in Figure 13. Each of the four multipliers accepts a signal from the E-W arm of the Cross that has been subjected to a delay which will maximize the coherence between the remote and local signals from sources within one of the barley-sugar diffraction beams shown on the right of Figure 13. The four multiplied outputs were recorded simultaneously on dual-pen chart recorders. Using this interferometer, the sky between +10 and −80° declination was surveyed at each of the baselines, and the observations were completed in the eighteen months between January 1961 and June 1962.

Paradoxically, the results of this innovative survey were never published. Chart recordings of interference fringes from three partially-resolved sources shown in Figure 14 were published by Scheuer et al. (1963) in a paper dealing with the design of the barley-sugar array and the principle of operation of the final interferometer. The fringes in Figure 14 demonstrate that very useful angular size information could have been derived for many sources. In fact, the observations were partially reduced and the whole set of chart recordings removed to Cambridge, where they languished untouched for the next forty years. Scheuer et al. reported a rather subjective summary of the results available in 1963 as follows:

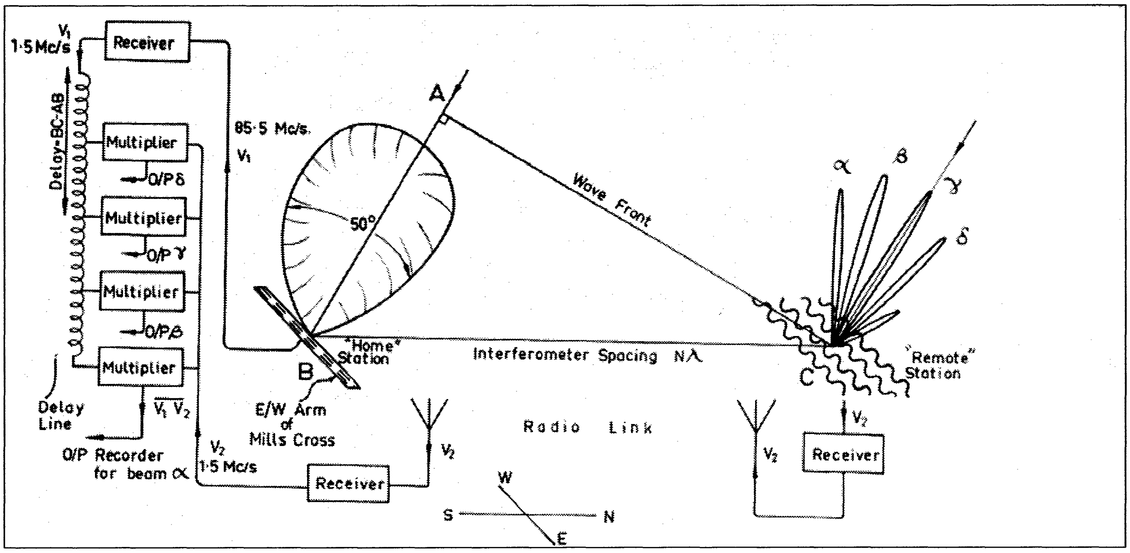

Figure 13: A schematic diagram of the barley-sugar–EW Mills Cross arm interferometer. See Section 6 for more details.

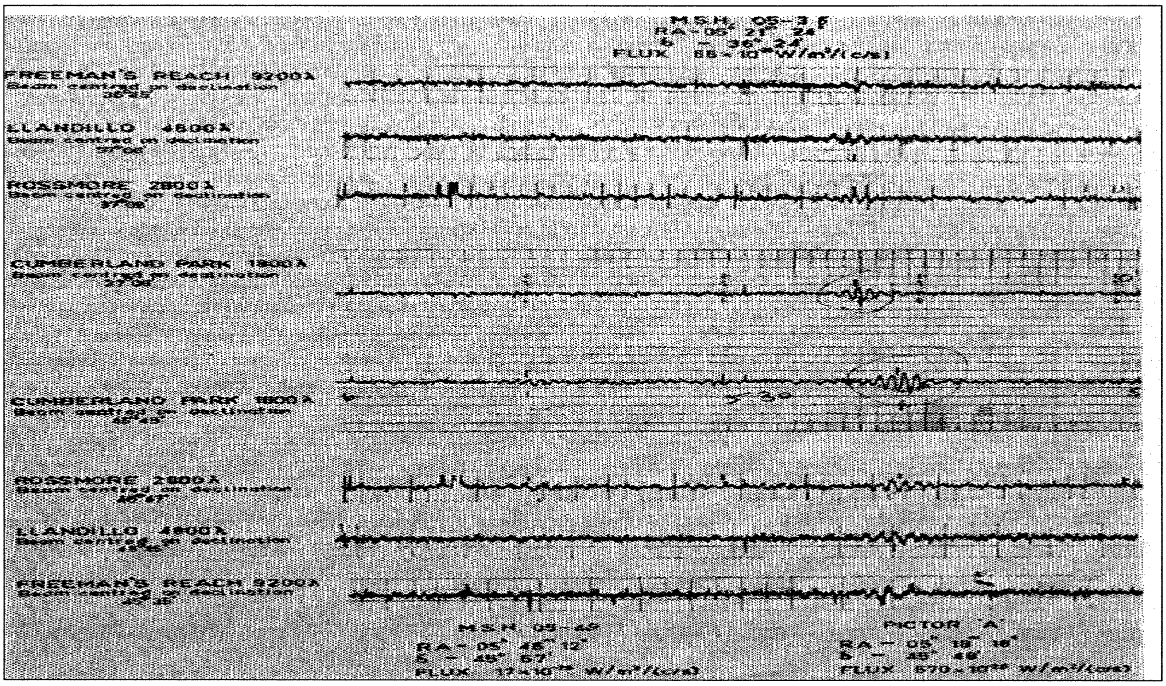

Figure 14: The only published fringes from the barley-sugar–EW-arm interferometer. The upper four traces depict the fringes from the N-galaxy PKS J0522-3627, which is almost completely resolved at the longest spacing. The four lower traces on the right side show the fringes from the strong radio galaxy Pictor-A; even on the shortest spacing, the source is highly resolved, leaving mainly the fringes from the weak core in the galaxy. The four traces at lower left show fringes from one of the weakest sources to yield fringes (MSH 05-49) with flux density of 17 Jy; this is clear on the shortest baseline, but well-resolved on the longest spacing.

> In agreement with the results obtained in the Jodrell Bank experiment, we find that the number of sources detected decreased rapidly as the baseline was increased; at our greatest spacing 9200 λ, only about 50 sources are visible and, except in a few cases, these all showed signs of being resolved. Hence, at this stage it seems possible to state that the great majority of sources having flux densities greater than 15 Jy have overall dimensions greater than 10"arc. The detailed results and their interpretation will be published in later papers.

7 DECAMETRIC INTERFEROMETRY OF JUPITER

Jovian decametric bursts were discovered serendipitously by Burke and Franklin in the USA in 1955 and subsequently confirmed by Shain (1956), who had in fact recorded 18.3 MHz burst-like emission at the Hornsby field station of Radiophysics as early as 1950, but had dismissed it as terrestrial interference (see Orchiston and Slee, 2005). Subsequent observations both in the USA and Australia established that the burst emission occurred when specific Jovian longitudes were facing the Earth and particularly when the major Jovian satellite, Io, was in certain positions relative to Jupiter. The bursts are usually of 1-2 seconds duration (occasional milli-second structure is also recorded) and are highly circularly polarized. The intensity of the bursts can often approach that of solar bursts in the decametric band. It had become clear by the early 1960's, that we were observing a non-thermal phenomenon that involved strong magnetic fields and charged particles in Jupiter's magnetosphere and, somehow, the generating mechanism was strongly influenced by the passage of Io through that medium. A parameter of particular interest was the angular sizes of the decametric source because this would determine the brightness temperature and linear size of the emitting region and lead perhaps to a physical model. Clearly, such a measurement could only be made with an interferometer of long baseline since the burst source could not be resolved on the short baselines then available such as the Shain Cross, which was constructed at Fleurs in the mid 1950's to primarily make a galactic survey at 19.7 MHz, but was also used extensively to make transit observations of Jupiter.

The Division of Radiophysics decided in 1963 to invest some effort into solving this problem, and we made some tests with a 19.7 MHz interferometer over the longest baseline used in the experiment described in Section 6. Using a lash-up of the existing radio link and various pieces of Shain's 19.7 MHz receiver, Slee and Higgins (1963) showed that it was feasible to record stable fringes over a 32.3 km baseline on winter nights when the ionospheric electron densities were lowest and terrestrial interference was infrequent. The fact that the Jovian bursts are almost 100% circularly polarized overcomes the problem of ionospheric Faraday rotation, which can cause serious fading of linearly-polarized and unpolarized signals.

In 1963 we set up a small field station on a mountain top near Jamberoo, 85.5 km south of Fleurs (see Figure 15), and moved a major part of Shain's 19.7 MHz equipment (some of it modified for this experiment) to the new site. We decided to make Jamberoo the home-site, where the signals from the ends of the three intended baselines would be multiplied and recorded. At the same time, a mobile laboratory (mounted in a disused bus) was constructed for use at the three proposed remote sites at Dapto, Fleurs and Heaton. The mobile laboratory contained a 19.7 MHz receiver with the same sophisticated gain control circuits that we had used in the interferometers described in Sections 4, 5 and 6. The receiver was connected at each site to a simple 4-dipole square array, in which the elements could be phased to respond to the circular polarization from Jupiter, which remained in the antenna beam for up to four hours around transit. A radio link, which preserved the coherence of the Jovian signal, transmitted the bursts from the remote site to the home station where they were multiplied by the appropriately-delayed home signals and the resulting fringes displayed on a dual-pen chart recorder. At the same time, one needed to monitor ionospheric scintillations by recording the total powers (unmultiplied signals) from the two sites on an identical dual-pen recorder.

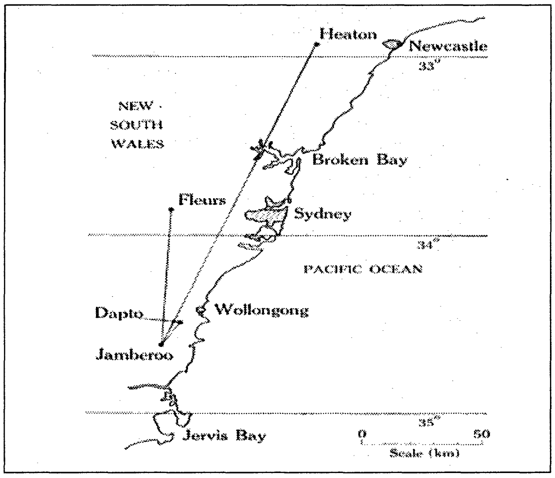

Figure 15: A map of the region near Sydney showing the three baselines used in Jovian decametric interferometry. The longest baseline of 200 km between Jamberoo and Heaton yielded a fringe spacing of 15.7 arcsec at 19.7 MHz.

Most of our recording was done during the apparitions of 1963-1964, when Jupiter was near the zenith at transit in the hours between midnight and dawn, when terrestrial interference via the ionosphere was negligible. The results were reported in two papers by Slee and Higgins (1966; 1968). Figure 16 is a good example of a highly-correlated sequence of bursts over the longest 200 km baseline, the upper pair of traces showing the sine and cosine components of the interferometer fringes (one set of fringes fills in the zero responses of the other), as well as the total powers from the separate sites in the lower two traces.

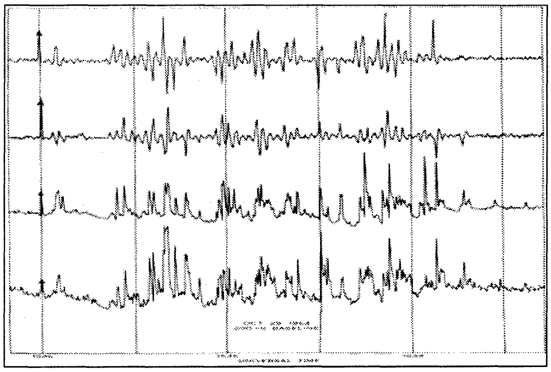

Figure 16: Fringes (upper pair of traces) and total powers (lower pair) recorded at 19.7 MHz over the 200 km baseline. See the text, Section 7, for further explanation.

Not all recordings showed this high degree of correlation, because of the presence of ionospheric scintillation (radio twinkling), which can suppress the intensity of the signal at one site while increasing it at the other, but the regularity (phase) of the fringe pattern is usually unaffected. An example of a marked scintillation occurs in Figure 16 near 15:45:15 UT.

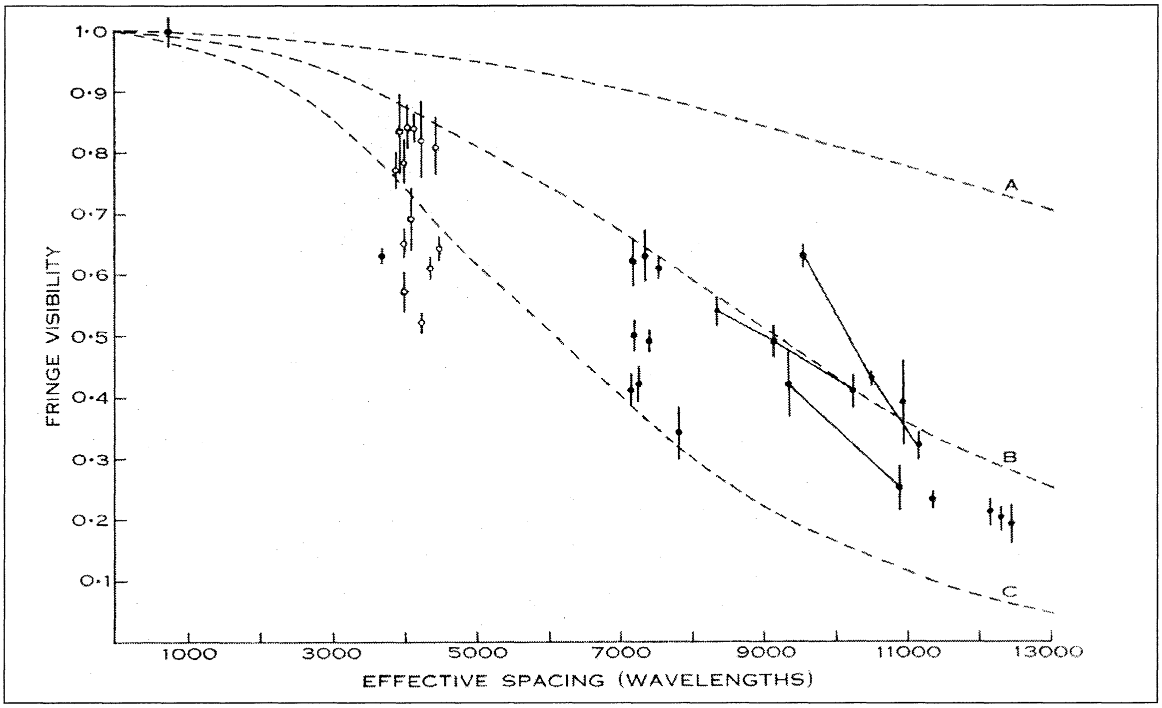

Figure 17: Plot of the fringe visibilities deduced from recordings such as shown in Figure 16. Each point represents an average for a nightly noise storm, except the points joined by straight lines, which indicate very extended noise storms.

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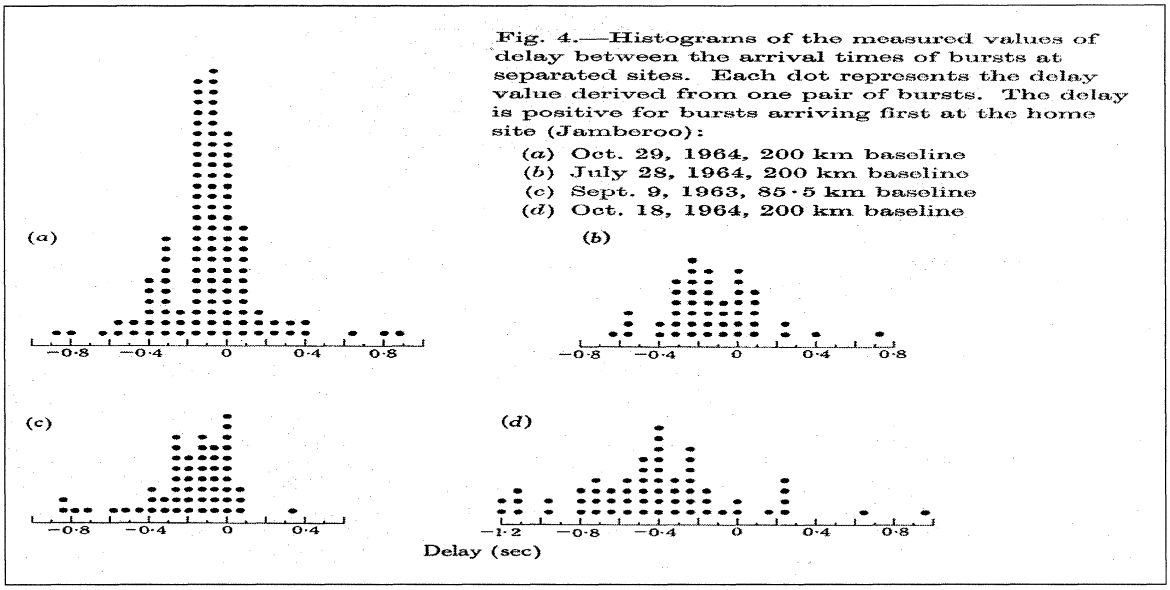

Figure 18: Measurements of the differences in arrival time of individual bursts at the ends of the baseline on four nights. The perceived negative average values indicate that the burst arrives first at the outstation. Further explanation is given in the text of Section 8.

The ratio of the fringe amplitude on the upper two traces to the total power amplitudes is a measure of the fringe visibility, which, as we have seen, can be transformed to an angular diameter by assuming a Gaussian brightness distribution over the source. Figure 17 shows the results from all effective observations with the three baselines in 1963-1964. The fringe visibility scale was calibrated by the fringes recorded over the shortest baseline of 17.4 km between Jamberoo and Dapto, when one extended storm gave strong correlated bursts and fringes. The dashed lines A, B and C in Figure 17 show the expected responses from Gaussian sources with angular diameters of 5, 10 and 15 arcsec respectively; it is clear that the observed angular diameters fell in the range 10 to 20 arcsec. An angular source diameter of 10 arcsec implies a linear diameter at Jupiter of about 40,000 km. (i.e. one quarter of Jupiter's diameter), but Slee and Higgins (1966) advanced several reasons for questioning the validity of this result for the intrinsic diameter of the source, and three years later (Slee and Higgins, 1968) extended their analysis of the 1963-1964 measurements to claim that both the bursts themselves and the measured angular sizes were due to scattering of a much steadier decametric source by turbulence in the solar wind.

Slee and Higgins, using twelve Jovian noise storms with well-correlated total power bursts at each end of the two longer baselines, measured the difference in arrival time of each burst at the two sites. The results from these measurements are illustrated in four noise storms in Figure 18, which showed decisively that in these four storms the bursts had a strong tendency to arrive first at the remote site by an average of 0.2 to 0.4 seconds. The average delays for the twelve storms varied between 0.08 and 0.41 seconds. Considerations of the geometry of the Earth, Sun and Jupiter with respect to the orientation of the interferometer baseline and the ecliptic led to the conclusion that the Jovian 'bursts' were in fact 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. This also naturally explained the relatively large measured angular diameters of 10-20 arcsec.

Our Jovian experiment had therefore failed to measure the intrinsic source diameter, but it had provided valuable information about the solar wind in the interplanetary space between the Earth and Jupiter. Our results were later confirmed by measurements of relative burst arrival times by Douglas and Smith (1967). A valuable piece of information about the Jovian source itself was that its intensity changes were at least two orders of magnitude slower than had been formerly believed; the emission seen in Figure 16 over an interval of two minutes is probably more like the intrinsic emission interval. Later experiments on the rarer millisecond bursts by Slee and Gent (1967) showed that they were unconnected to the interplanetary medium and were likely to be the intrinsic form of the emission coming from sources of very small angular size. It is now generally accepted that the source is an electron-cyclotron maser set up by the induced EMF formed by the passage of Io through Jupiter's magnetosphere.

8 CONCLUDING REMARKS

The interferometer observations made at the various field stations of the Division of Radiophysics during the interval 1947 to 1964 provided basic physical data on a wide range of sources. During this seventeen year interval, the highlights of the observing projects were:

- The first discrete radio sources were isolated from the galactic background with the sea interferometer at Dover Heights, and upper limits to their angular diameters were measured.
- More detailed measurements of the brightness distributions across the stronger sources were

made with a long baseline Michelson interferometer at Badgerys Creek.

- One of the first surveys of crude angular diameters of a complete sample of sources from the MSH Catalogue was completed with the Fleurs–Wallacia Interferometer.
- The first mapping of the scattering properties of the Sun's outer corona was made with the Fleurs–Wallacia Interferometer.
- An extensive interferometer survey of the MSH sources with a portable barley-sugar array and E-W arm of the Mills Cross was conducted; the four N-S baselines out to 32 km in length were used to improve the angular resolution by a factor of three.
- The first LBI on Jovian decametric emission was made over three baselines with lengths up to 200 km; these observations were the first to demonstrate that the so-called Jovian bursts were actually scintillations caused by scattering in interplanetary space.

During the late-1960s and through the 1970s and 1980s more sophisticated interferometry with dishes at Fleurs and Parkes, operating at higher frequencies, obtained more detailed brightness distributions for many sources. The epoch of field-station interferometry with specialized metre-wave arrays ended in 1964. This was followed by the 'big-science' experiments introduced by the 408 MHz Molonglo Cross, the 64-m Parkes Radio Telescope, the 1420 MHz Fleurs Synthesis Telescope and the 3-km circular array at Culgoora. Later, the 843 MHz Molonglo Synthesis Telescope and multi-wavelength Australia Telescope synthesis array were constructed, and they were still operating in 2005.

Although similar metre-wave and decimetric interferometry began in Cambridge and at Jodrell Bank in the early 1950s and was followed by the Owens Valley (California) interferometry of the early 1960s, the early Australian experiments at the Radiophysics field stations played a significant role in establishing some of the basic parameters of the stronger sources. The most notable of these properties included their radio spectra, and brightness temperatures, and, after optical identifications and redshifts were established, their total power outputs and linear sizes. The stage was set for the amazing plethora of discoveries that have continued to be made with 'big-science' instruments right up to the present time.

9 ACKNOWLEDGEMENTS

I am grateful to the Australia Telescope National Facility for supplying the figures for this publication and to Wayne Orchiston for his encouragement and a critical reading of the manuscript.

10 REFERENCES

Bolton, G.J., and Slee, O.B., 1953. Galactic radiation at radio frequencies. V. The sea interferometer. *Australian Journal of Physics*, 6, 420-433.

Bolton, J.G., and Stanley, G.J., 1948. Observations on the variable source of cosmic radio frequency radiation in the constellation of Cygnus. *Australian Journal of Scientific Research*, A1, 58-69.

Bolton, G.J., Stanley, G.J., and Slee, O.B., 1949. Positions of three discrete sources of Galactic radio-frequency radiation. *Nature*, 164, 101-102.

Douglas, J.N., and Smith, H.J., 1967. Interplanetary scintillation in Jovian decametric radiation. *The Astrophysical Journal*, 148, 885-903.

Goddard, B.R., Watkinson, A., and Mills, B.Y., 1960. An interferometer for the measurement of radio source sizes. *Australian Journal of Physics*, 13, 665-675.

Hewish, A., 1955. The irregular structure of the outer regions of the solar corona. *Proceedings of the Royal Society*, A228, 238-251

Mills, B.Y., 1952a. Apparent angular sizes of discrete radio sources. Observations at Sydney. *Nature*, 170, 1063-1064.

Mills, B.Y., 1952b. The positions of six discrete sources of cosmic radio radiation. *Australian Journal of Scientific Research*, A5, 456-463.

Mills, B.Y., 1953. The radio brightness distributions over four discrete sources of cosmic noise. *Australian Journal of Physics*, 6, 452-470.

Orchiston, W., 2004. From the solar corona to clusters of galaxies: the radio astronomy of Bruce Slee. *Publications of the Astronomical Society of Australia*, 21, 23-71.

Orchiston, W., and Slee, B., 2005. Shame about Shain! Early radio astronomy at Hornsby Valley. *ATNF News*, 55, 14-16.

Scheuer, P.A.G., Slee, O.B., and Fryar, C.F., 1963. Apparatus for investigating the angular structure of radio sources. *Proceedings of the Institute of Radio Engineers Australia*, 24, 185-190.

Shain, C.A., 1956. 18.3 Mc/s radiation from Jupiter. *Australian Journal of Physics*, 9, 61-73.

Slee, O.B., 1956. Occultation of a radio source by the solar corona. *The Observatory*, 76, 228-231.

Slee, O.B., 1959. Occultations of the Crab Nebula by the solar corona in June 1957 and 1958. *Australian Journal of Physics*, 12, 134-156.

Slee, O.B., and Gent, H., 1967. Decametric radio emission from Jupiter". *Nature*, 216, 235-238.

Slee, O.B., and Higgins, C.S., 1963. Long baseline interferometry of the Jovian decametric radio bursts. *Nature*, 197, 781-783.

Slee, O.B., and Higgins, C.S., 1966. The apparent sizes of the Jovian decametric radio sources. *Australian Journal of Physics*, 19, 167-180.

Slee, O.B., and Higgins, C.S., 1968. The solar wind and Jovian decametric radio emission. *Australian Journal of Physics*, 21, 341-368.

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Journal of Astronomical History and Heritage, 8(2), 107-121 (2005).

THE CONCEPT AND EVALUATION OF TEMPERATURE IN THE HISTORY OF ASTRONOMY

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Abstract: On a typical astronomical day we can gaze at the solar disc and see a 5,776 K gas radiating into space. Come night-time we are confronted with a panoply of stars with surface temperatures between 2,750 and 45,000 K, and maybe our Moon with a sub-solar-point temperature of around 410 K, and planets Jupiter and Saturn with cloud temperatures of around 150 and 110 K. On an unusual astronomical day we might experience a solar eclipse and catch a fleeting glimpse of the solar corona with its temperature of 2,500,000 K. Temperature is now recognised as a key astronomical parameter and much is learnt from its influence on the phase of astronomical materials and the radiation that they emit. But temperature is a very recent addition to the astronomical data base. Before the 1830s it was barely mentioned. Only since around 1900 have our estimates of astronomical temperatures born any relationship with reality. This paper reviews our concept of temperature in the recent history of our subject.

Keywords: Sun, stars, planets, temperature

1 INTRODUCTION

Today we often talk about how hot and cold things are, and we can go further, and quantify our impression using thermometers and temperature scales. But in the history of astronomy ‘temperature’ is a relatively new concept. The thermometer was invented at about the same time as the telescope. In fact many point to Galileo as the pioneer of both instruments, and recognise his air-thermoscope, constructed in about 1592, as being the first thermometer (see Wolf, 1968: 83). As the seventeenth and eighteenth centuries progressed, the invention of an alcohol-in-glass thermometer in 1709, and a commercially successful mercury-in-glass thermometer in 1714, both by Gabriel Daniel Fahrenheit (1686–1736), plus the introduction of the Fahrenheit, Réaumur and Celsius temperature scales, in 1714, 1730 and 1742 respectively, put the subject on a firmer footing. Measuring temperature on Earth, where the thermometer can be put *into* the substance of interest, and a direct physical contact can be made, is clearly much easier than measuring the temperature of astronomical objects, where the enquirer and the object of interest are separated by distances measured in astronomical units and parsecs.

Temperature is an extremely important astronomical parameter. Temperature governs the rate at which chemical and nuclear fusion reactions occur. The production of stellar energy by the conversion of say hydrogen into helium, and helium into carbon only occurs if the internal temperature of a star is above a specific value. The amount of energy that is released increases drastically as a function of the temperature at which the reaction takes place. Temperature is of paramount importance when it comes to assessing the state of the surfaces, atmospheres and interiors of astronomical bodies. It has a huge effect on the phase of a substance. Increase the temperature and the material transforms from being a solid, into a liquid, a gas and eventually into a plasma. Near to home it was this thermally-induced phase change that was the major factor leading to the division of the Solar System into an inner hot rocky terrestrial region surrounded by a cooler outer gas-giant planetary region. The effect of temperature on the rates at which stars and planets evolve is enormous. The colour of a radiating body varies drastically with temperature, as does the amount of energy it emits. And as the degree of excitation and ionisation of the elements in a star’s atmosphere varies as a function of temperature, the absorption and emission spectra produced by stellar material change as the temperature changes.

Planetary rock becomes more viscous as the temperature decreases and this has a profound effect on plate tectonics. As the Earth cools, the crustal plates will move more and more slowly, mountain production will lessen, and eventually volcanism and atmospheric renewal will cease. Temperature is a key parameter when it comes to ascertaining whether a planet can retain an atmosphere. It is also a major influence on the composition and extent of an atmosphere, the formation, heights and compositions of clouds, the amount of precipitation and the severity of winds and mixing processes. The interior temperature of a planet governs whether that planet becomes differentiated, and, if differentiated, whether magnetic fields are generated or not.

Moving to the cosmos, the temperature of the background radiation in the Universe and its spatial variability provide vital clues as to the form of early cosmological processes. The temperature of the primordial gas cloud affected the masses of the galaxies that could be produced. Also the temperature of giant molecular clouds in our Galaxy governs whether or not they can condense to form clusters of stars, and, assuming that they can, affects the distribution of stellar masses in those clusters. Here we are witnessing a conflict between the contraction governed by gravitational energy and the expansion controlled by thermal pressures.

Considering the influence of temperature on the large range of astronomical processes mentioned above, it is rather surprising that the concept of temperature only became a matter of astronomical concern in the mid-nineteenth century. Four factors are thought to be significant.

(A) The first is simple natural curiosity. As the science of physics developed, and laboratory instrumentation became more and more sophisticated, astronomy (the study of stellar and planetary positions and motions) was influenced by the new discipline of astrophysics (the measurement of the physical and chemical parameters of astronomical objects and the theoretical investigation of the processes that lead to these parameters). Let us take the Sun as an example. The early astronomer was quite happy just working out where the Sun was and how it rose and set and moved across the sky. Orbits, distances and timings were the matters of greatest concern. The astrophysicist, however, was interested in measuring such solar parameters as radius, mass, composition, surface temperature, age, variability and energy output. Furthermore, astrophysicists investigated why the Sun had these specific parameters and how they were inter-related; and then attempted to compare and contrast our Sun with other stars in the sky. During the dawn of astrophysics, astronomers tried to estimate the surface temperature of the Sun, the power radiated by the surface, and the physical and chemical processes that might be responsible for the long-term production of solar energy.

The measurement of solar surface temperature is a three-stage process. First one measures the so-called 'Solar Constant', the flux of solar energy passing through unit area perpendicular to the Earth-Sun vector per unit time at the Earth's orbit. In 1838, Claude Sevais M. Pouillet (1790–1868) used his pyreheliometer to measure the solar energy flux at the Earth's surface. The variability as a function of solar zenith angle enabled this flux to be converted into a value for the 'out-of-atmosphere' Solar Constant (see Hughes, 1994). Pouillet found this to be 1.44 kW m^{-2}, close to the modern value of about 1.37 kW m^{-2}. Knowledge of the Earth-Sun distance (see Hughes, 2001) then leads to an estimation of the power radiated by unit area of the solar surface. Pouillet's value was 69.3 MW m^{-2}. The final step is to relate this power to the temperature of the surface, using the relevant radiation laws. Unfortunately the relevant law was not known at the time. In 1838 Pouillet concluded that the solar surface had a temperature at least 1,461° C. This was the first astronomical temperature to be measured with any degree of rigor. In fact it was the first extraterrestrial temperature to be quoted in an astronomical paper.

(B) In the late 1840s the temperature of astronomical objects became an even more serious topic of investigation. By this time it was realised that energy was conserved in physical and chemical processes. In the following decades James Clerk Maxwell (1831–1879) and Ludwig Boltzmann (1844–1906) developed the kinetic theory of gasses, a theory of vital importance in stellar modelling. The universality of the law of the conservation of energy was only accepted by the majority of physical scientists after the experimental demonstration, in 1847, of the equivalence of mechanical work and heat, by James Joules (1818–1889). Further independent support was provided by R.J. Mayer (1814–1878) and Hermann von Helmholtz (1821–1894) (see Richtmyer, Kennard and Lauritsen, 1955: 32). The concept of converting potential and kinetic energy into thermal energy lay at the heart of the contemporary quest for the source of stellar energy.

The kinetic theory of gasses provided the first sound definition of the term 'temperature', and the absolute temperature scale. A substance in equilibrium had an absolute temperature, T K, that was directly proportional to the average kinetic energy of one of its molecules. The relevant equation was

$$\frac{1}{2}mv^2 = \frac{3}{2}kT \qquad (1)$$

where m is the mass of a the molecule, v^2 is the mean of the squares of the molecular velocity (averaged over time) and k is Boltzmann's constant (1.38×10^{-23} J K^{-1}). An expression similar to this was first published by Maxwell (1871: 295).

(C) The subject was revolutionised by the introduction of two empirical laws that expanded the definition of temperature and enabled the temperature of remote objects to be easily estimated. In 1879 Josef Stefan (1835–1893) suggested that the total energy radiated by a black body per unit time was proportional to the fourth power of the absolute temperature of its surface. This law was in stark contrast to Isaac Newton's much earlier law of cooling. Newton's law applied to convection, Stefan's to radiation. Newton noted that the forced convective heat loss by a body immersed in a fluid was proportional to the temperature difference between the body and the fluid. As the vast majority of astronomical objects are isolated (i.e. essentially in a vacuum) and not 'immersed in a fluid', the laws of energy radiation are of paramount importance. It is only in the interiors and surface regions of stars, planets and satellites that convection and conduction becomes significant. The difference between convection and radiation is not too important when the temperature difference between the body and its surrounds is small. Newton's law becomes very problematical when incorrectly applied to radiating bodies with much greater temperatures than their surroundings.

The second empirical law was introduced in 1893 by Wilhelm C.W.O.F.F. Wien (1864–1928). He suggested that the wavelength at which the radiated energy maximises is inversely proportional to the absolute temperature of the radiator. The colour of a radiating body is thus a function of its surface temperature. At a stroke, stellar spectral classification became physically meaningful. Stars of spectral class M appear to be 'red', K orange, G yellow, F creamy, A white and B and O blue-white, with surface temperatures increasing from 3,000 K to 35,000 K.

(D) The usefulness of the Stefan and Wien Laws depended on the development of astronomical photometers capable of measuring both the total amount of energy received from a star, and the way that energy varied with wavelength. A start had been made in 1725 by P. Bouger (1698–1758) who compared the brightness of the Sun and Moon to that of a standard candle (see Bouger, 1961). Stellar photometry was started in earnest by Sir John Herschel (1792–1871). In 1836 he used an 'astrometer' to compare images of certain bright southern stars to a minified, star-like lunar image that could be changed in intensity. A very commendable accuracy of ± 0.09 magnitudes was obtained (see Herschel, 1847). By 1861 J. Friedrich C. Zöllner (1834–1882), using a polarization astronomical photometer, listed the comparative brightness of 226 stars.

The major breakthrough in the measurement of stellar radiation temperature came with the invention of the bolometer by Samuel Pierpont Langley (1834–

1906). Instead of integrating over all received wavelengths, the bolometer used by Langley measured solar energy as a function of wavelength. Between 1882 and 1886 he had extended his infrared limit from 2.8 µm to 5.3 µm. These bolometric results could then be fed into Stefan's Law (and later on into Wien's Law) to give the temperature of the radiating surface (see Langley, 1901).

2 THE DEFINITIONS OF TEMPERATURE RELEVANT TO ASTRONOMY

In an astronomical context, temperature can be defined in five different ways.

Kinetic temperature, see equation (1) above, depends on the mean kinetic energy of the particles.

Molecular velocities can be compared to escape velocities and the temperature-dependent rates of planetary and stellar atmospheric loss can be estimated. In a multi-component gas the more massive isotopes, elements and molecules are moving more slowly than the lighter ones and this can lead to the chemical composition changing with time. In those gaseous stellar photospheres where turbulence and pressure broadening are insignificant, the opacity profiles of weak spectral lines are dominated by Doppler broadening, this being induced by the actual movement of the light-absorbing atoms and molecules. Line profiles can be translated into velocity distributions, these leading to the temperature of the absorbing region responsible for the line production. High-dispersion spectra (better than about 10 Å mm^{-1}) are required, and this technique became important in the stellar context in the 1930s (see Hearnshaw, 1986: 245). When it comes to planets, simple 'laboratory' resistance thermometers placed, for example, on the surface of Venus and Mars, or into the soil of the Moon, will measure the kinetic temperature.

The *effective temperature* (T_e) of the surface of a spherical body of radius R, is defined by the formula

$$L = 4\pi R^2 \sigma T_e^4 \tag{2}$$

where L is the total energy (i.e. integrated over all wavelengths) emitted by the body per unit time and σ is Stefan's constant. The quoted value of σ has changed little over the last hundred years. Today it is given as 5.67 × 10^{-8} W m^{-2} K^{-4}, whereas Coblentz (1923: 541) quoted 5.72 × 10^{-8} W m^{-2} K^{-4} and Preston (1904: 595) 5.32 × 10^{-8} W m^{-2} K^{-4}. Stellar effective temperatures can be difficult to estimate because stars, being totally gaseous, do not have specific surfaces, and their radiation comes from a range of depths in their atmospheres, these atmospheres usually having strong temperature variations with depth. Also the way in which the emitted energy varies with wavelength can deviate significantly from the Planck black-body relationship due to such things as strong spectral absorption lines, line blanketing, the Balmer discontinuity and the shape of the Paschen continuum. One of today's generally-accepted effective temperature reference points is the 5,780 K for the solar photosphere (see Böhm-Vitense, 1954).

Extending the flux measurements into the infra-red is important. Most cool stars emit the majority of their energy in this wavelength region. Coblentz (1922; 1923) used a bismuth, bismuth-and-tin thermocouple at the focus of both the 36-inch, and 40-inch reflector telescopes at the Lowell Observatory (altitude 2,200m) to investigate the infra-red emission from stars and planets. He showed that stellar radiation approximated black-body radiation in *both* the visual and the infra-red. Since the 1960s gallium-doped germanium bolometers have extended measurements into 10-µm N and 22-µm Q bands, leading to estimates of the effective temperatures of the cooler M stars and carbon stars (see Johnson, 1966).

Equation (2) has been 'turned around' and used to estimate the radii of stars (see Barnes and Evens, 1976).

The much cooler planets radiate the vast majority of their energy in the infra-red. The first measured planetary surface temperatures were reported by Menzel, Coblentz and Lampland (1926). Previously physicists had simply extended equation (2) to give

$$\frac{T_P}{T_E} = \left(\frac{r_E}{r_P}\right)^{0.5} \left(\frac{1-A_P}{1-A_E}\right)^{0.25} , \tag{3}$$

where T_P/T_E is the ratio of a planet's average effective temperature to that of the Earth's (taken to be 290 K), and r and A are the heliocentric distance and albedo, respectively. Poynting (1903) assumed that all planetary albedos were similar, and he quoted the temperatures of Venus and Neptune as being 69 and –200° C, respectively.

The first reliable stellar effective temperatures were obtained by Wilsing and Scheiner (1909), and Wilsing (1910). Here the brightness of starlight that had passed through five filters (4,480, 4,800, 5,130, 5,840 and 6,380Å) was compared with the brightness of a calibrated lamp. These results were than fitted to Planck radiation curves. In 1909 the relationship between spectral type and temperature was established and quantified for the first time. Of the 109 stars observed, the hottest was the B star Lambda Orionis (which was assigned a surface temperature of 12,800 K), and the coolest were two M stars, Mu Geminorum and Kappa Serpentis, at 2,800 K.

Wien's Law defines the *colour temperature* (T_c) as

$$T_c = \frac{2.898\times10^{-3}}{\lambda_{\max}} \text{ m K}, \tag{4}$$

where $\lambda_{\max}$ (m) is the wavelength at which the peak of the energy verses wavelength graph occurs. Values given in Preston (1904) indicate that the quoted value for Wien's constant has hardly varied over the last hundred years. More precise temperatures can be obtained by fitting the radiated continuous spectrum to the Planck function. Here

$$B_\lambda(T_c) = \frac{a/\lambda^5}{\left(e^{b/\lambda T_c} - 1\right)}, \tag{5}$$

where B_λ (T_c) is the energy emitted by the body per unit area per unit time in the wavelength region λ to $\lambda + d\lambda$, and a and b are constants. Equation (5) originated in 1900 from the quantum mechanical work of Max Planck (1858–1947). Wien's classical approach in 1896 produced a reasonable, but inexact fit to the radiation curve, his formula being

$$B_\lambda(T_c) = \frac{c_1 e^{-c_2/\lambda T_c}}{\lambda^5} . \tag{6}$$

Here constants c_1 and c_2 had to be found experimentally. An integration of the Planck function (equation 4) over wavelength, leads to Stefan's Law, an empirical law that had existed for twenty-one years before Planck and quantum mechanics proved its veracity.

Temperature was also estimated in the early twentieth century by comparing the gradients of two stellar continua over certain specific wavelength ranges. The gradient ϕ was taken to be

$$\phi = \frac{hc}{kT_c} \times \frac{1}{\left(1 - e^{hc/k\lambda T_c}\right)} \tag{7}$$

This 'gradient' approach followed on from the Rayleigh formula, first proposed in 1900. Here

$$B_\lambda(T_c) = \frac{8\pi k T_c}{\lambda^4}. \tag{8}$$

This formula fits quite well if $\lambda \; \Omega \; \lambda_{\max}$, but is completely incorrect at other wavelengths.

Pioneering photographic spectrophotometry was used to obtain stellar colour temperatures by, for example, Hnatek (1911) and Sampson (1923). These results were controversial, and between 1910 and 1940 there was a heated debate between the supporters of 'effective' and 'colour' temperatures. Comparing one star with another star, where both are assumed to radiate as black bodies (but do not), was clearly a problem. Agreement became closer in the 1930s when carefully-calibrated tungsten filament lamps were used as comparison standards (see Greaves, Davidson and Martin, 1932; 1934). Stellar temperatures only became reasonably consistent after both the Balmer discontinuity and non-grey atmospheres were well understood (see, for example, McCrea, 1931). These were two of the major factors causing deviation from the assumed ideal black body. The stellar temperatures given in the classic paper by Kuiper (1938) were accurate to about 20%, and the later UBVRIJKLMN photometry of Johnson (1966) improved this figure to about 5%. The spur of accurate stellar diameter determination in the 1970s improved things further (for example, see Ridgeway et al., 1980).

The *excitation temperature* (T_E) is defined by the Boltzmann equation

$$\frac{N_b}{N_a} = \frac{g_b}{g_a} \times e^{-(E_b - E_a)/kT_E} \tag{9}$$

where N_a and N_b are the number of excited atoms with energies E_a and E_b, and g_a and g_b are the number of degenerate states with these specific energies. Here k is again Boltzmann's Constant.

Finally we have the *ionisation temperature* (T_i), this being defined by the Saha Equation, which was first derived in 1920 by the Indian astrophysicist, Megnad Saha (1894–1956). This is usually written

$$\frac{N_{i+1}}{N_i} = \frac{2Z_{i+1}}{n_e Z_i} \left(\frac{2\pi m_e k T_i}{h^2} \right)^{3/2} e^{-\chi_i / kT_i}, \tag{10}$$

where N_i and N_{i+1} are the numbers of atoms in the initial and final stages of ionisation, and Z_i and Z_{i+1} are the partition functions for the atoms in there initial and final stages of ionisation, n_e is the number density of free electrons, m_e is the mass of an electron, h is Planck's Constant and χ_i is the ionisation energy required to move an electron from ionisation stage i to i+1. Saha (1921) used this equation to estimate stellar temperatures. His ionisation temperatures were close to the Potsdam colour temperatures, but at spectral type B0, for example, Saha's results were about 7,000 K higher. In the 1920s the Saha approach was the only accurate way of estimating the temperature of O stars (see Fowler and Milne, 1923). Saha's work underlined the fact that the majority of stellar spectral features are mainly dependent on temperature. Other characteristics, such as pressure and density, only have a minor influence.

The importance of ionization can be illustrated by considering the relatively common element calcium. Calcium is divalent and has two loosely-bound electrons in its outer electron shell. In the coolest stars calcium is not ionised and the absorption spectrum is that of the neutral atom. If the temperature is increased to that of the Sun, we find a plentiful supply of both neutral and singly ionised calcium, and the spectra of Ca and Ca^+ are prominent. At higher temperatures the spectrum of Ca disappears and only Ca^+ is left. At the highest stellar photospheric temperature (that of the O stars) one only sees the spectra of Ca^{++}.

When considering the temperatures of different regions of a star, the concept of thermodynamic equilibrium is extremely important. Let us take the lower regions of the solar photosphere as an example. The gas density is high and the distance moved by a gas particle between collisions is very small. Equilibrium is established between particles and photons due to plentiful collisions. The radiant energy that is absorbed by one gas particle will be distributed by collisions to other gas particles in the vicinity before it is reradiated. Under these conditions the distribution of the velocities of the gas particles, the distribution of the energies of the photons, the numbers of atoms in different excited levels, and the number of ionised and neutral ions and atoms will all be represented by a similar temperature. In other words the Maxwellian kinetic temperature, the Planckian radiation temperature, the excitation temperature and the ionisation temperature are the same in that specific locality. The ratio between the radiation emitted and the radiation that is absorbed is only a function of temperature and does not depend on things like pressure, composition and density. The condition is called local thermodynamic equilibrium (LTE), and much has been written about it in text-books on stellar atmospheres. LTE breaks down when the stellar region is optically and physically thin, and also when the gas is moving quickly (e.g. when it is being accelerated). The high temperature, expanding, diffuse solar corona is an example of a gas that is not in LTE. Other non-LTE regions are the thin atmospheres of very hot stars and the outer regions of cool stars. Here one would measure totally different 'temperatures', depending on whether you were defining temperature in terms of velocity, photon energy, excitation or ionisation.

3 THE FOUR EPOCHS OF ASTRONOMICAL TEMPERATURE ASSESSMENT

Astronomers had no true concept of temperature until physicists had performed four tasks. First, physicists had to differentiate between the terms 'heat' and

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'temperature'. Secondly, they had to establish reasonable temperature scales. Thirdly, they had to devise sensitive and reproducible methods of measuring the temperature. And fourthly, they had to establish the laws of heat transfer, and the specific conditions under which conduction, convection and radiation occur.

The difference between 'hot' and 'cold' had been established in ancient times. It was also clear to some ancient astronomers, but not all, that the Sun was hot. Even astronomers felt hotter when standing in direct sunlight than in the shade. In order to estimate the temperature of the Sun one had to know the mechanism by which it lost energy. Conduction requires physical contact. Here a fraction of the kinetic energy of a hot molecule is transferred to its cooler neighbour by collision. Convection relies on mass movement. Hot material is physically transported to a colder region, mixing occurs and heat is exchanged. Radiation needs no intervening medium and no physical contact. Radiated thermal energy can be efficiently transferred across the vacuum of space. Hot bodies emit electromagnetic radiation which then travels at the speed of light through space until it is absorbed by another body. As planets, stars and galaxies are distributed throughout the near-vacuum of space, the only relevant heat transfer mechanism is radiation.

Unfortunately the laws of thermal radiation are relatively recent and were only established indisputably by the work of Planck in 1901. Empirical relationships were introduced two decades before, but their relevance and significance were only slowly established and accepted. In 1879 Stefan suggested that the total power radiated by a hot body was proportional to the product of fourth power of its absolute temperature, and to its surface area (see equation 2). Seventeen years later, in 1896, Wien noted that the absolute temperature of a radiating body was inversely proportional to the wavelength, $\lambda_{\max}$, at which the energy emission peaked (see equation 3).

Due to the historical development of the relevant physical laws and instrumentation, the history of astronomical temperature divides into four main epochs, and these are discussed individually below.

3.1 Pre-1700

Prior to 1700 the concept of temperature was so primitive that astronomical opinions were to all intents and purposes irrelevant and useless. No distinction was made between 'heat', the total thermal energy in a system, and 'temperature', the degree of hotness, a quantity that is proportional to the average kinetic energy of a single atom or molecule. Anaximander of Miletos (610–ca 547 BC) typified the early Greek approach by suggesting that the Sun was filled with fire. Xenophanes of Kolophon (ca 570–450 BC) thought that the Sun was a collection of fiery particles which assembled in the morning to form a radiant cloud (see Pederson, 1974). The Ionian philosopher, Anaxagoras of Klazomenae (ca 500–428 BC), asserted that the Sun was a red-hot stone larger than the Peloponnesus (see King, 1957). Anaxagoras went on to suggest that the stony meteorite that fell at Aegos Potami in Trace (see Theodossiou, et al., 2002) had actually come from the Sun. The Greeks clearly thought that the Sun was hot.

The picture became more complicated as one moved towards the Renaissance. In 1626 the scholastic natural philosopher Bartolomeo Amico (1562–1649) resorted to astrology when trying to explain the four primary qualities of hotness, coldness, wetness and dryness. He regarded the Sun as being calefactive, and thus capable of causing heat in other bodies whilst not itself being hot. In like vein, Saturn was frigefactive, causing cold, but not itself being cold. Renaissance followers of Aristotle were convinced that hotness, coldness, wetness and dryness could not exist in the heavens. Their existence would cause change and alteration, and Aristotelians were convinced that the heavens did not change. It was suggested that the 'cold' Sun heated the air below the Moon because it was 'near' and its motion was sufficiently rapid (see Grant, 1994). So the warmth produced by the Sun was caused by the friction set up in the Earth's air by its motion, and not by a direct transfer of thermal energy. Warmth increases as the Sun gets nearer or higher or overhead (see Ronan, 1973). Raphael Aversa (ca 1589 –1657), a contemporary of Galileo, was interested in the physical nature of sunspots. He disagreed with the 'cold' Sun idea and suggested that the Sun was a fluid of molten metal contained within a spherical transparent vessel. Furthermore, inside this fluid (rather like in molten iron in a furnace) were certain opaque and dark parts, which, from time to time, rose to the surface exhibiting themselves as sunspots.

Isaac Newton (1687) clearly thought that the Sun was hot, and also stressed the fact that "… the heat of the sun is as the density of its rays, that is, inversely as the square of the distance of places from the sun". Solar heat was discussed in detail, in the *Principia*, when considering the tail formation and evaporation of the Great Comet of 1680. This comet came within 0.006222 AU (1.337 solar radii) of the centre of the Sun. Newton (1687: 918) wrote:

> … the heat of boiling water is about three times greater than the heat that dry earth acquires in the summer sun, as I have found [by experiment]; and the heat of incandescent iron (if I conjecture correctly) is about three or four times greater than the heat of boiling water; and hence the heat that dry earth on the comet would have received from the sun's rays when it was at perihelion, would be about two thousand times greater than the heat of incandescent iron. But with so great a heat, vapours and exhalations, and all volatile matter, would have to have been consumed and dissipated at once.

Clearly Newton was using the word 'heat' in the way we would today use the word 'temperature'. The crudeness of contemporary thermometers, and their limited range, helps to explain why Newton thought that the 'temperature' of molten iron was only three to four times that of boiling water.

3.2 1700–1870

The second epoch in astronomical temperature history starts in the early eighteenth century with the introduction of alcohol-in-glass and mercury-in-glass thermometers. As is often found, the advent of inexpensive and reliable instrumentation has a dramatic affect on the scientists' views of a physical phenomenon. The main spur to thermometric studies was the burgeoning interest in meteorology and steam engines. Meteorology was intimately entwined with the celestial cartography of the day because refraction affected stellar positions, and the degree of refraction varied as a function of the temperature, pressure and water content of the atmosphere through which the starlight travelled. Glass thermometers gave astronomers a convenient and accurate way of measuring temperatures in the –38 to +355° C range. The establishment of a temperature scale also required 'fixed points', and this led to the realisation that (under constant pressure conditions) substances such as water and mercury boiled and froze at fixed temperatures.

Thermometers, and the experiments that these cheap and easily-manufactured instruments encouraged, quickly led to the discovery of some fundamental thermal laws. In 1701 Isaac Newton introduced his 'law' of cooling, this indicating that the heat lost by a body under the conditions of forced convection was proportional to the temperature difference between the body and its surroundings. Here we see the foundations of the study of heat transfer. Unfortunately, forced convection rarely if ever applies to astronomical objects. Even though many nineteenth-century astronomers rushed to apply Newton's Law of Cooling, specifically to solar heat loss, the resulting solar temperatures were extremely wide of the mark.

The difficulty of estimating, or appreciating, the temperatures of remote stellar objects is underlined by the fact that even as late as 1795 William Herschel (and many others) were proposing that the main body of the Sun was cold, dark and solid, this supposedly temperate Earth-like globe being surrounded by a photospheric cloud region that was intensely hot and luminous (see Kawaler and Veverka, 1981). William Herschel's views were held in very high esteem at the time. His suggestion (Herschel, 1795: 63) that

> ... the sun ... appears to be nothing else than a very eminent, large, and lucid planet, evidently the first, or in strictness of speaking, the only primary one of our system ... Its similarity to other globes of the solar system ... leads us to suppose that it is most probably ... inhabited ... by beings whose organs are adapted to the peculiar circumstances of that vast globe ...

was accepted by a host of other proponents of the plurality of worlds, and life (see Crowe, 1986). Herschel's 'deduction' was clearly not based on observations; he simply regarded it as being philosophically attractive in as much as it "... removes the great dissimilarity ... between its [the Sun's] condition and that of the rest of the great bodies of the solar system." (ibid.). Arthur Berry (1898: 350) noted that Herschel's solar scenario "... attracted very general notice by its ingenuity and picturesque-ness, and commanded general assent in the astronomical world for more than half a century." This unusual picture was still astronomically acceptable by some in the 1850s. David Brewster (1854: 94), in his popular book on life in the universe wrote: "...we approach the question of the habitability of the Sun, with the certain knowledge that the Sun is not a red-hot globe, but that its nucleus is a solid opaque mass receiving very little light and heat from its luminous atmosphere." In the 1860s, however, Gustav Kirchhoff (1861; 1862), in an attempt to explain the production of the solar continuum spectrum, postulated that the Sun consisted of an incandescent liquid core which produced intense white light. Angelo Secchi (1864) was the first to propose that the solar core was gaseous and that the temperature steadily decreased from the core to the photosphere.

3.3 The Late Nineteenth Century

The third epoch encompasses the later parts of the nineteenth century. This century saw the blossoming of astrophysics, the introduction of photography, spectroscopy and photometry, a steady increase in the temperatures of laboratory heat sources and the empirical investigation of the relevant laws of heat radiation. Philosophical musings by the likes of William Herschel and David Brewster were replaced by scientific inquiry and experimentation. When, however, astronomers asked "What is the temperature?" the object of investigation was almost exclusively the solar photosphere. During the nineteenth century the Sun was transformed from a solid, temperate, inhabited realm, with verdant valleys and hills, into a gaseous maelstrom with a temperature much higher than earthly experience. To quote Young (1895: 304):

> The question of the sun's temperature is embarrassed by the fact that it has no *one* temperature; the temperature at different parts of the solar photosphere and chromosphere must be very different ... If we could depend on the laws deduced from laboratory experiments, by which it has been sought to connect the temperature of a body with its rate of radiation, the matter would then be comparatively simple: from the known radiated *quantity of heat* (in calories) we could compute the *effective temperature* in degrees. But at present it is only by a very unsatisfactory process of extrapolation that we can reach conclusions. The sun's temperature is so much higher than any we can manage in our laboratories, that there is not yet much certainty to be obtained in the matter. Rosetti, the most recent investigator, whose results seem to be on the whole the most probable, obtains 10,000° C. or 18,000° F. for the effective temperature.

In Young's seminal 1895 textbook views as to the temperature of other stellar surfaces are conspicuous by their absence.

Young rightly stresses the confusion about the relevant radiation laws. As mentioned above the *quantity of heat* emitted by the Sun had been measured with reasonable accuracy by Pouillet in 1838. As the century progressed accuracy improved, but there was little change to the magnitude of the radiated flux. The problem lay in the relationship between the radiated flux and the temperature of the radiating surface. Some researchers assumed a direct proportionality between surface temperature and radiated energy (i.e. the Newton Law of Cooling). Here the rate of cooling of a body of temperature θ surrounded by a fluid of temperature θ_0 is governed by an equation of the form

$$\frac{d\theta}{dt} = -E(\theta - \theta_0), \qquad (11)$$

where E is a coefficient depending on the nature of the body and its surface conditions. Experimentalists were, however, beginning to realise that this was inappropriate at $(\theta - \theta_0)$ values greater than a few tens of degrees. According to Dulong and Petite (1817) a better cooling law was

$$\frac{d\theta}{dt} = -E\left(a^{\theta} - a^{\theta_0}\right), \qquad (12)$$

where a is a quantity that is derived experimentally at different temperatures (see, for example, Preston, 1904: 530). This empirical Dulong and Petite Law combined both convection and radiation. It also became inaccurate at very large values of $(\theta - \theta_0)$ and when it was extrapolated beyond the temperature range over which the constant was established.

The confusion over astronomical temperatures in the nineteenth century is echoed by a similar confusion in both the physics laboratory and the factory. Burgess and Le Chatelier (1912: vi) note that, even by 1885, reasonably reliable temperature measurements could only be made up to about 500° C. Improvements in gas pyrometry and thermoelectric and resistance pyrometry meant that by about 1912 the melting points of metals such as palladium, platinum and tungsten could be quoted as being around 1,550 ± 15, 1,755 ± 20 and 3,000 ± 150° C respectively.

Let us briefly mention the history of thermoelectric thermometers and resistance thermometers during the nineteenth century, and the influence that these new instruments had on astronomy. In 1821 the Russian-born German physicist, Thomas Johann Seebeck (1770–1831), discovered that if, for example, an antimony metal wire is connected at each end to two bismuth metal wires, and the two antimony/bismuth junctions are held at different temperatures, then a voltage is produced that is a polynomial function of the temperature difference between the two junctions. These 'thermocouples' could be grouped together to form a 'thermopile'. Weaver (1946: 456) recounts how Huggins (1868) placed an antimony/bismuth thermopile at the focus of his eight-inch reflector in an attempt to measure the radiant flux from the bright stars Sirius, Pollux, Regulus and Arcturus, this flux being a function of the temperature rise in the thermopile. The temperature rose slowly, and it took ~10 minutes to obtain a reading on the galvanometer. It was not until the early 1910s that sensitive vacuum thermocouples at the focus of, for example, the 36-inch Crossley reflector at the Lick Observatory, yielded many useful results.

In 1871 the Prussian-born British engineer Sir William Siemens (1823–1883) quantified the relationship between the resistance of platinum and its temperature. Platinum resistance thermometers, however, only started to be used in earnest around twenty years later. Their usefulness in astronomy was greatly limited by their large thermal capacity.

3.4 The Twentieth Century

The fourth epoch essentially starts with the work of Max K.E.L. Planck (1858–1947). In 1901 he used the theory of quantum mechanics to provide the relationship between the *quantity of heat* radiated by a blackbody and the wavelength of that radiation and the temperature of the radiator. At a stroke, all the nineteenth century uncertainty exemplified by the Young quotation above, disappeared. Even though, in 1884, Ludwig Boltzmann (1844–1906) used the electromagnetic theory of light to show that the energy radiated by a black body was proportional to the fourth power of its absolute temperature, this relationship was not universally accepted until Planck provided the undisputed theoretical underpinning. Even though, in 1893, Wien suggested empirically that $\lambda_{\max} \propto (T_c)^{-1}$, this was also not accepted universally; in fact, Michelson (1887) and Rubens (1894) had $\lambda_{\max} \propto (T_c)^{-0.5}$. Again Planck's work in 1901 removed the uncertainty. After 1901 the quoted temperatures for the solar photosphere had values close to those accepted today.

During the fourth epoch (i.e. during the twentieth century) the interest in astronomical temperature blossomed. It was realised that the Harvard spectroscopic classification scheme was actually based on differences in stellar surface temperatures. Table 1 illustrates how quickly an accurate picture of the relationship between temperature and spectral type was established. The most important diagram in astrophysics, the Hertzsprung-Russell Diagram, introduced in the 1911–1914 period, had the logarithm of the stellar surface temperature as its ordinate. Theoretical work in the 1920s by astronomers like Eddington saw sensible estimates being made of the central temperatures of stars and the temperature variation with distance from the centre. The twentieth century saw a huge improvement in radiation detector sensitivity. It also saw a huge expansion of the wavelength range over which measurements could be made. This was coupled with an enhanced insight into spectroscopy, plasma physics and the mechanisms responsible for atomic excitation and ionisation. Slowly the kinetic, colour, effective, excitation and ionisation temperatures of specific astronomical regions (such as, say the solar photosphere, chromosphere and corona) fell into agreement.

Table1: Examples of recorded Main Sequence star effective temperatures (in K), as a function of date.

Spectral Type	T_{eff} Russell 1914	T_{eff} Payne 1925	T_{eff} RDS 1927	T_{eff} Becker 1935	T_{eff} Kuiper 1938	T_{eff} Johnson 1966	T_{eff} Schmidt-Kaler 1982
O5					80000		44500
B0	20000	20000	23000	22000	25000	26500	30000
B5	14000	15000	15000		15500	13800	15400
A0	11000	10000	11200	13500	10700	9850	9520
A5	9000	8400	8600		8530	8260	8200
F0	7500	7500	7400	8550	7500	7030	7200
F5	6000	7000	6500		6470	6400	6440
G0	5000	5600	6000	5800	6000	5900	6030
G5	4500	5000	5600		6360	5660	5770
K0	4200	4000	5100	4370	4910	5240	5250
K5		3000	4400		3900	4400	4350
M0			3400	3240	3400	3750	3850
M5						3100	3240
M8						2750	2640

For the first part of the twentieth century astronomers had the enviable advantage of being confronted with considerably higher temperatures than laboratory physicists. To quote Russell, Dugan & Stewart (1927: 735):

> It will be noticed that the stellar temperature scale begins not far from where the scale of temperatures readily attainable in the laboratory leaves off. The hottest part of the crater of a carbon arc is at about 3800° K, corresponding to Class K2. Even the temperature of an average N-star is well above the melting point of platinum, and would ordinarily be called an intense white heat.

Astronomers were also very fortunate that the majority of stellar surfaces radiated approximately like black bodies.

4 EXPERIMENTATION AND RESULTS

4.1 Thermometers

Galileo's invention of the air thermometer in 1579, Kircher's use of the mercury-in-glass thermometer in 1643 and the introduction of the Fahrenheit and Celsius temperature scales in 1724 and 1742 had little effect on the history of temperature in astronomy, but the later, and specifically the study of the fixed temperature points at which phase transition took place, at least paved the way for the differentiation between temperature and heat. These early instruments measured the kinetic temperature of the material in their immediate environment. Recent astronomical examples of temperature measuring devices (as opposed to energy flux measurers) have been the simple resistance thermometer on board the Venera 7 spacecraft that soft landed on the surface of Venus on 15 December 1970, recording a temperature of 747 ± 20 K (see Avduevsky, et al., 1970), and the resistance thermometers and thermocouples that were used to measure the subsurface temperature of the lunar soils during the Apollo missions (see Cadogan, 1981, for a review).

4.2 Solar Photospheric Temperature

The astrophysical appreciation of accurate colour and radiation temperatures can be illustrated by the estimates that were made as to the solar photospheric temperature over the last one hundred and seventy years. This temperature was the main calibration point when it came to establishing both the relationship between stellar spectral classes and stellar surface temperatures, and the relationships between the kinetic, effective, colour, excitation and ionisation temperatures mentioned above. The Sun's age, stability and position on the Main Sequence means that it is reasonable to assume that its temperature has not varied perceptibly during the last few centuries. Table 2 provides a chronological list of various values obtained and published for the solar photospheric effective temperature in the nineteenth and twentieth centuries. These temperatures are also plotted logarithmically as a function of date in Figure 1.

The divisions between the epochs mentioned above are very clear. The publication of Planck's Law in 1901 can be seen, in Figure 1 to mark a watershed. The data scatter changes drastically at this time. After 1901 the median value of the solar surface temperature is about 5,780 ± 60 K, the range being between 6,500 and 5,510 K. Even by 1903 Agnes Clerke could look back and write about the solar surface temperature "... of late the answers have become much more plausible than those discordant to the extent of some millions of degrees arrived at thirty years ago." (page 64). The main problem after 1901 was the estimation of the Earth's atmospheric absorption correction. Even though measurements were made at higher and higher altitudes, the fact that the absorption depended both on the mass of the atmosphere above the observer, and the atmospheric water vapour content, and was wavelength dependent, added to the uncertainty. Going back to the previous century, Rosetti, for example, gave the atmospheric zenithal heat absorption as being 29%, whereas Langley and Ångstrom used corrections of 41% and 64% respectively.

Table 2: Recorded values of the photospheric temperature of the Sun, listed according to date.

Date	Source	Temperature (K)
1687	Newton	2000 x incandescent iron (2,600,000 – 3,040,000)
1838	Pouillet	1730–2030
1847	J. Herschel	1823
1860	Waterstone	7,160,000
1861	Secchi	7,000,000
1867	Soret	10,000,000
1870	Zöllner	68,700 (28,000–68,700)
1870	Lane	32,000
1871	Ericsson	2,200,000
1871	Spoerer	27,000
1872	Vicaire	1671
1876	Violle	1800–2800
1878	Langley	2200 (2100–2300)
1879	Rosetti	10,000
1879	Rosetti	20,650
1881	Violle	3300
1884	Hirn	2,000,000
1892	Le Chatelier	7900
1894	Wilson and Grey	6500
1894	Scheiner	6200
1895	Ebert	40,000
1895	Paschen	5400
1899	Scheiner	6203
1901	Wilson	6860
1908	Abbot and Fowle	6430 (Wien, λ_{max} = 0.433 μ) 5840 (effective)
1909	Millochau	5510
1909	Nordmann	5610
1910	Wilsing and Scheiner	5640
1911	Kurlbaum	5730
1911	Kurlbaum	6390
1913	Sampson	6000
1917	Wilsing	6500
1926	Russell, Dugan and Stewart	6150 Wien 5750 (effective)
1938	Unsold	5713 ± 30
1938	Abetti	5770
1949	Hoyle	5740
1950	Allen	5784
1954	Böhm-Vitense	5780
1972	Allen	5770
1973	Kaye and Laby	5800
1988	Durrant	5783
1990	Zombeck	5770
1991	Lang K. R.	5780

Table 2 shows that the quoted solar surface temperature quickly approached a reasonably constant value after 1901. It was, however, clear that the different temperatures provided by the three main observing techniques were real, and not just the product of experimental error. Abetti (1938: 320) noted that the photospheric temperature obtained by (i) measuring the energy emitted by the Sun and then using the Stefan-Boltzmann Law, (ii) attempting to fit the Planck formula to the solar radiation energy curve, and (iii) estimating the wavelength at which the energy curve maximised and then using Wien's Law gave temperatures of 5,770 K, 5,950 K and 6,080 K respectively. Nearly twenty years later Payne-Gaposchkin (1956: 65) quoted these temperatures as 5,750 K, 5,600–6,150 K and 6,150 K. Clearly there is no single 'correct' temperature for the solar surface. The Sun, a huge gaseous sphere, does not *have* a surface; the photosphere that we see, is a layer ~500 km thick, throughout which the temperature varies in a complex fashion with depth. The fact that the photosphere is cooler than both the corona above and the solar interior beneath does not help physical interpretation either.

Let us briefly digress to sunspots. The first proof that spots were cooler than the surrounding photosphere came from Mt Wilson spectral studies in 1906 (see, for example, Bray and Loughhead, 1964). Pettit and Nicholson, for instance, measured the temperatures across sunspots, finding (from luminosity measurements) that the mean umbral temperature was about 4,790 K.

Moving instrumentation into space has helped hugely when it comes to measuring solar temperatures. The Active Cavity Irradiance Monitor (ACRIM) on board NASA's Earth-orbiting Solar Maximum Mission produced a twenty-four year mean value (1979–2003) for the solar constant of 1,366.0 ± 0.1 W m^{-2}. This result, when coupled with an astronomical unit of 149,587,870 ± 2 km, a solar radius of 695,990 ± 10 km and a Stefan's Constant of 5.670512 × 10^{-8} W m^{-2} K^{-4} yields a photospheric effective temperature of 5,775.9 ± 0.2 K.

Between 1838 and 1901 the quoted solar surface temperature values ranged from 1,670 K to 7,000,000 K, the lowest being similar to the temperature of liquid iron and the highest being three times that now attributed to the highly ionised and escaping solar corona. The normal experimental errors affected the deduced value of the flux of radiation received at the Earth. The main reason for the discrepant results in this period was the choice of the relationship between this flux and the temperature of the radiating solar surface. The range of quoted solar temperatures was probably a source of considerable embarrassment to astronomers. Ledger (1882: 45) quoted this as being between "... less than 2000° Centigrade, and rising up to 5,000,000° Centigrade ...", and concluded that "... as to what is the actual temperature of the solar photosphere we can say very little." Astronomers suggesting that the temperature was above 1,000,000 K were incorrectly using Newton's Law of Cooling. Those suggesting that the temperature was ~3000 K were incorrectly using Dulong and Petit's Law. To quote Young (1895: 304): "There has been a great deal of pretty vigorous discussion as to the temperature of the sun."

Many astronomers did not even mention the solar temperature in their text-books, concentrating instead on the result over which there was at least some agreement (i.e. the energy received each year by the Earth's surface). Chambers (1889: 7), for example, just discusses the terrestrial flux:

> ... our annual share would be sufficient to melt a layer of ice all over the Earth 100^{ft} in thickness, or to heat an ocean of fresh water 60^{ft} deep from 32° F. to 212° F ... Another calculation determines the direct light of the Sun to be equal to that of 5563 wax candles of moderate size, supposed to be placed at a distance of one foot from the observer.

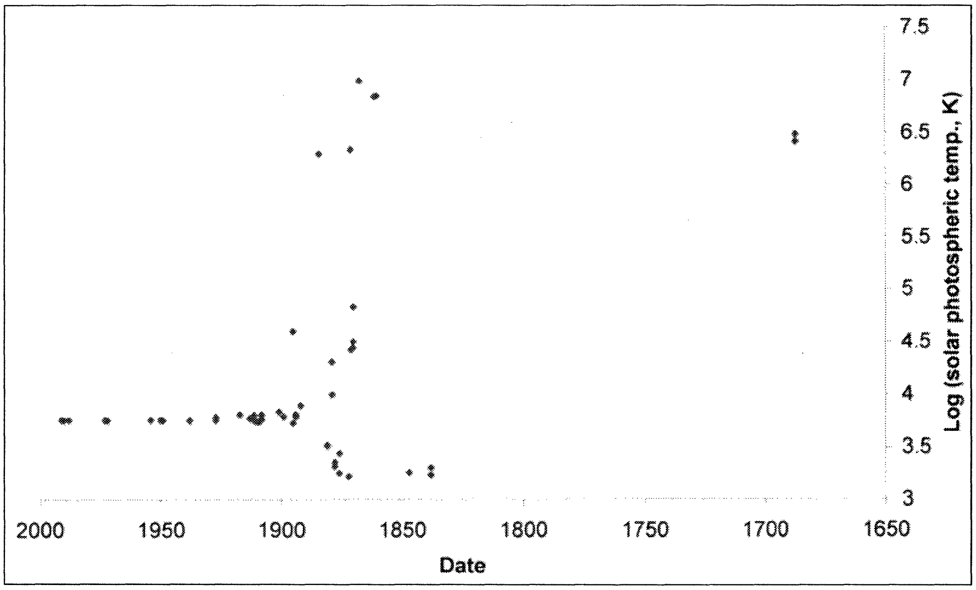

Figure 1: The logarithm of the quoted and measured values for the temperature (K) of the solar surface (i.e. photosphere) is plotted as a function of date. Three key dates are worth mentioning. Stefan's Law indicating that radiated flux was proportional to T^4 was proposed in 1879. Wien's Law was proposed in 1896, and the Planck formula was published in 1901. Prior to 1900 the higher temperatures were obtained by assuming that the Sun radiated according to Newton's Law of cooling, and the lower temperatures assumed a form of the Dulong and Petit relationship.

Others turned to empirical comparisons. Scheiner (1894) measured the relative intensities of the magnesium lines at 4,482 and 4,352 Å in the solar spectrum and concluded that the reversing layer responsible for their production must have a temperature similar to that of an electric arc. Unfortunately this arc temperature was not measurable at the time. Everyone was clearly hampered by the fact that the solar surface temperature "… must greatly surpass any degree of heat with which we can experiment in our laboratories." (Ledger 1882: 45). Put more prosaically, "… the highest temperatures of our furnaces, that of the melting of gold, of silver, of platinum, of iron, are but ice compared to the solar heat." (Flammarion and Gore, 1894: 244) The disparate nature of the nineteenth century results had a further unfortunate consequence. Some thought that, like the solar cycle of spot activity, the solar surface temperature varied with time. Clerke (1903: 69) wrote that "… divers indications lead almost irresistibly to the conclusion that the Sun is hotter at certain times than others."

The flux of radiation received at the Earth, multiplied by the area of a sphere of radius one astronomical unit, yields the solar luminosity. This quantity (and *not* the solar temperature) was of vital importance when it came to assessing the total rate of energy loss by the Sun over the age of the planetary system. Quoting Newcomb (1883: 519) "… how this supply of heat (is) kept up … is one of the most difficult questions of cosmical physics."

4.3 The Temperatures of Other Stellar Surfaces

The spectroscopic observations made by Joseph von Fraunhofer in 1817 showed that different stars had different spectra. Spectral classification started in 1866 when Father Angelo Secchi crudely divided stars into white, yellow, red and deep red groups. In the previous year Zöllner, had already stressed the importance of stellar temperature and had suggested that yellow and red stars were simply white stars that had cooled off. Unfortunately H.C. Vogel, in 1874, and J.N. Lockyer, in 1888, confused the issue by introducing their respective stellar evolution theories into the classification system. Lockyer insisted that white stars, like Sirius, were young, the yellow Sun was middle-aged, whereas red stars were, according to Clerke (1885: 415) "… effete suns, hastening rapidly down the road to final extinction." Thus every star, at different stages of development, supposedly passed through all the types of the spectral sequence. E.W. Maunder (1892), however, disagreed, insisting that "… spectrum type does not primarily or usually denote epoch of stellar life, but rather a fundamental difference of chemical constitution."

The famous and resilient Harvard system of stellar spectral classification started in 1886 and flourished due to the hard work of E.C. Pickering, Williamina Fleming, Antonia C. Maury and Annie J. Cannon. The classification in the original 1890 *Draper Catalogue of Stellar Spectra* (*Harvard Annals*, Volume 27) used sixteen classes these being A, B, C, D, E, F, G, H, I, K, L, M, N, O, P and Q. In 1901 Cannon introduced decimal subgroups and re-arranged the sequence such that O and B came before A. Also some classes were omitted and other classes were combined. Classes R and S were added in 1908 and 1922 respectively, and the culmination was the publication of 225,300 stellar spectral classifications in the Henry Draper Catalogue between 1918 and 1924. It was recognised at an early stage in the classification work that the O, B, A, F, G, K, M, R, N and S classes were ordered in a decreasing temperature sequence. The theoretical explanation had to wait until the research of Saha (1920; 1921) who quantified the temperatures (and to a lesser extent the pressures) in the photospheres in terms of the strengths of the spectral lines. We have noted above that a well-accepted value for the solar photospheric temperature was only established after about 1901. When it came to estimating the temperatures of the much more distant stars the most effective technique was that of Planck-curve fitting. Pioneering work in this field was carried out by the Potsdam astrophysicists J. Wilsing and J. Scheiner, who carefully compared visual stellar spectra with those of extremely hot laboratory analogues. Their 1909 paper listed the temperatures of 109 bright stars. This technique was quickly extended using astrophotography.

In the first decade of the twentieth century the German astronomer Karl Schwarzschild (1873–1916) pioneered the measurement of the brightnesses of stars in a series of wavelength bands, such as B and V, using photographic techniques. The blue magnitude was found using a filter centred on 4,400 Å with a band-width of 980 Å, and the visual, V, filter was at 5,500 Å with a bandwidth 890 Å. In 1899 Schwarzschild could measure the magnitudes of stars to an accuracy of between ± 0.02 and 0.04 magnitudes. He introduced the colour index, ($m_B - m_V$), a logarithmic measure of the difference in brightness of a star when photographed (i.e. *B*) and when seen visually (i.e. *V*). The former magnitudes were listed in *Göttingen Aktinometrie* and the latter in the Potsdamer Photometrische Durchmusterung (see, for example, Waterfield, 1938: 102). This colour index was subsequently used by E. Hertzsprung in 1911 when plotting his first 'Hertzsprung-Russell Diagram'. The colour index varied from –0.3 for the bluish-white B0 stars to about +1.6 for the red M0 stars. In 1909, at a meeting in Paris of the Permanent Committee of the Astrographic Conference, it was agreed that the star Vega (Alpha Lyrae, spectral class A0, surface temperature 11,000 K) should be taken as the zero colour index 'standard'. Needless to say, the colour index can be obtained for the faintest star that can be seen and photographed using a large telescope, whereas the whole spectral energy distribution can only be plotted for the brighter stars.

If it is assumed that the stellar intensity distribution follows the Planck Law then colour index can be related to surface temperature using an equation of the form

$$m_{\lambda_1} - m_{\lambda_2} = -\log_{10}\frac{B_{\lambda_1}(T_c)}{B_{\lambda_2}(T_c)} + C, \qquad (13)$$

where C is a constant. If stellar temperature is not too high, Wien's formula can be used to simplify this equation giving

$$m_{\lambda_1} - m_{\lambda_2} = a + \frac{b}{T_c}, \quad \text{i.e.} \quad (m_B - m_V) = a + \frac{b}{T_c}, \qquad (14)$$

where a and b are constants. If the stellar radiation is perfectly black-body this equation becomes

$$m_B - m_V = -0.71 + \frac{7090}{T_c}. \quad (15)$$

As, however, stars do not radiate like perfect black bodies, an empirical relationship for 4,000 K < T_C < 10,000 K stars on the Main Sequence, turns out to be

$$m_B - m_V = -0.865 + \frac{8540}{T_c}. \quad (16)$$

During the early decades of the twentieth century astronomers were extremely active in the field of stellar temperature measurement. There were many tasks. One of the most important was the marrying of spectral type to stellar surface temperature. Additional problems arose when it was realised that the relationship differed slightly for stars on the super-giant, giant and main sequence branches of the Hertzsprung Russell diagram. Two famous early versions (for main sequence stars) were Russell's 1914 *Popular Astronomy* paper and Cecelia Payne's 1925 monograph, *Stellar Atmospheres* (see Table 1). Over the last ninety years or so the estimated temperatures of the surfaces of B0 and B5 stars have increased, as have the temperatures of F5, G0, G5 and K0 stars. The median temperature stars (A0, A5 and F0) are now thought to be slightly cooler than they were in 1914. All in all, Russell (1914) is to be congratulated on getting temperatures reasonably close to the values accepted today. Typical variations over the period have been of ~10–25%.

The problem of explaining the observed differences between effective and colour temperature was addressed, and this eventually led to detailed visual and infra-red photometry and the UBVRIJKLMN system (see Johnson, 1966). Over the period covered by Table 1, hotter and hotter laboratory light sources became available and this led to considerable improvements in stellar temperature determinations. Greaves et al. (1932) used acetylene burners, and Greaves et al. (1934) tungsten filament lamps.

In certain cases, neither the effective temperature nor the colour temperature could be measured satisfactorily. The rare 'helium stars' of class B and A are at such great distances that interstellar scattering reddens their radiation too much for the temperature to be calculated. Here Cecilia Payne (1924) used Saha's equation to establish an ionisation temperature by investigating the appearance and disappearance of lines due to singly, doubly and triply ionised silicon. The ionisation of helium, oxygen, nitrogen and carbon was also used to estimate the surface temperatures of O stars. Typical values for O8, O9, B0 and B5 stars were 30,000, 25,000, 20,000 and 15,000 K respectively.

Many astronomers, starting with Hertzsprung in 1922, have reversed the problem. Here stellar temperatures were not the end point, and the colour temperatures and luminosities of stars were utilised to determine stellar diameters.

4.4 The Temperatures of Stellar Interiors

The role of the theoretician in the field of astronomical temperature estimation is exemplified by the work of the Cambridge astronomer Sir Arthur Stanley Eddington (1882–1944). He used physics, coupled with the observed stellar surface boundary condition, to probe throughout the stellar interior (e.g. see Mestel, 2004). In 1917 he extended Karl Schwarzschild's theory of stellar atmospheres by applying it to low density giant stars. He assumed that these stars were completely gaseous and that *all* their material obeyed the ideal gas law. Not only did he realise that radiation pressure played an important role in the establishment of stellar equilibrium, he also found that the material at the centre of a star was completely ionised, so the number-density of particles in these regions is almost independent of composition. Assuming an average atomic weight of 54 (i.e. that the star was made of iron!) he obtained a central temperature of 7 million degrees for these giant stars. Between 1916 and 1925 Eddington wrote over a dozen papers on stellar interiors, and in 1926 he extended this theoretical work to cover all stars, finding that the central temperature, T_{cent}, was given by

$$T_{cent} = \frac{0.856 G \mu \beta M}{R_g R} \quad (17)$$

where G is Newton's constant of gravitation, μ is the mean molecular weight in terms of hydrogen, β is the ratio of the gas pressure to the total pressure, M is the stellar mass, R_g is the universal gas constant and R is the stellar radius. Eddington (1926: 151) quoted the central temperatures of the stars Capella, Delta Cephei, V Puppis, the Sun and Krueger 60 as being 9.08, 6.16, 42.4, 39.5 and 32.2 million degrees C. His precision was somewhat immodest. In 1932 he assumed (correctly) that the Sun was made of hydrogen, as opposed to iron, and his estimated central temperature decreased by a factor of four. By the 1950s the solar central temperature had been reduced to the more reasonable 13.5 x 10^6 K (see Kuiper, 1952), and a typical present-day value is "... about 15 million degrees ..." Foukal, 1990: 189). Notice that we now recognise the rather uncertain nature of our knowledge.

4.5 The Temperatures of More Exotic Astronomical Regions

For millennia the solar corona has been a marvellous sight at the rare times of solar eclipse but initially few observers guessed that it had a temperature that, until very recently, far exceeded those producible in physics laboratories. The average temperature is about 2,500,000 K. The easiest way of estimating this huge temperature was by observing the Doppler-broadened profiles of bright emission lines such as 5,302.86 Å. Interpretation relied on realising that this line was produced by a forbidden transition in an extremely tenuous iron vapour, the atoms of which had lost thirteen of their electrons (see Edlén, 1941).

Even though the corona is extremely conductive, there is an indication (by comparing the line widths of different emissions) that the temperature in a single concentration may vary from 1,500,000 to 2,500,000 K. The kinetic temperature can also be compared with both the ionisation and excitation temperatures obtained from the coronal emission spectra. Many used the 10^5 K temperature contour as the dividing line between the chromosphere and the corona. The coronal heating mechanism is such that, at solar maximum and minimum, the mean temperatures are ~5 × 10^6 and ~2 × 10^6 K respectively (see Golub and Pasachoff, 1997: 104).

A second way of estimating the coronal temperature (T_{cor}) is by measuring the radial density gradient and using an equation of the form

$$N = N_o e^{-\left(\frac{\mu g}{kT_{cor} r^2}\right)h}, \tag{18}$$

where N is the number of particles per cm^3 at a height h above the surface of the Sun, μ is the mean molecular weight per particle (typically just over 0.5), N_o and g are the density and gravity at the solar surface, k is Boltzmann's Constant, and r is the distance from the centre of the Sun (see Zirin, 1966: 119). A third approach is through radio-wave observations. Here the 'quiet' radio-wave flux is produced by free-free electron emissions, and these electrons usually have a Maxwellian energy distribution. The radio intensity (I_ν), integrated along a line of sight, is given by

$$I_\nu = S_\nu\left(1 - e^{-\tau_\nu}\right), \tag{19}$$

where τ_ν is the optical depth and S_ν is the Planck function. In the radio region the later can be approximated by the Rayleigh-Jeans formula

$$S_\nu = 2kT_{cor}\left(\frac{\nu}{c}\right)^2, \tag{20}$$

where ν is the frequency of the radiation and c is the velocity of light. Zirin (1966: 178) notes that each method gives a somewhat contradictory estimation of the temperature, simply because each is essentially measuring a different quality of the corona. The Doppler-broadening of emission lines might, for example, yield a temperature of about 2,000,000 K, the density gradient 1,600,000 K, the brightness of the quiet radio waves longer than 10 cm in wavelength 1,500,000 K and the observations of the distribution of atoms in various stages of ionization 750,000 K. The solar corona is a perfect example of an astronomical region that is not in local thermodynamic equilibrium.

Moving from an outer stellar atmosphere to the interstellar medium between the stars a similar Doppler broadening approach can be applied, but this time to the 21 cm line produced by neutral hydrogen. In the early 1950s it was shown that this medium has a typical temperature of about 100 K (for example, see Ewen and Purcell, 1951; van de Hulst, 1954). These results confirmed the observations of 'interstellar' absorption lines in the visual stellar spectrum (see Spitzer and Savedoff, 1950). These authors also found that the ionized H II regions in the immediate vicinity of hot stars had a temperature of around 11,000 K.

The measurement of temperature variations in variable stars was pioneered in 1922 by Seth B. Nicholson and Edison Pettit using a vacuum thermo-couple at the focus of the 100-inch telescope at Mount Wilson. Zanstra (1927) measured the temperatures of planetary nebulae and their central stars. He suggested that the brightness and emission spectrum of a planetary nebula was due to its central star having a very high temperature and radiating mainly in the ultraviolet. Typical results indicated that B0 central stars had a temperature of 28,000 K, and O stars, around 34,000 K. Turning to supernovae, Minkowski (1942) concluded that the central stellar remnant of the Crab supernova had a surface temperature greater than 120,000 K, and probably of order 500,000 K.

4.6 The Temperature of Planets and Satellites

The surface temperatures of the planets in our Solar System vary from around 700 K to 50 K. In many cases the temperatures of a specific planetary surface vary drastically from equator to pole and from day to night. Planetary thermal radiation has to be differentiated from scattered sunlight, and this is normally done by concentrating on the far infrared between say 2μ and 30μ. Here one uses thermocouples and bolometers, and the techniques of infrared spectrophotometry. Another approach is to use measurements of the centimetre wavelength radio emission. Even though infra-red radiation from the Moon was first detected by the Earl of Rosse (1869) and from Jupiter and Saturn by Nichols (1901), reasonable planetary temperatures were first obtained only around the early 1920s when, for example Coblentz and Lampland (1923) used radiometers at the focus of the 40-inch Lowell reflector. Three excellent historical reviews are Pettit (1961), Sinton (1961) and Mayer (1961).

Pettit and Nicholson (1930b) used thermocouples to measure the temperature at the centre of the lunar disc when it was sub-solar, and the Moon was full. It was found to be 407 K. At the time of quarter phase that point had moved to the terminator and the temperature had cooled to 358 K. In 1927 the dark side of the Moon was found to have a temperature of about 125 ± 5 K (see Pettit, 1961). In the same year, 1927, observations of the cooling of the lunar surface during a lunar eclipse (150 K in an hour) provided values of the thermal inertia (this being $(k/\rho c)^{0.5}$, where k is the thermal conductivity, ρ the density and c the specific heat), which indicated that the lunar soil was similar to a powdered layer of volcanic ash (see Epstein, 1929).

Moving further from Earth, Pettit and Nicholson (1924) made pioneering measurements of the surface temperature distribution over the disc of Mars. In the same year Coblentz and Lampland (1924) measured the variations of Martian temperatures as a function of season and time of day. The temperature of the Martian sub-solar point also varied from 300 K to 273 K between perihelion and aphelion (see Adams, 1933). The accuracy of these results was improved by the introduction of infrared spectrophotometry. Sinton and Strong (1960) used infrared filters, a 1.5 sec arc diameter aperture, and the 100- and 200-inch telescopes at the Mount Wilson and Palomar Observatories to produce a series of temperature scans across the Martian disc. The mean temperature of the planet was found to be 215 K, the winter and summer poles having temperatures of 130 and 190 K respectively.

The radio spectrum ($3 < \lambda < 10$ cm) of the thermal emission from the surface of Venus indicated that the mean temperature was about 600 K (see Mayer, 1961). Recent space-probes and landers have increased this to around 733 K, this high value being produced by a strong greenhouse effect due primarily to the large concentrations of carbon dioxide in the atmosphere. Visual radiation studies of this planet, however, gave temperatures of 240 K for the dark side and 235 K for the bright side. These clearly refer to upper cloud regions (see Pettit and Nicholson, 1955).

The further a planet is from the Sun, the colder it is. A simple assumption as to the equilibrium between the absorbed solar radiation and the radiated thermal radiation on a fast-spinning planet indicates that the mean surface temperatures (T_m) in K is given by

$$T_m = 392\sqrt[4]{\left(\frac{1-A}{r_p}\right)},$$

where A is the albedo of the planet and r_p is its mean distance from the Sun in astronomical units. This equation indicates that the mean surface temperatures for Jupiter and Saturn are 149 and 111 K respectively. Direct measurements of these temperatures were made by Coblentz (1923). Radio-wave observations could be problematic. Jovian radio observations started in the 1950s, and the spectrum showed no similarity to that of a black body. In fact, the flux density as a function of wavelength indicated that the apparent black-body 'disk' temperature rose from 150 K at 3 cm to 50,000 K at 68 cm (and the 68 cm flux was later found to be due to radiation from relativistic particles trapped in the Jovian Van Allen belts). 3.4 cm observations of Saturn indicated that the apparent black-body disc temperature was 106 ± 21 K. After recent spacecraft observations (see for example Hubbard et al., 1995) the effective temperatures of Jupiter, Saturn, Uranus and Neptune have been found to be 124.4 ± 0.3, 95.0 ± 0.4, 59.1 ± 0.3 and 59.3 ± 0.8 K respectively. These planets are hotter than expected and seem to have internal heat sources, the ratio between the emitted energy and the absorbed energy being 1.67 ± 0.09, 1.78 ± 0.09, 1.06 ± 0.08 and 2.61 ± 0.28 respectively.

Thermally, the centre of a planet is just as remote as the centre of a star. Modelling of accretion, differentiation and radioactive decay heat sources, coupled with estimates of the heat flux through the surface and the physics of conduction and convection indicates that the centres of Earth, Moon, Mars, Jupiter and Saturn have temperatures of ~6,000, 1,800, 2,000, 20,000 and 10,000 K respectively (for example, see Hubbard, 1984 and de Pater and Lissauer, 2001).

4.7 The Temperature of the Universe

Temperature has a key role to play in cosmology and was pivotal in deciding between the Big Bang and the Continuous Creation hypotheses. Alpher and Herman (1948) note theoretically that the temperature (T_{rad}, in K) of the radiation in the Universe is inversely proportional to the radius of the Universe, and that approximately

$$T_{rad} = \left(\frac{3c^2}{32\pi\sigma G}\right)^{\frac{1}{4}} \times \frac{1}{\sqrt{t}} = \frac{1.5\times10^{10}}{\sqrt{t}}, \qquad (22)$$

where c is the velocity of light, σ is Stefan's Constant, G is Newton's Gravitational Constant and t seconds is the time that has elapsed "… from the singular state representing the "beginning" of the Universe." It was this temperature that, by black-body radiation curve fitting, was found to be 3.5 ± 1.0 K by Penzias and Wilson (1965).

5 CONCLUSIONS

Temperature is a vitally important characteristic of astronomical material. There are very few astrophysical processes that do not depend on temperature. The temperature of the radiation in the Universe is inversely proportional to the age of the Universe; the temperature at the centre of a star governs the rate at which that star can produce energy by nuclear fusion and the rate at which a star evolves; the average temperature of a star governs its size; the temperature of an interstellar gas cloud dictates whether that cloud is expanding, in equilibrium, or condensing to produce new stars; the temperature of a terrestrial planetary surface governs the rate of volcanic activity, whether continents occur and move, whether liquid water can flow, and if life can or cannot break out; the temperature of a pre-planetary disc governs whether terrestrial or gas-giant planets are going to be formed; and the temperature of a cometary nucleus governs its rate of decay and the formation of coma and tail. The quest for accurate astronomical temperatures has been a major spur for the development of precision instruments that are capable of measuring radiation fluxes and their variation with wavelength.

Historically, 'temperature' was a late developer. Before 1835 the topic was hardly discussed. By 1900 astronomers had just about obtained a reasonable value for the temperature of the solar surface. 1914 saw reasonable estimates of the temperatures of other stars but we had to wait until the late 1920s before reliable planetary and satellite temperatures were available. The quest for accurate temperatures underlined the synergy between astronomy and physics. The astrophysicist had to rely on the work of the theoretical and experimental physical scientist. But if physicists really 'liked it hot' and wanted to study material at temperatures way in excess of what they could produce in their laboratories, they had little choice but to look to the heavens.

6 ACKNOWLEDGEMENTS

I would like to thank Alan H. Batten of the Dominion Astrophysical Observatory, Victoria, Canada for his careful reading of the original manuscript and his extremely helpful and encouraging comments.

7 REFERENCES

Abetti, Giorgio, 1938. *The Sun: Its Phenomena and Physical Features*. Crosby, London, Lockwood.

Adams, W.S., 1933. Summary of the year's work at Mount Wilson. *Publications of the Astronomical Society of the Pacific*, 45, 271-280.

Alpher R.A., and Herman R.C., 1948. Evolution of the Universe. *Nature*, 162, 174-775.

Amico, Bartolomeo, 1626. *In Aristotelis Libros de Caelo et de Mundo*. Napoli, Secondinno Roncaliolo.

Avduevsky, V.S., Marov, M.Y. Noykina, A.I., Polezhaev, V.I. and Zavelevich, F.S., 1970. Heat transfer in the Venus atmosphere. *Journal of Atmospheric Science*, 27, 569-579.

Barnes, T.G., and Evans, D.S., 1976. Stellar angular diameters and visual surface brightness. I Late spectral types. *Monthly Notices of the Royal Astronomical Society*, 174, 489-502.

Becker, W., 1935. Lichtelektrische farbenindizes von 738 sternene II. *Veröff. Berlin-Babelsberg*. 10 (Heft 6) 1. See, also, Herrmann, Dieter B., 1973. *The History of Astronomy from Herschel to Hertzsprung*. Cambridge, Cambridge University Press.

Berry, Arthur, 1898. *A Short History of Astronomy*. London, John Murray.

Böhm-Vitense, E., 1954. Über die temperatur – und druckschichtung des sonnenatmospäre. *Zeitschrift für Astrophysik*, 34, 209-228.

Bouger, P., 1961. *Traité d'Optique sur la Graduation de la Lumière*. Toronto, University of Toronto (reprint of 1760 original).

Bray, R.J., and Loughhead, R.E., 1964. *Sunspots*. London, Chapman and Hall.

Brewster, David, 1854. *More Worlds than One: The Creed of the Philosopher and the Hope of the Christian*. London, John Murray.

Burgess, G.K., and Le Chatelier, H., 1912. *The Measurement of High Temperatures*. New York, John Wiley.

Cadogan, Peter, 1981. *The Moon – Our Sister Planet*. Cambridge, Cambridge University Press.

Chambers, G.F., 1889. *A Handbook of Descriptive and Practical Astronomy. Volume 1. The Sun, Planets and Comets. (Fourth Edition)*. Oxford, Clarendon Press.

Clerke, Agnes M., 1885. *A Popular History of Astronomy*. Edinburgh, Adam and Charles Black.

Clerke, Agnes M., 1903. *Problems in Astrophysics*. London, Adam and Charles Black.

Coblentz, W.W., 1922a. New measurements of stellar radiation. *Astrophysical Journal*, 55, 20-23.

Coblentz, W.W., 1922b. Further measurements of stellar temperatures and planetary radiation. *Proceedings of the National Academy of Science*, 8, 330-333.

Coblentz, W.W., 1923. *A Dictionary of Applied Physics. Volume 4*. London, Macmillan.

Coblentz, W.W., and Lampland, C.O., 1923. *Lowell Observatory Bulletin*, 3 (10). See, also, Some measurements of spectral components of planetary radiation (abstract). *Popular Astronomy*, 32, 546, and Radiometric measurements of Mars in 1924. *Popular Astronomy*, 32, 570.

Coblentz, W.W., and Lampland, C.O., 1924. Radiometric measurements of Mars. *Publications of the Astronomical Society of the Pacific*, 36, 272-274.

Cook, J.J., Cross, L.G., Blair, M.E., and Arnold, C.B., 1960. Radio detection of planet Saturn. *Nature*, 188, 393-394.

Crowe, Michael J., 1986. *The Extraterrestrial Life Debate 1750-1900: The Idea of a Plurality of Worlds from Kant to Lowell*. Cambridge, Cambridge University Press.

Dulong, P.L., and Petit, A.T., 1817. Des recherches sur la mesure des temperatures et sur les lois de la communication de la chaleur. *Annales Chimie et de Physique*, 7, 225 and 337.

Eddington, A.S., 1926. *The Internal Constitution of the Stars*. Cambridge, Cambridge University Press.

Eddington, A.S., 1932. The hydrogen content of stars. *Monthly Notices of the Royal Astronomical* Society, 92, 471-481.

Epstein, P.S., 1929. What is the Moon made of? *Physical Review*, 33, 269.

Ewen, H.I., and Purcell, E.M., 1951. Radiation from Galactic hydrogen at 1,420 MHz. *Nature*, 168, 356.

Flammarion, Camille, and Gore, J. Ellard, 1894. *Popular Astronomy: A General Description of the Heavens*. London, Chatto and Windus.

Foukal, Peter V., 1990. *Solar Astrophysics*. New York, Wiley Interscience.

Fowler, R.H., and Milne, E., 1923. The intensities of absorption lines in stellar spectra, and the temperatures and pressures in the reversing layers of stars. *Monthly Notices of the Royal Astronomical Society*, 83, 403-424.

Golub, Leon, and Pasachoff, Jay. 1997. *Solar Corona*. Cambridge, Cambridge University Press.

Grant, Edward, 1994. *Planets, Stars, & Orbs: The Medieval Cosmos 1200-1687*. Cambridge, Cambridge University Press.

Greaves, W.M.H., Davidson, C.R., and Martin, E., 1932. *Observations of Colour Temperatures of Stars*. London, His Majesty's Stationary Office.

Greaves, W.M.H., Davidson, C.R., and Martin, E., 1934. The zero point of the Greenwich colour temperature system. *Monthly Notices of the Royal Astronomical Society*, 94, 488-507.

Hearnshaw, J.B., 1986. *The Analysis of Starlight: One Hundred and Fifty Years of Astronomical Spectroscopy*. Cambridge, Cambridge University Press.

Herschel, J.F.W., 1847. *Results of Observations Made During the Years 1834, 5, 6, 7, 8 at the Cape of Good Hope*. London, Smith Elder and Co.

Herschel, W, 1795. On the nature of the Sun and fixed stars. *Philosophical Transactions of the Royal Society*, 85, 46-72.

Hnatek, A., 1911. Bestimmung einiger effektiver sterntemperaturen und relativer sterndurchmesser auf spektralphotographischem wege. *Astronomische Nachrichten*, 187, 369-382.

Hubbard, W.B., 1984. *Planetary Interiors*. New York, Van Nostrand Reinhold.

Hubbard, W.B., Podolak, M., and Stevenson, D.J., 1995. The interior of Neptune. In Cruikshank, D.P. (ed.). *Neptune and Triton*. Tucson, University of Arizona Press. Pp. 109-138.

Huggins, W., 1869. Note on the heat of the stars. *Proceedings of the Royal Society*, 17, 309-311.

Hughes, D.W., 1994. How hot is the Sun? *Physics Review*, 3, 23-26.

Hughes, D.W., 2001. Six stages in the history of the astronomical unit. *Journal of Astronomical History and Heritage*, 4, 15-28.

Hulst, H.C. van de, Muller, C.A. and Oort, J.H. 1954. The spiral structure of the outer part of the Galactic system derived from the hydrogen emission at 21 cm wavelength. *Bulletin of the Astronomical Institute of the Netherlands*, 12, 117-149.

Johnson, H.L., 1966. Astronomical measurements in the infrared. *Annual Review of Astronomy and Astrophysics*, 4, 193-206.

Kawaler, S., and Veverka, J., 1981. The habitable Sun: one of William Herschel's stranger ideas. *Journal of the Royal Astronomical Society of Canada*, 75, 46-55.

King, Henry C., 1957. *The Background of Astronomy*. London, Watts.

Kuiper, G.P., 1938. The magnitude of the Sun, the stellar temperature scale and bolometric corrections. *Astrophysical Journal*, 88, 429-471.

Langley, S.P., 1901. The new spectrum. *Philosophical Magazine*, 2, 119-130.

Ledger, Edmund, 1882. *The Sun. Its Planets and their Satellites*. London, Edward Stanford.

Maunder, E.W., 1892. Stars of the first and second types of spectrum. *Astronomy and Astrophysics*, 11, 145-151.

Maxwell, J. Clerk, 1871. *Theory of Heat*. London, Longmans Green.

Mayer, C.H., 1961. Radio emission of the Moon and planets. In Kuiper G.P., and Middlehurst, B.M. (eds,). *Planets and Satellites (The Solar System Volume III)*. Chicago, Chicago University Press. Pp. 442-472.

McCrea, W.H., 1931. Model stellar atmospheres. *Monthly Notices of the Royal Astronomical Society*, 91, 836-857.

Menzel, D.H., Coblentz, W.W., and Lampland, C.O., 1926. Planetary temperatures derived from water-cell transmissions. *Astrophysical Journal*, 63, 177-187.

Mestel, L., 2004. Arthur Stanley Eddington: pioneer of stellar structure theory. *Journal of Astronomical History and Heritage*, 7, 65-73.

Michelson A. A., 1887. Essai théorique sur la distribution de l'énergie dans les spectres des solides. *Journal de Physique*, 6, 474-479.

Minkowski, Rudolph, 1942. The Crab Nebula. *Astrophysical Journal*, 96, 199-213.

Newcomb, Simon, 1883. *Popular Astronomy (Second Edition)*. London, Macmillan.

Newton, Isaac, 1687. *The Principia*. See Cohen, I. Bernard, 1999. *The Principia: A New Translation*. Berkeley, University of California Press.

Newton, I., 1701. Scala graduum caloris. *Philosophical Transactions of the Royal Society*, 22, 824-829.

Nichols, E.F., 1901. On the heat of radiation of Arcturus, Vega, Jupiter and Saturn. *Astrophysical Journal*, 13, 101-142.

Pater, I. de, and Lissauer, J.J., 2001. *Planetary Sciences*. Cambridge, Cambridge University Press.

Payne, Cecilia, 1925. *Stellar Atmospheres*. Cambridge, Harvard University Press (Harvard Observatory Monograph, No 1).

Payne-Gaposchkin, Cecilia, 1956. *Introduction to Astronomy*. London, Eyre and Spottiswoode.

Pederson, O., 1974. *Early Physics and Astronomy*. Cambridge, Cambridge University Press.

Penzias A.A., and Wilson R.W., 1965. A measurement of excess antenna temperature at 4080 MHz. *Astrophysical Journal*, 142, 419-421.

Pettit, E., 1961. Planetary temperature measurements. In Kuiper G.P., and Middlehurst, B.M. (eds,). *Planets and Satellites (The Solar System Volume III)*. Chicago, Chicago University Press. Pp.400-428.

Pettit, E., and Nicholson, S.B., 1924. Radiation measurements on the planet Mars. *Publications of the Astronomical Society of the Pacific*, 36, 269-272.

Pettit, E., and Nicholson, S.B., 1930a. Spectral energy–curve of sun-spots. *Astrophysical Journal*, 71, 153-162.

Pettit E., and Nicholson S.B., 1930b. Lunar radiation and temperature. *Astrophysical Journal*, 71, 102-103.

Pettit E., and Nicholson, S.B., 1955. Temperatures on the bright and dark sides of Venus. *Publications of the Astronomical Society of the Pacific*, 67, 293-303.

Planck, M., 1901. Ueber das gesetz der energieverteilung in normalspectrum. *Wiedermann's Annalen der Physik*, 4, 553-563.

Pouillet, C.S.M., 1838. *Memoire sur le Chaleur Solaire*. Paris, Bachelier.

Poynting, J.H., 1903. Radiation in the Solar System: its effect on temperature and its pressure on small bodies. *Proceedings of the Royal Society*, 72, 256-266.

Preston, T., 1904. *The Theory of Heat (Second Edition)*. London, Macmillan.

Richtmyer, F.K., Kennard E.H., and Lauritsen T., 1955. *Introduction to Modern Physics*. New York, McGraw Hill.

Ronan, Colin, A., 1973. *Astronomy (Illustrated Sources in History)*. Newton Abbot, David and Charles.

Rosse, 4th Earl of, 1869. On the radiation of heat from the Moon. *Proceedings of the Royal Society*, 17, 436-443.

Rubens, H., 1894. Prüfung der Ketteler-Helmholtz'schen dispersionsformel. *Wiedemann's Annalen der Physik und Chemie*, 53, 267-286.

Russell, Henry Norris, 1914. Relations between the spectra and other characteristics of stars. *Popular Astronomy*, 22, 75-294. See, also, Hearnshaw, J.B., 1996. *The Measurement of Starlight: Two Centuries of Astronomical Photometry*. Cambridge, Cambridge University Press.

Russell, H.N., Dugan, R.S., and Stewart, J.Q., 1927. *Astronomy: A Revision of Young's Manual of Astronomy. Volume II, Astrophysics and Stellar Astronomy*. Boston, Ginn and Company.

Saha, M.N., 1920. Elements of the Sun. *Philosophical Magazine*, 40, 811-824.

Saha, M.N., 1921. On the physical theory of stellar spectra. *Proceedings of the Royal Society*, 99, 135-153.

Sampson, R.A., 1923. On the estimation of the continuous spectrum of stars. *Monthly Notices of the Royal Astronomical Society*, 83, 174-204.

Scheiner, J., 1894. Temperature on the surface of fixed stars and of the Sun compared to that of terrestrial heat sources. *Publications of the Astronomical Society of the Pacific*, 6, 172-173.

Sinton, W.M., and Strong, J., 1960a. Radiometric observations of Mars. *Astrophysical Journal*, 131, 459-469,

Sinton, W.M., and Strong, J., 1960b. Radiometric observation of Venus. *Astrophysical Journal*, 131, 470-490.

Sinton, W.M., 1961. Recent radiometric studies of the planets and the Moon. In Kuiper, G.P., and Middlehurst, B.M. (eds.). *Planets and Satellites (The Solar System Volume III)*. Chicago, Chicago University Press. Pp. 429-441.

Spitzer, Lyman, and Savedoff, M.P., 1950. The temperature of interstellar matter. *Astrophysical Journal*, 111, 593-608.

Theodossiou, E.Th., Niarchos, P.G., Manimanis, V.N., and Orchiston, W., 2002. The fall of a meteorite at Aegos Potami in 467/466 BC. *Journal of Astronomical History and Heritage*, 5, 135-140.

Waterfield, R.L., 1938. *A Hundred Years of Astronomy*. London, Duckworth.

Weaver, H.F., 1946, The development of astronomical photometry. *Popular Astronomy*, 54, 211-236, 287-299, 339-351, 389-404, 451-464, 504-526.

Wilsing, J., and Scheiner, J., 1909. Temperaturbestimmung von 109 hetteren sternen aus spekralphotometrischen beobachtungen. *Publications of the Astrophysical Observatory Potsdam*, 19(1).

Wilsing, J., 1910. Remarks on Wilsing and Scheiner's memoir on the temperature of 109 stars. *Astrophysical Journal*, 32, 130-141.

Wolf, A., 1968. *History of Science, Technology and Philosophy in the 16th & 17th Centuries*. London, George Allen and Unwin,

Young, C.A., 1895. *The Sun* (Revised edition). London, Kegan Paul, Trench, Trübner.

Zanstra, Herman, 1927. An application of quantum theory to the luminosity of diffuse nebulae. *Astrophysical Journal*, 65, 50-70.

Zirin, Harold, 1966. *The Solar Atmosphere*. Watham, Blaisdell Publishing.

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Journal of Astronomical History and Heritage, 8(2), 123-128 (2005).

ASTRONOMY IN SERVICE OF SHIPPING: DOCUMENTING THE FOUNDING OF BERGEN OBSERVATORY IN 1855

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Abstract: Bergen Observatory was founded in 1855 to serve Norway's most important harbour and was initially affiliated with the three years older public nautical school. A transit instrument and a pendulum clock were used for time determination, a necessity in order to operate the time ball accurately and to offer control of chronometers to ship captains. In 1857 the Observatory was separated from the school when a full-time position as City Astronomer was jointly funded by the City of Bergen and the National Government. The founding history of this geodetic and astronomical facility has been explored from new source material in several archives. We document the chain of events that led to the establishment of the Observatory. We also describe the initial instrumentation and observing programmes, and review the results from a re-analysis of the geodetic and astronomical data.

Keywords: Bergen Observatory, instruments, astronomical positioning, time determination, Johan Julius Åstrand

1 INTRODUCTION

In the nineteenth century Bergen was the main international harbour in Norway (see Figure 1 for localities mentioned in the text). Sailing vessels and steam ships bound for distant ports needed accurate time and position as a starting point for navigation. At sea, a ship's captain could readily determine his latitude with a sextant by observing elevations of the Sun near the local meridian. From these observations he deduced the solar meridian altitude. The declination of the Sun on the date of observation was available in nautical almanacs, and simple arithmetic thus yielded the latitude. The longitude was a more complex challenge. Earth rotation ensures a correspondence between time and longitudinal arc. If the longitude is known for a reference position and an accurate clock adjusted to local time for that position is brought along on a journey, then the longitude of another location may be deduced by simple subtraction when the local time at the new site is determined. Observing the meridian transit of the Sun (i.e. maximum solar elevation) yielded time on the ship's chronometer. This event would have corresponded to local noon if the Earth's orbit around the Sun were circular. Since the orbit is elliptical the Sun moves across the sky with slightly different speed at different times of the year. This effect is expressed in the equation of time, which the captain must apply for his longitude computation.

The main challenge, however, was the technological state of chronometers at the time. Pendulum clocks were useless at sea and even the best mechanical clockworks ran unevenly. This was caused by mechanical stresses that varied in magnitude with changes in temperature and air pressure. The properties of lubricants also changed with ambient conditions and with age. The clocks might show abrupt deviations if they were exposed to sudden movements or blows. Reliable navigation thus required regular control of the chronometers. Their bias and rate should thus be accurately determined when in port. A prerequisite for this was that local position and time were accurately known. Before time signals were distributed by telegraphy or radio, the only way to know local time was to carry out astronomical observations of solar and stellar transits with a transit instrument set up exactly in the local meridian. Time was read from a pendulum clock. Ships' chronometers could be adjusted by comparing them to the pendulum clock.

Figure 1: Localities mentioned in the text.

2 THE QUEST FOR THE GEOGRAPHICAL COORDINATES OF BERGEN

The first astronomical latitude determination of Bergen was pre-telescopic. It was made in August 1590, probably with a Jacob staff (cross staff). Peder Jakobsen Flemløs had served as First Assistant to Tycho Brahe on the island of Hveen since 1578. In 1589 he was appointed Physician in Ordinary to Viceroy Axel Gyldenstjerne in Norway. The following summer he accompanied the Viceroy on an inspection tour along the coast of southern Norway, arriving in Bergen on 30 July 1590. During the next two weeks he made five observations of the Sun's elevation on the local meridian and derived an average latitude value of 60° 27′ (Friis, 1904; Schroeter, 1905). This is 3′

larger than the modern value for the Bergenhus Fortress complex, the likely residence of the Viceroy and his court during the visit. A similar precision was obtained from observations at Akershus Fortress in Oslo (Pettersen, 2002).

Almost two centuries later a revised latitude value was obtained by Jørgen Nicolai Holm. Born in Norway, he was a Professor of Mathematics at Copenhagen University in Denmark. Since 1755 he had served on a royal surveying committee to establish and measure the border between Norway and Sweden. On his way by ship to join the committee for summer field work in northern Norway, he measured the latitude of the Cathedral in Bergen on 8 June 1768 (Hansteen, 1823; N. Voje Johansen, pers. comm., 2004: information extracted from Maximillian Hell's papers at Vienna Observatory). Using a geographical circle made by Daniel Ekstrøm in Stockholm he found a latitude of 60° 23′ 40″ (Bugge, 1784). The estimated accuracy was about 1′ (Wargentin, 1784), but the value itself is only 2″ larger than our own result obtained by repeated GPS measurements at the Cathedral on three days in May 2003.

The first complete set of coordinates for Bergen was determined twenty-five years later by Niels Andreas Vibe and Benoni Aubert. They were army surveyors assigned to the Geographical Survey of Norway to establish a triangular arc along the west coast of Norway. In Bergen they set up a small observatory at the hill Klosterhaugen on the Nordnes Peninsula in 1791. It was equipped with a transit instrument and a geographical circle by instrument maker Johan Ahl in Copenhagen, and a pendulum clock by Jahnson. A 7 feet long refractor by Dollond was used to observe eclipses of Jupiter's satellites. The purpose was to establish a reference meridian for their field surveying. In 1792 they observed meridian altitudes of the Sun and stars on fifty-four occasions (Vibe and Aubert, 1792). We derive a latitude of $\varphi = 60° 23' 39''\pm72''$ from their data, which is only 5″ from our own GPS result in May 2003. In 1792 and 1793 lunar occultations of stars and eclipses of Jupiter's satellites were observed simultaneously in Bergen and elsewhere. Wurm (1831) derived what he considered an uncertain longitude of $\lambda = 21^m\ 18^s$ east of Greenwich from two occultations. We derive $\lambda = 21^m\ 08^s\pm60^s$ east of Greenwich from corresponding Jupiter eclipses in Bergen, Berlin, Greenwich, and Viviers. GPS observations in May 2003, corrected for deflection of the vertical, gave $\lambda = 21^m\ 13.5^s$.

In 1814 army major Hans Jørgen Wetlesen and mathematics teacher Christian Fredrik Gottfried Bohr began joint observations from Sverresborg Fortress to improve these coordinates. Two years later Bohr received permission from the City of Bergen to set up a small observatory inside Fredriksberg Fortress, a few hundred meters southwest of Klosterhaugen. He used the same type of instruments as Vibe and Aubert, but the Dollond refractor was replaced by a smaller English refractor of 2 feet focal length. He also had a small sextant. Bohr (1824) quotes $\varphi = 60° 23' 45''$ and $\lambda = 11^m\ 47.4^s$ east of Paris as his best values. With Paris $9^m\ 21^s$ east of Greenwich, his longitude is $\lambda = 21^m\ 08.4^s$ east of Greenwich. GPS observations in May 2003 gave $\varphi = 60° 23' 47''$ and $\lambda = 21^m\ 12.5^s$ east of Greenwich, corrected for the deflection of the vertical.

3 DECISION TO BUILD A CITY OBSERVATORY

When the City Council of Bergen decided on 22 April 1852 to establish a public Nautical School, the main purpose was to improve the educational level and skills of mates and sailors. Chronometers were winning access to more ships and Bergen's stature as an international port disclosed the need for accurate navigational support services. A skilled teacher of nautical science was expected also to monitor time and control chronometers, a service to ship captains that had not previously been available in Bergen. The Board of the Nautical School thus concluded that an observatory equipped with appropriate instruments was required. They suggested that this be an integral part of the Nautical School in Bergen and argued that the necessary investments would immediately release the qualifications of the nautical teacher and allow shipping to benefit from his observing skills. The outcome would be reliable control of chronometers.

The Chairman of the Board of the Nautical School was Captain Carl Frederik Diriks (Figure 2). He was born in Larvik on 26 March 1814, where his father was City Judge. An appointment to Professor of Law at the University moved the Diriks family to Oslo. Carl Frederik Diriks was educated a naval officer at the Norwegian Naval Academy in Fredriksvern between 1826 and 1833, and he served in several functions over the next twenty years. In 1855 he was appointed the first Director of the lighthouse system in Norway and he initiated important constructions along the coast. He resigned in 1881, and died in Oslo on 3 March 1895.

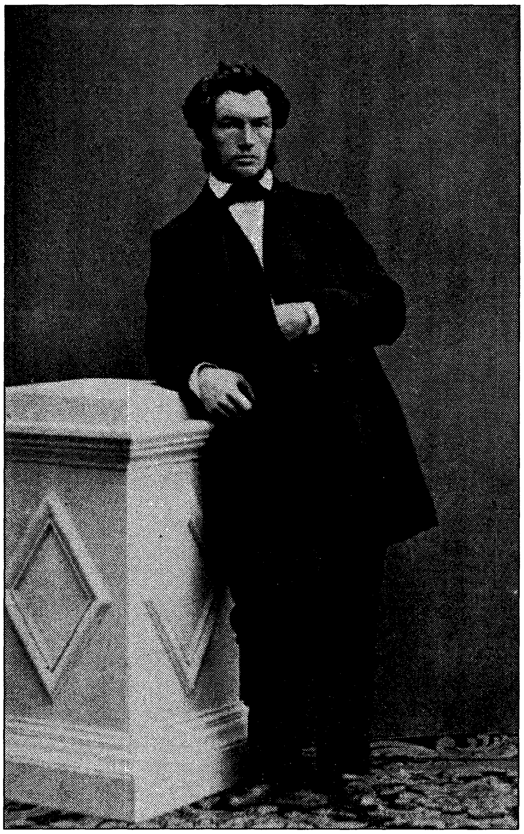

Figure 2: Carl Frederik Diriks, founder of the Bergen Observatory.

In 1852 he was engaged in bathymetry along the coast of Norway under the auspices of the Geographical Survey of Norway, a Government agency directed by Christopher Hansteen who was also Professor of Astronomy and Director of the University Observatory in Christiania (now Oslo). Diriks and Hansteen had collaborated previously. During the summer of 1847, Hansteen organised seven crossings between Oslo and Copenhagen of up to twenty chronometers in order to determine the longitude difference between the Observatories of the two capitals. Astronomer Carl Fredrik Fearnley made astronomical observations with the meridian circle at the University Observatory to determine local time in Oslo, and compared the chronometers to the Observatory pendulum clock each time they arrived Oslo. Hansteen was in Copenhagen to compare chronometers there, while astronomer J. Siewers at the Round Tower Observatory performed astronomical observations to determine local time in Copenhagen. During the crossings with the steam liner *Christiania* the chronometers were stored in Captain Diriks' cabin, and he also wound them up according to a pre-set scheme.

Immediately following his appointment in 1852 as Chairman of the Board of the Nautical School, Diriks (1854) contacted Christopher Hansteen to request advise and assistance regarding instruments for an observatory. On Diriks' behalf, Hansteen (1852) wrote to instrument makers A. & G. Repsold in Hamburg to request the cost of a transit instrument with a broken optical axis. Repsold (1852) replied immediately and offered recommendations with respect to the size of the vertical circle and optical dimensions, so that both the Sun and the Polaris could be observed during the daytime. Hansteen communicated the technical recommendations and the approximate cost estimate to Diriks on 17 October, who responded twelve days later:

> As the observatory is a case for the City Council, a rapid decision may not be expected since the financial situation will be evaluated after the nautical school has started up. I believe, however, that it is wise to prepare everything well in advance, including cost estimates for building and instruments. (Diriks 1852)

Diriks' letter also reveals his understanding of political decision making when he requests "... the opinion of the professor, whose evaluation and statement will determine the final solutions." (ibid.).

Diriks then produced a budget proposal for an observatory based on the costs of the Navy a few years earlier for a similar facility at their main base, Fredriksvern, near Stavern:

Building	300 Spd.
Transit instrument	500 Spd.
Pendulum clock	200 Spd.
Total	1000 Spd.

Fund-raising had already begun. In its statement to the City Council, the Board of the Nautical School argued that the project had already received popular support. Private donations amounting to 230 Spd had been collected by Consul Michael Krohn in Bergen, and two local insurance companies had contributed 100 Spd for the purchase of instruments for the Nautical School. The remaining 670 Spd were requested from the City Treasury.

The City Council received the case as Agenda No. 18 for 1853, *Proposition to grant the necessary financial funds from the City Treasury for the purpose of constructing an observatory equipped with a transit instrument and a pendulum clock.* The meeting took place in City Hall on 3 November 1853. The proposal to be voted upon suggested that 700 Spd should be granted from the City Treasury to set up a fully-equipped observatory. Hans Holmboe, Headmaster of Bergen Cathedral School and an influential politician throughout his life, was concerned about the economic situation and suggested that the amount should be compensated for by requesting Government funds on a later occasion. This was adopted against one vote (Bergens kommuneforhandlinger, 1853).

4 THE OBSERVATORY AND ITS INSTRUMENTS

With funds available, Diriks (1854) ordered a pendulum clock with mercury compensator from clockmaker C. Höeg in Bergen, and requested Hansteen to order the transit instrument. Hansteen (1854a) mailed the order to Repsold on 22 January 1854. A brief exchange of letters (Hansteen, 1854b; Repsold 1854) took place to decide the technical details and in March 1854 the instrument was put in production. It arrived in Bergen on 9 May 1855 (Diriks, 1855; Åstrand, 1855b). The objective lens had a diameter of 53 mm and a focal length of 600 mm. The instrument was of the 'broken-tube' type (see Figure 3) such that the eyepiece remained in a fixed horizontal position during observations. The telescope was used with a magnification of 60×, which produced a field of view of 27′ 15″. The diameter of the vertical circle was 22 cm.

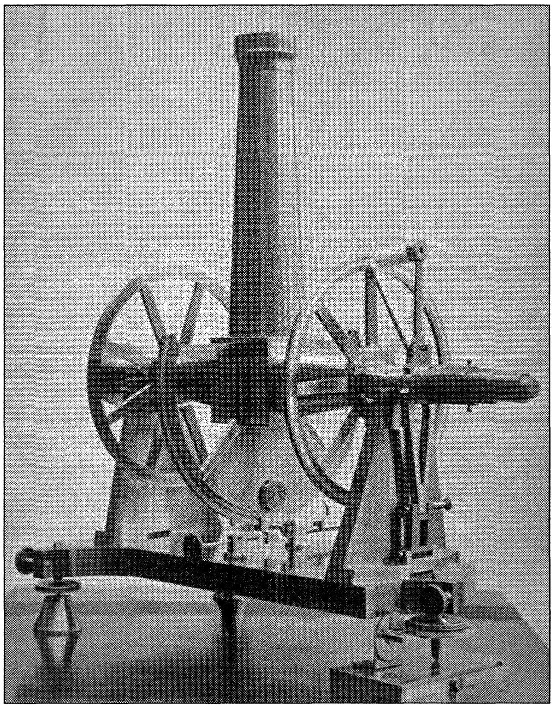

Figure 3. The Repsold transit instrument.

The tender for the Bergen Observatory building revealed that significant inflation was affecting the construction costs, so the Mayor acted swiftly and contracted the architect Kaas for 450 Spd. This was unanimously approved by the City Council after the fact, on 13 October 1854, when they also added 100 Spd to the budget (Bergens kommuneforhandlinger, 1854).

The Observatory (Figures 4 and 5) was erected northwest of Fredriksberg Fortress on the Nordnes Peninsula in Bergen. The simple, one-storied wooden building was 4.7 × 8.0 m and consisted of a central observing room with small residential rooms on each side. The observing room had meridian slits in the roof and two stone instrument pillars for the transit instrument and the pendulum clock. The construction work was completed on 20 June 1855 (Åstrand, 1855b). The final accounts by the City Chamberlain (Bergens kommuneforhandlinger, 1857a) reveal that the total costs came to 1531 Spd 84 sh, which was covered by private donations (235 Spd), contributions from insurance companies (350 Spd), a Government grant to promote the use of chronometers in shipping (450 Spd), and the City Treasury of Bergen (496 Spd 84 sh). In all, this was a very substantial expenditure, being equivalent to six times the annual salary of the City Astronomer (and in 1850, nine spesiedaler (Spd) bought one pound sterling).

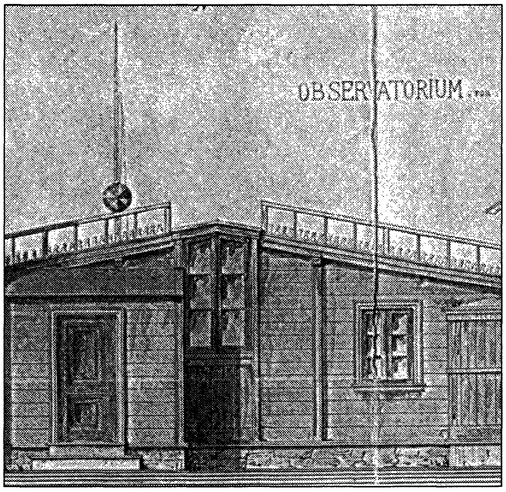

Figure 4: Bergen Observatory from the south (part of a larger drawing by F.H. Stockfleth made in 1859).

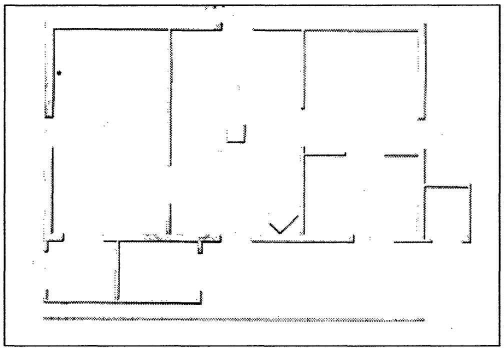

Figure 5: Floor plan of the Observatory (Åstrand, 1862).

Johan Julius Åstrand (Figure 6) had been appointed Principal at the Nautical School in Bergen on 1 February 1855 (Åstrand, 1855a) following advertising of the position in Norway, Denmark, and Sweden. Åstrand was born in Gothenburg, Sweden, on 29 September 1819. In 1838 he attended lectures in mathematics and physics by H.C. Ørsted at the University of Copenhagen, and then went to London to study astronomy. From 1839 to 1855 he taught mathematics and nautical sciences at the Nautical School in Gothenburg. In addition to teaching duties in Bergen, his responsibilities also included the Observatory and the chronometer service. Åstrand (1855b) mounted the transit instrument on the observation pillar on 21 June 1855, and set up the pendulum clock on a separate pillar in the observing room. Over the next two days he aligned the transit instrument with the meridian. Test observations were carried out throughout the summer to adjust the pendulum clock to sidereal time. Diriks (1855) wrote to Hansteen on 14 August 1855 to inform him that the transit instrument was operational. A report from Åstrand (1855b) was enclosed, and this explained the details of the adjustment.

During his first year, Åstrand's (1857) main tasks at the Observatory were time determination and chronometer service. His attempts to determine the latitude of the Observatory failed because the width of the transit slit in the roof was too narrow for observations of several bright stars on the prime vertical. In addition, longitude determinations could not be attempted because a refractor was not available to observe lunar occultations and other events. The living conditions at the Observatory turned out to be less than satisfactory. The walls had no insulation and the interior walls were painted canvas. J.K. Christie (1857), a teacher at Bergen Cathedral School and a local politician, proposed to the National Assembly that Observatory ownership be transferred to the State and that funds be made available for an immediate upgrading and expansion of the Observatory, including an annual salary for an observer who would also carry out meteorological and magnetic observations. The proposal was rejected (Åstrand, 1858a), but a compromise solution led to Åstrand being appointed full time as City Astronomer on 1 July 1857 (Bergens kommuneforhandlinger, 1857b). His salary was equally shared between the Government and the City of Bergen. The City Council also separated the Observatory organisationally from the Nautical School (Bergens kommuneforhandlinger, 1857a) and provided funds to improve the quality of the residential rooms (Åstrand 1858b). Åstrand married in June 1858, and he and his wife moved into the Observatory.

5 THE INITIAL OBSERVING PROGRAMME AND ITS RESULTS

During the first two years Åstrand was both a teacher and an observer. When the sky was clear, teaching activities were halted around noon in order for Åstrand to walk to the Observatory and observe the meridian transit of the Sun. At night he observed stars, also for the purpose of determining local time. In 1856 he observed a long series of lunar culminations and corresponding meridian transits of stars, for all observable phases of the Moon. He derived the angular distances between bright stars and the Moon and compared them to numerical values computed for Greenwich. This allowed him to determine the longitude of Bergen. Applying the method of least squares to combine the results, he found $\lambda = 21^{m}\ 12.0^{s}$ east of Greenwich (Åstrand, 1859b). This computational task was time-consuming and was completed only when he resigned as a teacher and became the full-time City Astronomer in 1857. In August of that year he also received two new chronometers from Altona in Germany. They had been set to local time at departure from Altona, and Åstrand (1859b) determined the local time upon their arrival in Bergen. The longitude derived for Bergen by this method was λ = 21^{m}08.1^s east of Greenwich.

During 1857 Åstrand (1858a) made almost 300 transit observations of the Sun and stars. The pendulum clock was continuously checked, and was used for control of twenty-seven ships' chronometers. Each month he checked the collimation of the transit instrument and found it never deviated more than 0.1s. He repeatedly observed β Cam and δ Cas in the prime vertical which yielded a preliminary latitude value of φ = 60° 23′ 54.0″. These coordinates were slightly larger than those determined at Gottfried Bohr's private observatory at Fredriksberg Fortress between 1816 and 1824. Using a sextant, Åstrand (1859b) triangulated from Bohr's location to his own observing pillar, which he found to be 0.67^s further west and 4.59″ further north. Bohr's values (1824) imply φ = 60° 23′ 50″ and λ = 21^m 07.7^s east of Greenwich for Bergen Observatory.

In the early summer of 1858 Åstrand (1858b) completed his fine adjustment of the pendulum clock, using a method described by Hansteen (1851). The height of the mercury column attached to the pendulum was changed in very small steps to adjust the clock rate in accordance with the astronomical time determinations. However, he was less fortunate during maintenance of the transit instrument. A local optician, Mr. Sjøgren, accidentally destroyed the eyepiece crosshairs when cleaning the lenses, and the instrument had to be sent to Repsold in Hamburg for a replacement set. Since the new crosshair distances were not exactly as before, Åstrand again determined the instrument's parameters and derived correction tables for the observations.

Towards the end of September Donati's Comet was a spectacular evening view in the west when the skies cleared after three weeks of rain. On 27 September 1858 the tail was developing rapidly and Åstrand had computed an ephemeris based on an orbit derived from observations in Florence, Kremsmünster, and Washington. He announced a public lecture on comets, including a prediction of the evolution of Donati's Comet (Bergensposten 1858a). People turned up in great numbers, and astronomy and Bergen Observatory were well promoted. In early October the coma and tail reached such proportions that the Comet was visible to the naked eye just after 6 o'clock in the evening (i.e. at astronomical sunset). The light distribution of the coma suggested to Åstrand that matter was flowing out from a bright spot facing the Sun and then was bent backwards into two branches stretching towards the tail with a dark space between them (Bergensposten 1858b). After perihelion the Comet's tail reached a length of 40°, standing almost perpendicular to the horizon. Åstrand predicted that the Comet would sweep across the bright star Arcturus on 5 October.

In December 1858 and January 1859 Åstrand continued a series of public lectures on topics which he could illustrate from Hinds astronomical atlas (Åstrand 1859a; Bergensposten 1858d). Public interest remained high and Åstrand took the opportunity to propose to the City Treasury that an equatorially-mounted refractor equipped with an eyepiece micrometer should be acquired. He wanted to improve the longitude by observing lunar occultations of stars, and also suggested that weekly observing evenings should be organised for the public.

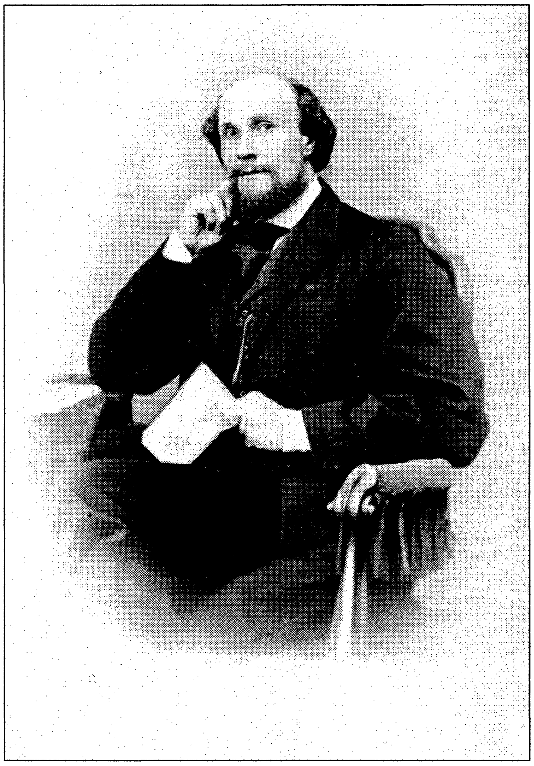

Figure 6: J.J. Åstrand, City Astronomer of Bergen (courtesy: Photographic Collection of the University Library in Bergen).

At this time the telegraph system was being established in Norway. A line from Oslo to Bergen along the southern coast of Norway was established between 1854 and 1857. Two years later an alternative line across the mountainous interior of Norway was completed, which linked Oslo to both Bergen and Trondheim. At the Naval Observatory in Horten, Captain C.T.H. Geelmuyden had collaborated since 1855 with university lecturer Carl Fredrik Fearnley in Oslo in experimenting with telegraphic transfer of time signals to determine the longitude difference. In the spring of 1859 Geelmuyden proposed to apply the method to Bergen. On six dates in May and June 1859, Åstrand received time signals from the Naval Observatory in Horten at the telegraphy office in Bergen. Hand-carrying his chronometer, he then walked to Bergen Observatory to compare the received time with local time by the pendulum clock there. This experiment yielded a longitude difference between Horten and Bergen of 20^m 46.05^s (Åstrand 1859c). A similar experiment between Oslo and Horten on eight dates between March and June yielded 0^m 54.00^s (Geelmuyden, 1859). Thus, Bergen was 21^m 40.05^s west of Oslo. The longitude of the University Observatory in Oslo was 42^m 53.5^s east of Greenwich, implying that the longitude for Bergen Observatory was 21^m 13.45^s east of Greenwich. Two of the experiments for Bergen deviated almost 2.5^s from the average value, but the rest were within ½–1^s. An estimated standard deviation of 1.5^s brought the results from lunar culminations and telegraphic time signals in good accord.

6 CONCLUDING REMARKS

In just a few years Åstrand succeeded in determining the position of Bergen Observatory with even better accuracy, and he started a regular time service by dropping a time ball at noon every Saturday (Bergensposten 1858c) and by offering a control service for ships' chronometers based on comparison with the Observatory's pendulum clock. During the first six years he collected 1,724 transit observations for determination of local time, which allowed 97 chronometers to be controlled.

In 1859 a proposal was submitted to the National Assembly, suggesting that Government funds should be made available to construct a new Observatory building in Bergen and expand the instrument collection. The City of Bergen promised to carry all future maintenance costs. It took another decade to realise this project, and Åstrand remained City Astronomer until he retired in 1898. He died in Bergen on 19 February 1900.

7 ACKNOWLEDGEMENTS

The help of librarians and archival officials are gratefully acknowledged, and thanks are also due to a referee for his helpful comments on the original version of this paper. The portrait of Diriks (Figure 2) was found on the website of the National Library of Norway (http://www.nb.no/baser/diriks/bilder/diriks1a/normalbilder/nyrecto/2ad1a-7rb.jpg). Other figures were produced by scanning photocopies of archival material in the University of Oslo Astrophysics Archives (Figure 3) and at the Bergen City Archives, (Figures 4 and 5). Figure 6 is reproduced with the permission of the Photographic Collection at the Bergen University Library.

8 REFERENCES

The following abbreviations are used:

CAB=City Archives Bergen.
NMA= Norwegian Mapping Authority Archives.
SAH=Staatsarchiv Hamburg.
UOA=University of Oslo, Astrophysics Archives.

Åstrand, J.J., 1855a. Letter to Christopher Hansteen, dated February 19. Original in UOA.

Åstrand, J.J., 1855b. Beretning om Opstillingen og Benyttelsen af Transit-Instrumentet paa Bergens Observatorium, dated August 6. Original i UOA.

Åstrand, J.J., 1857. Letter to Christopher Hansteen, dated January 7. Original in UOA.

Åstrand, J.J., 1858a. Letter to Christopher Hansteen, dated February 18. Original in UOA.

Åstrand, J.J., 1858b. Letter to Christopher Hansteen, dated June 14. Original in UOA.

Åstrand, J.J., 1859a. Letter to Christopher Hansteen, dated January 1. Original in UOA.

Åstrand, J.J., 1859b. Letter to Christopher Hansteen, dated March 5. Original in UOA.

Åstrand, J.J., 1859c. Letter to Christopher Hansteen, dated June 12. Original in UOA.

Åstrand, J.J., 1862. Report to the Magistrate of Bergen. Original in CAB.

Bergens kommuneforhandlinger, 1853. Journal No. 576/53, pp. 221-228; Formandskabets protokol No. 3, pp. 27-33. Original in CAB.

Bergens kommuneforhandlinger, 1854. Journal No. 494/54, pp. 313-15; Formandskabets protokol No. 3, p. 337. Original in CAB.

Bergens kommuneforhandlinger, 1857a. Formandskabets kopibog No. 4, pp. 145-153; Formandskabets protokol No. 4, pp. 179-187. Original in CAB.

Bergens kommuneforhandlinger, 1857b. Formandskabets kopibog No. 4, pp. 288-303; Formandskabets protokol No. 4, pp. 343-349. Original in CAB.

Bergensposten, 1858a. September 28 (No. 77).

Bergensposten, 1858b. October 15 (No. 82).

Bergensposten, 1858c. October 19 (No. 83).

Bergensposten, 1858d. December 3 (No. 96).

Bohr, G., 1824. Stjernen υ Leo Bedækning af Maanen. *Magazin for Naturvidenskaberne*, 4, 261-267.

Bugge, T., 1784. Observationes Astronomicæ Annis 1781, 1782 & 1783. Copenhagen, Nicolai Möller.

Christie, J.K., 1857. Til Norges femtende ordentlige Storting. Handwritten proposal to the National Assembly, dated January 16. Original in UOA.

Diriks, C.F., 1852. Letter to Christopher Hansteen, dated October 29. Original in UOA.

Diriks, C.F., 1854. Letter to Christopher Hansteen, dated January 9. Original in UOA.

Diriks, C.F., 1855. Letter to Christopher Hansteen, dated August 14. Original in UOA.

Friis, F.R., 1904. *Peder Jakobsen Flemløs, Tyge Brahes første Medhjælper, og hans Observationer i Norge.* Kjøbenhavn, G.E.C. Gads Universitetsboghandel.

Geelmuyden, C.T.H., 1859. Letter to Carl Fredrik Fearnley, dated July 21. Original I UOA.

Hansteen, C., 1823. *Sphærisk Astronomie*. Christiania, no publisher listed.

Hansteen, C., 1851. En simpel Methode til nøjagtigt at regulere et astronomisk Pendeluhr. *Nyt Magazin for Naturvidenskaberne*, 6, 30-36.

Hansteen, C., 1852. Letter to Repsold, dated September 28. Original in SAH.

Hansteen, C., 1854a. Letter to Repsold, dated January 22. Original in SAH.

Hansteen, C., 1854b. Letter to Repsold, dated March 1. Original in SAH.

Pettersen, B.R., 2002. Christopher Hansteen and the first observatory at the University of Oslo, 1815-1828. *Journal of Astronomical History and Heritage*, 5, 123-34.

Repsold, A., and G., 1852. Letter to Christopher Hansteen, dated October 5. Original in UOA.

Repsold, A., and G., 1854. Letter to Christopher Hansteen, dated February 3. Original in UOA.

Schroeter, I.F., 1905. De ældste breddebestemmelser i Norge. *Naturen*, 29, 234-242.

Vibe, N.A., and Aubert, B., 1792. Logbook of astronomical observations. Original in NMA.

Wargentin, P., 1784. Nogle Norske Stæders Geographiske Beliggenhed. *Nye Samling af det Kongelige Norske Videnskabers Selskabs Skrifter*, 1, 411-430.

Wurm, J.F., 1831. Ueber die Länge von Yenikale, Tagauros und Tula in Russland, Bergen in Norwegen und der neuren Sternwarte in Hamburg. *Nachrichten*, 9, 139-144.

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Journal of Astronomical History and Heritage, 8(2), 129-130 (2005).

A CHINESE OBSERVATORY SITE OF 4,000 YEARS AGO

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The southern part of the Shanxi Province has been considered as the region where the capital of the Xia Dynasty (ca. 2,000–1,600 B.C.), the first Chinese Dynasty, was located. In this area, more than eighty archaeological sites of the Longshan Culture (ca. 3,000–2,000 B.C.) have been reported, including the most famous one at Taosi Village, Xiangfen County, Shanxi Province, which was found in the 1950s. From 1978 to 1984, large-scale excavations were carried out at this site. The data from more than 1,300 tombs and a large number of houses indicate that the contemporary society was hierarchical. Other unearthed artifacts included an enormous number of implements and utensils (made of stone, pottery and wood), and sacrificial items such as large chime stones and drums. It has been confirmed by radiocarbon dating that the Taosi Culture existed from 2,500 to 1,900 B.C.

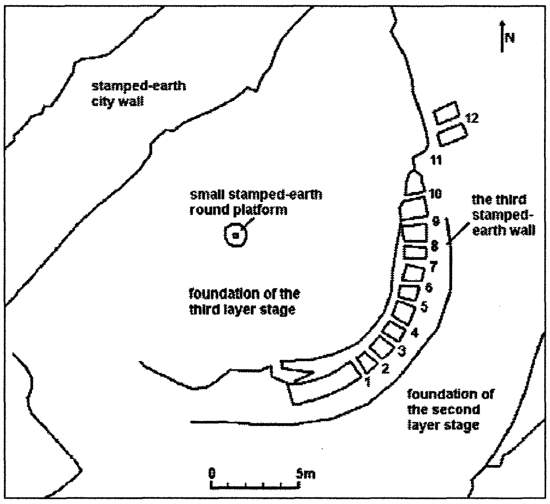

Figure 1: Sketch of the central part of Site II FJT1.

Most recently, the Archaeology Institute of Chinese Academy of Social Sciences, the Archaeology Institute of Shanxi Province and the Culture Relics Bureau of Linfen City (abbreviated hereinafter as AICASS, AISP and CRBLC, respectively) have jointly conducted a further round of excavations. They have found and identified a small city of early Taosi Phase, a large city of middle Taosi Phase, another small city of middle Taosi Phase, areas for sacrifice and storage, palaces, etc. The most exciting discovery is Site II FJT1, a large round stamped-earth building (AICASS, AISP, and CRBLC, 2003).

The large city of middle Taosi Phase is approximately square in shape and its area is almost 3 million square meters. Its southeast wall is shared by a rectangular enclosure, which is the so-called small city of middle Taosi Phase and is regarded as the area for sacrifices. Site II FJT1 is located in this small city, immediately adjacent to the city wall of the large city, and comprises a three-layered semi-round stage that faces southeast and is surrounded by three stamped-earth walls. Along the top layer stage are a set of curved stamped-earth pillars whose bases are 2~3m in depth (see Figure 1). Those extant pillars are 6~10cm high and contain intervening gaps that are filled with unstamped earth. Excavations show that the tops of the pillars, the three walls, and the wall of the large city are roughly at the same level, which is about 1m below the current ground level (see Figure 2).

Archaeologists at the site immediately realized that these pillars possibly belonged to a building that was used to observe sunrise and determine the seasons (He Nu, 2005). In order to test this hypothesis, they spent a whole year making sunrise observations. First, they determined the center of the circles to which the curved wall and the pillars belonged. The distance between the center and the inner side of gaps 1-10 in Figure 1 is ~10m. From the center, one can see through all of these gaps. Then, the archaeologists made a 4-m high iron frame, which was adjustable so that it could be positioned in each of the twelve gaps. By setting up the iron frame, the archaeologists were able to reconstruct the ancient observations.

According to the observations, the Sun was seen through gap 7 when the bottom of the Sun just touched the top of a mountain to the east on both the Spring and Autumn Equinoxes. However, the Sun could not be seen through gap 2 when the Sun rose on the Winter Solstice (the bottom of the Sun just touched the top of the mountain): instead, by the time it was visible through gap 2 several minutes later, the Sun was already above the mountain. Considering the half degree change in the obliquity of the ecliptic over the past 4,000 years, an astronomical calculation shows that a 'sunrise' just take places at the center of gap 2 on the Winter Solstice! The same situation occurred on the Summer Solstice: a calculation proved that 4,000 years ago sunrise was visible through 12 gap (Wu Jiabi, and He Nu, 2005)—whereas it is not visible today.

These observations and modern astronomical calculations provide convincing evidence that one reason for the construction of these stamped-earth pillars was to observe sunrise and determine the seasons. As for some of the other gaps between the pillars, it is suggested that they were used to determine certain dates of the contemporary calendar. For instance, gap 1 was possibly connected with lunar observations.

It needs to be pointed out that the center used by the archaeologists to observe sunrise had not been excavated when they conducted their observations. Subsequent excavations showed that there was a small round stamped-earth platform under this spot. The difference between the center of that spot and the center of the platform was only 4 cm! This discovery provides further evidence that Site II FJT1 was an astronomical observatory (AICASS, AISP, and CRBLC, 2005).

Subsequent excavations did not reveal any site used for sunset observations.

It has been confirmed, both by early Chinese texts and by astronomical relics, that it had all along been a tradition for the Chinese to determine seasons and calendar dates by measuring the length of the solar shadow at noon. This is an obvious difference between Chinese civilization and other civilizations of the world. In early Chinese texts, there are very few, if any, records about determining the seasons through observation of the sunrise or sunset. Furthermore, no Chinese sites used to observe sunrise or sunset had been found prior to the discovery of II FJT1. Therefore, this discovery is of great significance to historians of Chinese astronomy. Archaeological evidence and astronomical analyses both show that it is a Chinese observatory site that was built about 4,000 years ago.

REFERENCES (all in Chinese)

AICASS, AISP, and CRBLC, 2003. A brief report on excavation of large foundations in the sacrificial area of the city at Taosi, Xiangfen, Shanxi in 2003. *Kaogu*, 7, 9-24.

AICASS, AISP, and CRBLC, 2005. New progress of excavations of the site at Taosi, Xiangfen, Shanxi in 2004 and 2005. *Bulletin of the Center of Ancient Civilizations of CASS*, 10.

He Nu, 2005. Notes about the excavation of a large building II FJT1 in the small city of middle Taosi Phase. *Bulletin of Studies in Ancient Civilizations*, 47-58.

Wu Jiabi and He Nu, 2005. A preliminary study about the astronomical date of the large building II FJT1 at Taosi. *Bulletin of the Center of Ancient Civilizations of CASS*, 8, 50-55.

Figure 2: Scene of excavation, and showing the iron frame.

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OBITUARY: JOHN LOUIS PERDRIX (1926-2005)

On 27 June 2005 the *Journal of Astronomical History and Heritage* lost its founder and Australia lost one of its leading historians of astronomy when John Louis Perdrix died in Dubai after a brief battle with cancer.

John Louis Perdrix (Figure 1) was born in Adelaide on 30 June 1926, the third and final child of Alf and Winifred Perdrix. His parent led an almost peripatetic existence, so young John was educated at a succession of boarding schools before studying chemistry at Melbourne Technical College. After working as a research chemist for a company and then setting up his own business, in the early 1970s he joined the Commonwealth Scientific and Industrial Research Organisation and became involved in geochemical research. In 1974 the Division of Minerals and Geochemistry was relocated to Perth, and John spent the remainder of his life in the Western Australian capital (on the far side of the Australian continent) where he developed close bonds with geological colleagues that were to endure long after retirement.

From his teenage years John was interested in astronomy, and he was able to indulge this through the Astronomical Society of Victoria and the short-lived Victorian Branch of the British Astronomical Association. He served two sessions as President of the former society and was Secretary/Treasurer of the latter for much of its existence. After moving to Perth, he founding the Astronomical Society of the South West, while at the national level, he co-founded the National Australian Convention of Amateur Astronomers (NACAA), and religiously attended the triennial conventions. On the international front, John was a long-standing member of both the BAA and the RAS. He was also a member of the IAU, and was active in Commission 41 (History of Astronomy).

John's principal astronomical passion was the history of astronomy, and over the years he published a succession of research papers, popular articles, reports and book reviews in a variety of journals and conference proceedings. Most of these contributions dealt with aspects of Australian astronomical history, and the most significance ones are listed at the end of this obituary.

To sustain his historical interests and support his research activities, John built up an extensive library which developed a personality of its own and quickly took over his house and garage before invading commercial storage facilities.

Apart from editing the *Journal of the Astronomical Society of Victoria* for many years and producing various NACAA proceedings, from 1985 to 1997 John issued the *Australian Journal of Astronomy* through his own publishing house, Astral Press. In the main, this featured research papers and reports from Australian and New Zealand amateur and professional astronomers, but by 1997 John was seeking new challenges and en route from Australia to Japan for the Kyoto IAU General Assembly the two of us spent the long flight discussing various options.

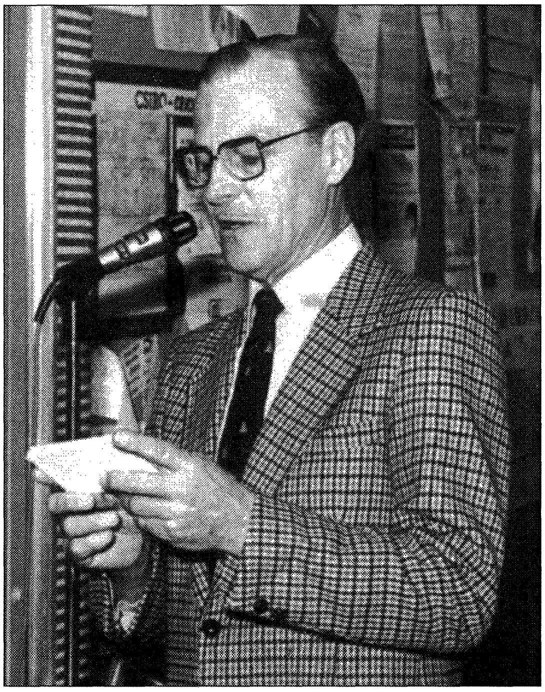

Figure 1: John Louis Perdrix, 1926-2005 (Orchiston Collection).

By the time we landed in Japan we had decided to close down the *Australian Journal of Astronomy* and launch a new international journal, which we dubbed the *Journal of Astronomical History and Heritage* (with the distinctive acronym, *JAH*^{2}). The final choice of journal, incidentally, was between astronomy education and history of astronomy, as we felt these were the only two astronomical fields that urgently needed a new specialist international journal at that time. Both of us had a passion for astronomical history, and although the *Journal for the History of Astronomy* played a vital role in servicing the international community, the recent demise of the RAS's *Quarterly Journal* and the more or less simultaneous decision by the new masters of *Vistas in Astronomy* to refuse historical papers made our final decision an easy one. So, John would serve as Managing Editor, and would look after subscriptions, book reviews, production and mail outs, while I would assemble an Editorial Board, seek the support of C41, chase up papers and IAU reports, and serve as Papers Editor. Both of us would market the new journal.

Fortunately, we were able to assemble an outstanding Editorial Board, C41 readily gave us its blessing, and Steve Dick (then President of C41), Mary Brück and Jay Pasachoff all agreed to supply substantial papers for the inaugural issue. The rest is history … and for seven years John and I worked closely together, despite living on opposite sides of the Australian continent. I would send him the edited papers, along with figures and tables, and he would assemble the journals (e.g. Figures 2 and 3), and see each issue through the press and off to subscribers. Because of our frequent e-mails and regular lengthy telephone calls there were few problems.

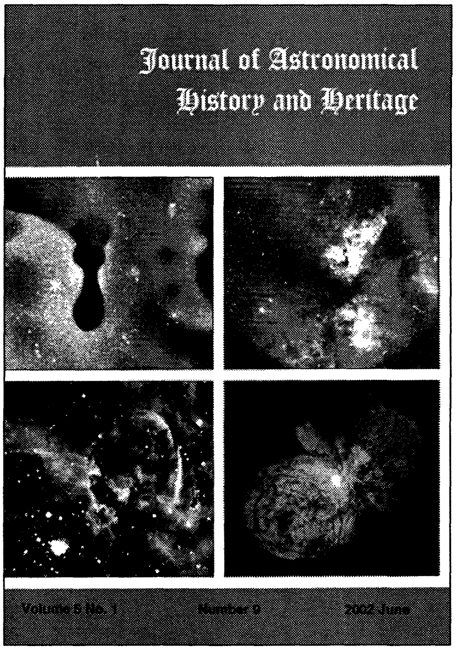

Figure 2: The cover of the original B4 version of the journal included four different images of η Car, two of which were in colour.

This idyllic existence changed dramatically in June 2004 when John was diagnosed with terminal cancer, but he continued to share his time between his Perth friends, astronomy and chemotherapy. Eventually it became obvious that the long-term survival of the *Journal* required a new arrangement, and John was very relieved when we reached an agreement with James Cook University for their newly-founded Centre for Astronomy to take over *JAH*^{2}. Astronomer and Deputy Vice-Chancellor, Professor Harry Hyland, played a key role in facilitating this.

John's last issue was to be the December 2004 number, and its production proved an almost insurmountable challenge. Yet this was something that he insisted on doing, before formally handing the journal over to the University. John then joined the Editorial Board, and I took over all editorial responsibilities, as I prepared to join the staff and move to Townsville (where my other primary role would be to develop history of astronomy at the masters and doctoral levels). The first James Cook issue came off the press in June, complete with a cover 'make-over' and a revised internal format. My principal regret is that John did not live to see this new version of the journal he so cherished.

After completing his last journal John noticed that the cancer seemed to go into remission and he decided to make one last overseas trip, a long-anticipated visit to St Petersburg. It was while he was returning to Australia that the illness aggressively reappeared, and he was taken off the aeroplane at Dubai. He died peacefully in Rashid Hospital three days later, just three days short of his seventy-ninth birthday.

Always the consummate gentleman, John possessed a sharp intellect and a keen sense of humour. He was wonderful company and a dear friend, and will be greatly missed. But his legacy—in the form of *JAH*^{2}—will live on. Our condolences go to his six children, Louise, John, Timothy, Fleur, Lisa and Angella.

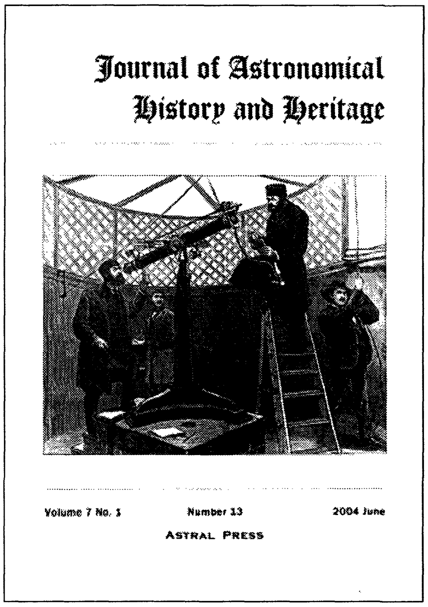

Figure 3: In 2003 the A4 format was introduced. From this time on, each cove featured a different image.

John Perdrix: Selected Research Papers

Perdrix, J.L., 1961. Melbourne Observatory. *Journal of the Astronomical Society of Victoria*, 14, 19-25, 45-48, 60-64.

Perdrix, J.L., 1970. The Great Melbourne Telescope. *Journal of the Astronomical Society of Victoria*, 23, 54-67.

Perdrix, J.L., 1972. The Astronomical Society of Victoria: the beginning. *Journal of the Astronomical Society of Victoria*, 25, 30-36.

Perdrix, J.L., 1988. The Stockport Starcastle Observatory. 1: The Building. *Australian Journal of Astronomy*, 2, 159-164.

Perdrix, J.L., 1990. Flagstaff Hill and its Observatory. *Australian Journal of Astronomy*, 3, 113-124.

Perdrix, J.L., 1992. The last great speculum: the 48-inch Great Melbourne Telescope. *Australian Journal of Astronomy*, 4, 149-163.

Orchiston, W., and Perdrix, J., 1990. The British Astronomical Association in Australia: a centennial perspective. *Australian Journal of Astronomy*, 3, 163-179.

Orchiston, W., and Perdrix, J., 2002. A history of the British Astronomical Association in Australia: the fate of the Branches. *Journal of the British Astronomical Association*, 112, 68-77.

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Journal of Astronomical History and Heritage, 8(2), 135-139 (2005).

BOOK REVIEWS

***The Emergence of the Telescope: Janssen, Lipperhey, and the Unknown Man, by* M. Barlow Pepin (Duncanville, Texas, T Tauri Productions, 2004), pp. 42, ISBN 0-9758527-0-1 (paperback), US$19.95 plus postage.**

Who invented the telescope? Good question. The short answer is that no-one knows, exactly. We do know that the first name associated with the telescope's debut on the world stage is that of Hans Lipperhey, a humble spectacle-maker who petitioned the government of the fledgling Dutch republic for a patent on the invention late in September 1608. His timing was perfect, coinciding with tense diplomatic negotiations between the Dutch and the Spanish, who had been at war since 1568. But within three weeks, two other individuals had applied for similar patents, so it is questionable whether Lipperhey was the true originator of the telescope.

The contemporary documents that relate these events were uncovered early in the twentieth century by another Dutchman, Cornelis de Waard, and presented, together with related evidence, in his *De Uitvinding der Verrekijkers* (The Hague, 1906). It was in assembling and translating these original sources for a wider readership that the modern historian, Albert Van Helden, performed perhaps the greatest service to today's scholars. He wrote a detailed analysis of their contents in 'The Invention of the Telescope' (*Transactions of the American Philosophical Society*, Volume 67, Part 4, 1977), a monumental work that has become the yardstick against which all subsequent commentaries on the origin of the telescope are judged. It should not be assumed, however, that Van Helden solved all the problems (and, indeed, he made no claim to have done so). The evidence is a maze of contradictory statements and reports, often with well-known historical names intermingled with shadowy figures in confusing circumstances. It is a very difficult area.

Into this minefield has stepped the brave author of *The Emergence of the Telescope*, the late M. Barlow Pepin. His stated purpose is to take a 'fresh look' at the circumstances under which the telescope emerged. While no significant new evidence has come to light since Van Helden's work, Pepin does draw some previously unrecognised threads together in arriving at a conclusion not too different from de Waard's of a century earlier—but with rather greater emphasis. The telescope was perfected not by Lipperhey, says Pepin, but by one Saccharias Janssen, a spectacle-maker, peddler and small-time crook, who secretly presented an example to the authorities shortly before Lipperhey got around to it.

Whether or not you agree with this verdict doesn't really matter. The pleasure is in the journey, for *The Emergence of the Telescope* presents the evidence in a thoughtful, well-written and at times very entertaining way. The book is well-illustrated and delightfully presented. You still have to keep a clear head to avoid sinking in the mass of documentation, but the cross-referencing is, for the most part, up to the task. *The Emergence of the Telescope* is a worthy adjunct to Van Helden's work, and a useful contribution to the scholarly literature. I only wish I'd had a copy a few years ago, when I made my own foray into this morass …

Fred Watson
Anglo-Australian Observatory

***The Early Years of Radio Astronomy. Reflections Fifty Years after Jansky's Discovery* (Reprint edition), edited by W.T. Sullivan III (Cambridge, Cambridge University Press, 2005), x + 421, ISBN 0 521 61602 6 (paperback), AU$130:00.**

For many years, Woody Sullivan's 1984 edition of *The Early Years of Radio Astronomy* has been one of my favourites. It takes pride of place in the radio astronomy section of my library, is frequently referred to, and consequently over the years has become rather tired-looking. What I needed was a second copy, but for far too long this 'classic' of historic radio astronomy has been out of print.

Now Cambridge University Press has finally come to the rescue by issuing a long-anticipated reprint. This faithfully reproduces the original volume, which is split into five discrete sections: "The Earliest Years", "Australia", "England", "The Rest of the World" and "Broader Reflections". Chapters in the first section were penned by Woody himself, Grote Reber and Jesse Greenstein, and they focus on those acknowledged 'founding fathers' of radio astronomy, Karl Jansky and Grote Reber. The Australian and UK sections which follow reflect the pre-eminent position of these two nations during the late 1940s and throughout the 50s, as nicely documented in papers by Taffy Bowen, Ron Bracewell, Robert Hanbury Brown, Chris Christiansen, Frank Kerr, Bernard Lovell, Bernie Mills, Peter Scheuer and Grahame Smith. The fact that half of these luminaries are still alive reminds us that radio astronomy is a comparatively recent phenomenon. "The Rest of the World" features papers about early radio astronomy in Canada, France, Japan and Russia, four nations that were particularly active during the 1950s, and the final section of the book goes beyond national perspectives by looking at the sociology of early radio astronomy, the radio astronomy-cosmology interface and possible future research trends.

The *Early Years of Radio Astronomy* may have first appeared more than twenty years ago, but this 431-page tome remains as valid and important today as it was then. It is mandatory reading for all those wishing to embrace the history of radio astronomy; indeed, it is the first book I have all my new history of radio astronomy doctoral students read! I congratulate CUP on having the vision to reprint this book, and recommend it to anyone with an interest in radio astronomy—past or present.

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***England's Leonardo: Robert Hooke and the Seventeenth-Century Scientific Revolution*, by Allan Chapman (Bristol, Institute of Physics Publishing, 2004), pp. xv + 330, ISBN 0 7503 0987 3 (hardcover), £24.99, US$ 39.99.**

Although I went to school in Robert Hooke's native country, I was not taught much about him. Of course we learned Hooke's Law—in its Latin form, *ut tensio sic vis*—and I soon became aware of his pioneering work with the microscope, if only because his drawing of the eye of a fly has been so frequently reproduced. I went on, however, to graduate in astronomy without learning much more about the man. Even his quarrel with Newton was something of which I was only dimly aware. As a graduate student, I met a fellow-student who told me that he was fascinated by Hooke and thought that the man had been sadly neglected. I not only could not enlighten him, I could hardly either agree or disagree. My friend was ahead of his time; our conversation took place half a century ago, just before what Chapman describes in his Preface as "… the first modern scholarly study of Hooke's whole life and career …" was published by Margaret Espinasse. But for a most unfortunate accident that took his life only a few months after our conversation, my fellow-student might have become one of the scholars who contributed to rectifying the neglect of Hooke. That past half-century has seen considerable scholarly activity in the study of Hooke and his period, culminating in a flurry of books published around the time of the tercentenary, in 2003, of his death. At least one other author has compared Hooke to Leonardo da Vinci. In the meantime, although I have not been even on the fringe of this work, I have at least progressed beyond the abysmal ignorance of my schooldays. I came to Chapman's account fully prepared to learn of Hooke's wide-ranging versatility, but still a little skeptical of the comparison between him and Leonardo.

Hooke's versatility is beyond question and brooks comparison with Leonardo's, including as it did experiments with model flying machines. Chapman emphasizes that versatility by devoting successive chapters, each to one or two fields of Hooke's work. Thus we have chapters on "Breathing, Burning and Flying", "Microscopes and Meteorology", "Hooke and the Astronomers", "Surveyor to the City of London" and "Hooke's Geological Ideas", to mention only some. I found the last of these the most interesting. Seventeenth-century geology has seemed to me to offer nothing but a choice between John Ray's hesitant speculations about what the discovery of fossils might imply for what he called the 'novity' of the Earth, and the (to our minds) fantastic scheme of Thomas Burnet. Chapman shows Hooke's approach to have been more modern in spirit than either of these; in some respects he anticipated the ideas of Hutton and Lyell more than a century after him.

Why has Hooke been so forgotten? Of course, the quarrel with Newton is a factor, especially since Newton, the younger man, outlived him and was in a position to impose his own version of history on the record. Chapman also suggests that Hooke often did not claim credit for his many inventions until his priority was questioned, so genuine doubts existed, even in his lifetime, about many of his achievements. Hooke's very fertility of invention may have counted against him; he became known as a 'mechanic'—a term that later was to have connotations of someone inferior to natural philosophers.

This book is a biography of the man and not just an account of his scientific work. Chapman is at pains to give us a rounded portrait of Hooke's personality. Newton's version of events has left us with the picture of a sour, curmudgeonly recluse. There *was* an irascible and quarrelsome side to his nature, but Hooke had many friends—particularly Sir Christopher Wren and Samuel Pepys—who enjoyed the society of the London coffee shops, and he had a distinguished international reputation when Newton was still relatively unknown.

Hooke lived through a time of turmoil in England, including the Civil War, the Commonwealth and the Restoration. Although he was only in his teens when Charles I was beheaded, Hooke's sympathies seem to have been Royalist; he disliked Puritans and Puritanism. This can perhaps be attributed to his upbringing; his father (who also died while the son was in his teens) was a clergyman, probably of Laudian persuasion. Later in life, Hooke came under the influence of quite senior clergy of that persuasion, and, indeed, counted them among his friends. Since the work of R.K. Merton, it has become fashionable to see the flowering of natural philosophy in seventeenth-century England as connected in some way with the rise of Puritan or Calvinist values. Hooke would provide an interesting counter-example, were it not for the fact that, for much of his life, his religious observances seem to have been entirely nominal. Unlike his mentor Boyle, and his adversary Newton, Hooke does not seem to have been motivated in his research by religious ideas.

Chapman even discusses Hooke's sexual life, which was certainly not Puritan and probably would have offended his Laudian clerical friends as well, had they been aware of it. Hooke never married but he was certainly not celibate. He seemed to regard it as a matter of right to enjoy sexual relations with his maidservants, and had a long incestuous affair with his niece, in a period when the taboo against incest was especially strong. Considering that the niece was not only a minor, but his ward at the time, even today Hooke would be in danger of a long period of imprisonment should the relationship become publicly known.

Ideally in a review like this, I should tell readers how this book compares with the other recent books about the man. Having only browsed through those others, which Chapman himself praises in his Preface, I cannot do so. My impression is that this is the most comprehensive as a biography. The book is readable and errors of proof-reading are few, although, surely, on p.74, where we are told that Hooke "seems to take the facts of both geocentricism and cosmological vastness as read", the context demands "heliocentricism". More serious and surprising is the quoting, on p.92, of Aristotle's belief that stars may be seen in daytime from the bottom of a deep well, without any reference to modern discussions of the matter. I was also puzzled by the reference on p.198 to a falling body increasing "its velocity by a factor of 32 for every second of fall". Surely Hooke would have realized that the numerical value of the factor depends on our measuring distances in feet and time in seconds. Would he not have seen, as Newton did, that Galileo's discovery that the distance travelled is proportional to the square of the time provides the more fundamental relation, independent of the units used?

Such details are relatively minor, however. The book can be safely recommended as providing an excellent account of a major figure in the scientific revolution who has been unjustly neglected. But was Hooke really another Leonardo? He was versatile and highly competent, but did he have the touch of genius? Here, different opinions can be honestly held. We still remember Leonardo primarily for his paintings. Hooke was a highly skilled draughtsman (Chapman provides enough examples in the illustrations to his book to place that beyond all doubt) and also a skilled architect, although most of his buildings no longer exist. Hooke, however, never left us a *Last Supper* or a *Mona Lisa*, and for that reason I place the Italian on a higher level—but perhaps I am idealizing Leonardo.

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***The Astronomer of Rousdon. Charles Grover 1842–1921*, by Barbara Slater (Norwich, Steam Mill Publishing, 2005), pp. [iv] + 276, ISBN 1 898 737 30 4 (paperback), £9.95.**

What a fascinating book about a truly remarkable character! Although I had heard of Charles Grover, I have to admit that I knew embarrassingly little about him before I plunged into this delightful little book. And what an adventurous journey it proved as we traced Charles' life from humble British beginnings; through his acquaintance with distinguished astronomers and instrument-makers like Dr John Lee, the Reverends Cooper Key and T.W. Webb, and George With; a brief period of employment with John Browning; that unforgettable expedition to Australia in order to observe the 1882 transit of Venus; and his subsequent career as Astronomer at Cuthbert Peek's Rousdon Observatory.

Charles Grover is the perfect example of Allan Chapman's working class astronomer, but one who definitely 'made good'. Trained as nothing more than a brush-maker and with little formal education, he taught himself astronomy, acquired a (very) small refractor, made and reported his observations, came to the attention of men of influence, and eventually went on to fulfill his lifetime ambition and work as an astronomer. In the process, he was elected an FRAS, came to be respected by people like Professor H.H. Turner, established a reputation as a variable star worker, and published a succession of notes and research papers mainly in the *Journal of the British Astronomical Association*.

Of special interest for me was Grover's Australian sojourn of 1882 associated with the transit of Venus. He went along as the astronomical assistant of a wealthy young British amateur astronomer named Cuthbert Peek, who was a member of the British expedition led by Captain William Morris. After the passage of more than a century, perhaps the best-known member of Morris's party would have to be Lieutenant Leonard Darwin. Morris' party was well-equipped, and arrived in Australia with ample time to spare. After visiting Melbourne and Sydney Observatories, they ventured further north to Jimbour—a day's journey west of Brisbane—where they settled into a stately mansion, and set up their portable observatories and instruments nearby. Unfortunately, all these careful preparations counted for naught on the vital day when heavy cloud cover denied them even a glimpse of the Sun, and they returned to England empty-handed. This whole episode occupies about ~45% of the book and therefore is described in intimate detail, often by way of lengthy quotations drawn directly from surviving Grover manuscripts. Also included in the Australian section of the book are sketches that Grover made, and photographs of the transit party personnel and their instruments.

Upon returning from Australia, Grover was offered and accepted the post of Astronomical Observer at Peek's Rousdon Observatory in Devon, which featured the 6-in Merz refractor that traveled with them to Queensland for the transit. Despite its very modest aperture, Grover was able to make a useful series of variable star observations. He also maintained a fully-equipped meteorological station. Observations continued to flow out of the Rousdon Observatory until 1920, just one year before Grover's death at the age of 79.

In assembling this book, Barbara Slate has succeeded in weaving a fascinating web that entwines adventure, astronomy, social history and even a splash of Australiana. Along the way we are exposed to shipboard life and the Australian Aborigines, and at the end of the book we are introduced to the idea that Thomas Hardy may have used Charles Grover as inspiration for his astronomer, Swithin St Cleve, in *Two on a Tower*. And, throughout its 276 pages we also learn much about astronomy. But the author does not claim to be an astronomer and this is no scholarly reference book, so we should perhaps excuse those occasional astronomical lapses, such a thinking that Tebbutt's 'Great Comets' of 1861 and 1881 were one and the same when in fact they were two quite distinct visitors. Nor did Tebbutt possess an observatory—let alone a 4.5-in Cooke refractor—back in 1861, as these only came later, in 1863 and 1872, respectively. These issues aside, *The Astronomer of Rousdon …* is a delightful read, and I thoroughly recommend that you add it to your library. At just £9.95 it is both affordable and excellent value.

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***Stromlo, An Australian Observatory,* by Tom Frame and Don Faulkner (Sydney, Allen and Unwin, 2003), pp [xiv] + 364, ISBN 1 86508 659 2 (paperback), $A35.**

This is an exciting well-researched history of the life of Stromlo Observatory from its conception until it was partially destroyed by a bush fire in January 2003, nearly eighty years later. The book was written by a leading historian, Tom Frame, and one of the Observatory's senior research astronomers, the late Don Faulkner, and they detail the personalities involved and the significant contributions that have been made to international astronomical research.

The Foreword is by Professor Jeremy Mould, a former Director, and he highlights how the Observatory's history witnessed its ups and downs. He also points out that the authors had access to a wealth of documentation to drawn on, not to mention verbal contact with many of the 'key players'.

The book opens with a long introduction, where it is suggested that many philosophers of science consider that the two hundred and fifty years from Copernicus in 1473 to Newton in 1727 witnessed the birth of science and the 'need to know'. This same 'need to know' was instilled in Geoffrey Duffield while still a research student, and it drove him for the next twenty years as he fought to establish a solar observatory in the Southern Hemisphere. His efforts were finally rewarded when site pegs were driven into the ground at Mount Stromlo, near the nation's capital, in 1911. Quite rightly so, Duffield became the first Director, and he oversaw the establishment and construction of the first buildings. He also hired staff and obtaining the first telescopes. Without his efforts it is unlikely that non-positional astronomy would have been established in Australia so soon after the Federation of the nation. Geoffrey Duffield died on the Mountain in 1929, and was buried there.

The authors then document the activities of the Observatory through the various Directors as they impose their different astronomical ambitions and interests. Because the Observatory was dependent on Government funding, the successive Directors spent a significant portion of their time lobbying politicians. Woolley, who succeeded Duffield, worked hard to get astronomy introduced into the new Australian National University and although this eventually happened, the struggle between the Observatory and the CSIRO's Division of Radiophysics (which concentrated on radio astronomy) is entertaining to read about.

As the years passed the city of Canberra began to grow rapidly and it became obvious that light pollution would become a problem. Under the Directorship of the inimitable Bart Bok, an extensive site survey program was carried out, and Siding Spring Mountain in mid-west New South Wales was ultimately chosen as the field station for all future major developments. Initially, 16-in, 24-in and 40-in Boller and Chivens telescopes were installed there.

When Woolley became Astronomer Royal in 1956, he took with him to England an ambition to build a large telescope at Siding Spring as a joint venture between Britain and Australia. Although he was successful and the 3.9-m Anglo Australian Telescope (AAT) was built, politics intervened and Stromlo was not able to play the key role that was initially intended.

From this point Stromlo moved relatively quickly from individual research projects to large-scale international projects, and under the various Directors became known internationally as a builder of new and innovative instruments (including the 2.3 m Advanced Technology Telescope, which was installed at Siding Spring in May 1984).

Frame and Faulkner note that some of the research that was carried out during this period did not receive the attention it deserved. For example, the fourth Director, Olin Eggan, followed his own research interests and obtained an unexpected and largely unheralded result when he identified some of the moving groups in the halo of our Galaxy.

The first Director appointed from the internal staff was the former radio astronomer, Don Mathewson, and he widen Stromlo's involvement in multi-wavelength research by using the CSIRO's new 64-m Parkes Radio Telescope to show that there is a bridge of gas linking our Galaxy and the Large and Small Magellanic Clouds. Mathewson is also credited with bring Stromlo into the Space Age.

Alex Rodgers was the next Director appointment from among the existing staff, and it was he who decided to assign the refurbished Great Melbourne Telescope to the MACHO Project, an ambitious search for the enigmatic 'missing mass'. This began in 1992 as a four year project, but ended up running until 1999. During this period, the MACHO team took 200,000 million individual photometric measurements, and numerous microlensing events were identified. While this was a significant result, the success of the MACHO Project caused some ill feeling amongst other astronomers at Stromlo who missed out on funding for their projects.

The next Director was Jeremy Mould, and he took Stromlo further into the arena of major international projects by committing the Observatory to the 2dF Galaxy Redshift Survey and Mapping of the Galaxies. Unfortunately, his successor, Penny Sackett, hardly had time to settle into her new role before the 2003 bush fire swept across Mount Stromlo and destroyed much of the Observatory. But her first words to the staff after the fire are worth noting: "Fortunately, the Research School's most valuable assets remain entirely intact—its people, its reputation and its spirit."

A real feature of this book is not just the detailed historical narrative, but also the description of the changing face of the Observatory as different staff members (and not just the various Directors) came and went. If there are two minor criticisms, they are that the book could have been more copiously illustrated and that there is sometimes a little too much detail about peripheral matters that did not really impact on the future of the Observatory. Nonetheless, for historians of Australian astronomy, and other astronomers interested in how a major observatory functions, this book is well worth buying and reading.

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***Transit of Venus. The Scientific Event that Led Captain Cook to Australia*, by Nick Lomb (Sydney, Allen and Unwin, 2004), pp. 24, ISBN 1 86317 103 3 (paperback), $A5:95.**

This is a thin high-quality production of the Powerhouse Museum in Sydney, Australia, prepared by the Curator of Astronomy at Sydney Observatory. There are 24 pages and 28 figures.

This pretty volume was published for the festivities relating to the 2004 transit of Venus and is aimed at the popular end of the book-buying market. It was, one assumes, an item designed to be sold at Sydney Observatory and in other sales outlets of the Powerhouse Museum. It is designed for school students, the general public and amateur astronomers. For me it was a quick and entertaining read that condensed two historic transits of Venus.

As is well known, there is an historic connection linking the 1768-1771 voyage of James Cook, the transit of Venus of 1769 and the English claim on the continent of Australia. It was in April 1770, during the return voyage after the transit, that Cook landed at Botany Bay, near Sydney. It is natural, therefore, that Dr Lomb and Sydney Observatory should participate in the celebrations of the 2004 transit of Venus.

This little tome is beautifully presented. It is A4 in size and tastefully printed on quality paper. The art work is top-end and the reproductions are large, clear and colourful. The cover, for example, is in tones of blue and sand, with a touch of red—this is a 'must pick-up-and-buy' item.

Dr Lomb's book is essentially in two parts. The first is about James Cook and the 1769 transit. Here the story is told at a comprehensive, albeit popular, level. Dr Lomb has included quotes from Cook's Log Book and from his 1771 report to the Royal Society, and these bring the story to life. The illustrations are of Cook, Fort Venus, a Shelton clock of the type used on the 1769 expedition, and Cook's own description of the transit (which shows the notorious black-drop effect). Missing from this chapter are technical data and the description by Cook of the quality of the timings—Cook was unnecessarily disappointed with the consistency of the Tahitian observations and talked down their quality. I would have liked to have seen a modern analysis of the quality of these data (Cook's observations resulted in a value of the AU within 1%). There is no statement of the other timings collected as part of the Royal Society's program, or the wealth of other data collected world-wide from non-Royal Society observers. The other voyages of Cook also do not receive a mention.

The second part of Dr Lomb's book reports the observations of the 1874 transit of Venus that were coordinated by Sydney Observatory. This is a popular insight into a small part of Australian scientific history, but it is specific to that work, and again the bigger picture—the observations of this event made elsewhere in Australia, and world-wide—is not mentioned.

Lomb's book draws heavily on the book *Observations of the Transit of Venus, 9 December, 1874* by H.C. Russell (which I will henceforth refer to as *Observations - 1874*), which is an account of the observations made at Sydney Observatory and at three field stations established by the Observatory. Aficionados of astronomical history will note that *Observations - 1874* was not published until 1892, some eighteen years after the transit itself. Even then, the only reason Russell (who was then Government Astronomer of New South Wales) published this book was to respond to public criticisms made by John Tebbutt that Sydney Observatory was neglecting its astronomical duties in preference to meteorological work. Russell retorted by publishing *Observations – 1874* as a demonstration of the astronomical work of Sydney Observatory and in an attempt to head off such attacks. For more on this episode see Orchiston (2002).

Observations - 1874 was itself a grandiose production, and the attractive colourful cover is reproduced, approximate full size, as the frontispiece in Dr Lomb's book, as are many of the plates. But Lomb also includes new material in the form of reproductions of original drawings of the transit, which he located in the New South Wales State Records. Much of this new material is annotated with what one assumes to be notes that were made on the day by the observers.

Dr Lomb's little book reports the observations made at Sydney Observatory, and three country New South Wales stations located at Eden, Woodford and Goulburn. The fifteen male observers who worked under the supervision of Russell are shown in one plate. There are also plates showing substantive prefabricated wooden observatory buildings and canvas-covered temporary domed observatories at Eden and Woodford. In addition, there is a fine image of Sydney Observatory's 11.25-in Schroeder refractor that will satisfy any romantic historic telescope-dreamer, and plates of the telescopes used at Eden and Woodford. Sadly, there is no photograph of Sydney Observatory, even though the work was coordinated from there.

Much discussion is given to the appearance of the planet Venus at the time of both transits. The black-drop effect is readily seen in the drawings by Cook, and was confirmed by observers of the 1874 transit who reported "parachutes" and a "narrow line" connecting the planet to the edge of the solar disk. Others observing that transit reported a halo resulting from the atmosphere of Venus—seen by them in exaggerated (and unbelievable) glory. Lomb reports observers as having seen "... white and red flames mixed and so close together that they formed a continuous ring ..." and halos that were "... one-third as wide as the planet, and ... greenish yellow with outer edge shaded orange".

In short, Nick Lomb's book is a great read for the train trip home after a visit to Sydney Observatory. I loved it!

Reference:

Orchiston, W., 2002. Tebbutt vs Russell: passion, power and politics in nineteenth century Australian astronomy. In Ansari, S.M.R. (ed.). *History of Oriental Astronomy*. Dordrecht, Kluwer. Pp. 169-201.

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***Science Technology and Learning in the Ottoman Empire. Western Influence, Local Institutions, and the Transfer of Knowledge*, by Ekmeleddin Ihsanoglu (Aldershot, Variorum, 2004), pp. 352, ISBN 0 86078 924 1 (hardback), £60.**

The Ottoman Empire, the last great Islamic dynasty, was the inheritor of the Islamic and Arabic civilization along with its scientific tradition. By the sixteenth century the Ottoman

Empire expanded to engulf most of the Byzantine Empire and a large area of central and Eastern Europe, Asia Minor (or what is now known as the Turkish state) and most of the Arab world. But by the seventeenth century the Empire started to decline in relation to the emerging European states.

In this book, Professor Ihsanoglu uses a collection of studies to examine the scientific development which took place after the decline of the Ottoman Empire, and its relationship with the newly-emerging Western scientific traditions. The interesting idea in this book is how the Ottomans reacted to these new scientific traditions and how they eventually adopted some of these new concepts.

The main idea which Ihsanoglu emphasizes in his book is that the Ottomans had always been aware of scientific developments in the West. However, in the beginning they did not embrace these foreign concepts, as in the case of the heliocentric theory of Copernicus. Ihsanoglu then goes on to show how several astronomical books were translated into Arabic or Turkish. The Ottomans then gradually acknowledged these new European sciences, and accepted that they conflicted with their own traditional Islamic heritage.

Ihsanoglu also writes about the developments of institutes of higher learning in the Ottoman Empire, which went by the name of *medreses*. He examines how Western scientific concepts and ideas were eventually adopted when the first Ottoman university (called 'Darulfunun') was established and it utilized the ideas and methods of the new European sciences and technologies. However, Ihsanoglu also points out the failure of the Ottomans to develop scientifically-based research like that found in Europe.

The decline of Islamic scientific activity after a brilliant and successful start has attracted the attention of a great number of scholars and historians. In this book Ihsan-oglu tries to shed some light on Ottoman scientific activity during this decline. He also points out that, contrary to some beliefs, there was not as great a conflict between science and religion in the Ottoman world as there was in Europe.

I would strongly recommend this book to those who are interested in trying to find the answers to many of these puzzling historical questions.

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***John Herschel's Cape Voyage. Private Science, Public Imagination and the Ambitions of Empire,* by Steven Ruskin (Aldershot, Ashgate, 2004), pp. xxx + 229, ISBN 0 7546 3558 9 (hardback), £45.**

There is already an extensive bibliography on Herschel's sojourn at the Cape of Good Hope, so when I first encountered Ruskin's new book I could not help but wonder whether there really was anything new to say on the subject. Wouldn't it simply traverse territory that was already well-trodden in the volumes and papers by Evans, Warner and others?

Well, how wrong I was! Instead, Ruskin introduced me to a totally new John Herschel, an individual trapped in the cultural and political milieu of his day where astronomy was merely part of the overall story. Ruskin was interested in what historical analyses of (1) the private, public and political interpretations of Herschel's voyage, and (2) the preparation, publication, distribution and reception of his *Cape Results* volume, might tell us about British science, British and colonial Cape culture, and the British Empire.

After a lengthy Introduction, Ruskin queries the general explanation for Herschel's Cape voyage (that it was carried out as a filial duty) and shows that Herschel had exploratory aspirations in the best tradition of Humboldtian scientific traveling, and that his Cape voyage—although undertaken as a private venture—was perceived by the public to be an official affair (and therefore Government-sanctioned and -supported).

The third and final chapter in Part I ("Herschel's Cape Voyage") deals with Herschel's astronomical observations, but not for their scientific content (which Ruskin correctly points out has already been adequately discussed by others). Instead, he goes to some pains to demonstrate that Herschel's observations

> ... were appropriated differently in different cultural contexts. In Britain, Herschel's voyage fueled the public imperial imagination. In the Cape colony, Herschel's presence was seen as a way to promote colonial self-esteem ... [and] in America, his voyage was used to expose a cultural susceptibility, as well perhaps as to provide a rallying point in American notions of the extension of civilization in uncivilized areas.

In the course of two interesting chapters, Part II details the preparation, publication, distribution and reception of *Results of Astronomical Observations Made ... at the Cape of Good Hope ...* (henceforth referred to simply as *The Cape Results*). This massive tome—now an expensive and highly sought-after collectors' item—was published in 1847 (five years after Herschel's triumphant return to London) thanks to financial assistance provided by Hugh Percy, the Third Duke of Northumberland. When he was preparing his book for publication, Herschel had two principal aims: (1) to provide readers with the results of his Cape observations, and (2) to "... promote a particular view of nature in postulating dynamic, Humboldtian explanations of phenomena." However, Ruskin examines *The Cape Results* in the context of the production of scientific books, and views it as an agent of scientific change.

Despite a limited print run and privileged distribution list, the book was, for the most part, well received and attracted excellent reviews. Not so laudable were the actions of Peter Stewart, Sir John's brother-in-law, whose embezzlement of funds almost brought the publishers, Smith, Elder and Company, to the point of bankruptcy. More pointedly, both Herschel and his wife suffered financially from their relative's thieving, as they had personally invested in the company. As some small measure of compensation, through the carefully-orchestrated publication and dissemination of *The Cape Results*, Sir John Herschel "... obtained in the eyes of the British government, and public, a new national role."

The third and final section of Ruskin's book draws together his concluding remarks on "Herschel, Icon", and is followed by two appendices and a useful 13-page bibliography.

While most astronomers will find *John Herschel's Cape Voyage* well-written and liberally footnoted, and will applaud Ruskin's frequent use of quotations from manuscript sources, those without a committed Southern Hemisphere perspective may find some of his diversions into the history of science a little tedious at times. They may also wonder at those specialist terms 'metropolis' and 'periphery', and realize that to claim Australia's Parramatta Observatory as a British government initiative is a gross over-simplification of the facts—for it began life as a private observatory. Nonetheless, these are minor quibbles and cannot detract from the overall merits of this welcome addition to Southern Hemisphere astronomy. I recommend that you add it to your library.

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JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807

INDEX VOLUME 8, 2005

JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807
VOLUME 8 NUMBER 2 DECEMBER 2005

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