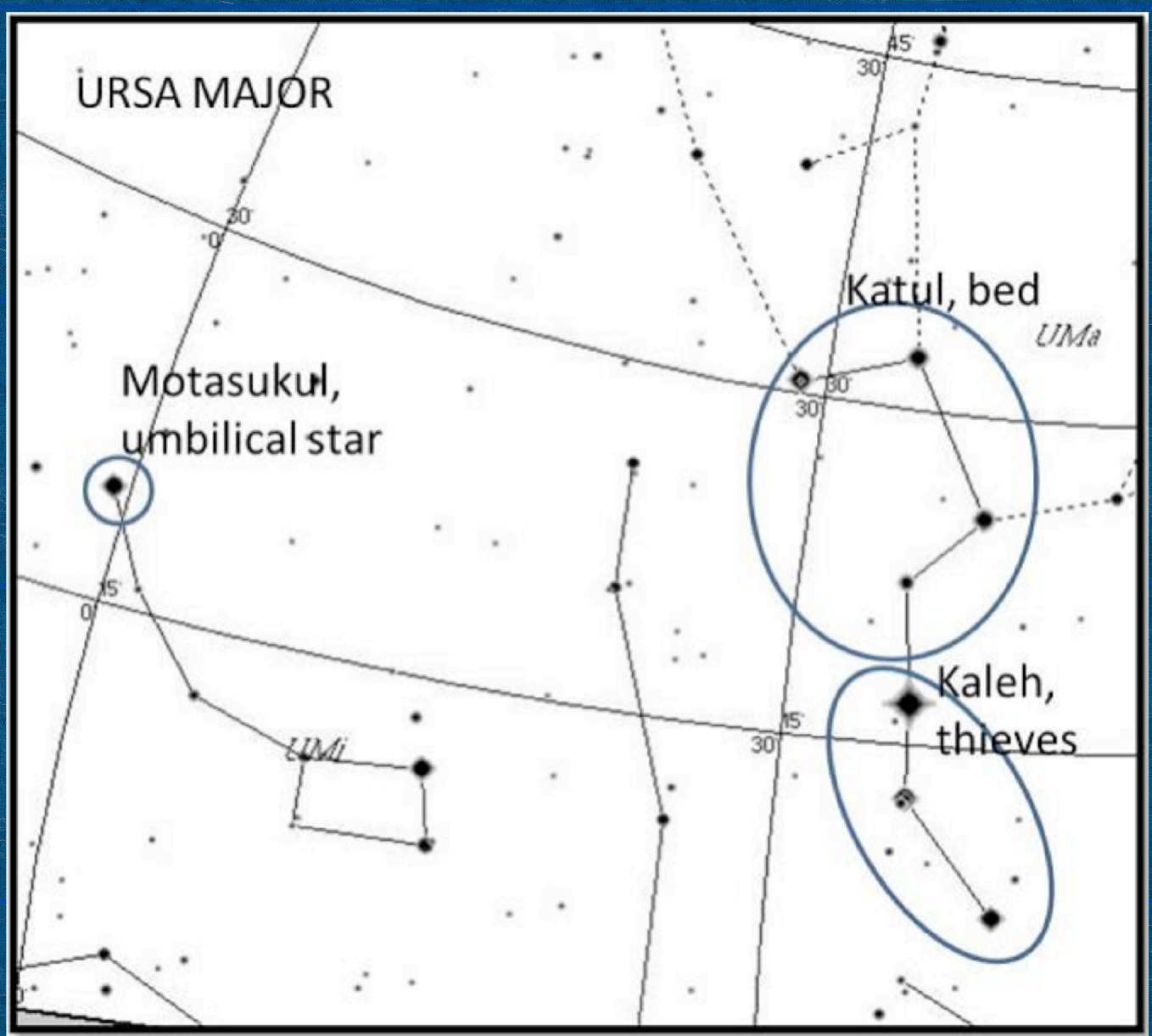
JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE



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COVER IMAGE

Most readers will recognize the asterism in Ursa Major, seen by many cultures as a container (Big Dipper in America, Northern Dipper [*Beidou*] in China, *steelpan* [saucepan] in Dutch). For the ancient Gonds of central India, the box is the cot of an old woman, *Sedona*, who cannot sleep for fear that 3 thieves (Alkaid, Mizar, Alioth) will steal her precious bed. To learn more about Gond astronomy, see the article by Mayank Vahia and Ganesh Halkare on pp. 29-44.

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THE AUSTRALIAN NATIONAL UNIVERSITY'S 2.3m NEW GENERATION TELESCOPE AT SIDING SPRING OBSERVATORY

Don S. Mathewson, John Hart, Hermann P. Wehner, Gary R. Hovey and Jan van Harmelen
Mt Stromlo and Siding Spring Observatories, Cotter Road, Weston Creek, ACT 2611, Australia.
Emails: donsmathewson@gmail.com; john.hart@anu.edu.au, hermann.wehner@bigpond.com.au; hovey@mso.anu.edu.au; jan@mso.anu.edu.au

Abstract: The story of the birth and construction of the 2.3m Telescope at Siding Spring Observatory is told. Details of the intricate control system of the telescope, building and instrumentation are described. The Telescope encompassed all the features of the New Generation Telescopes of the late 1970s: a thin primary mirror, an alt-azimuth mount and a rotating building. It has operated continuously for 28 years, used by Australian and international astronomers. It has a prodigious science output helped by state of the art instrumentation developed by engineers and astronomers at Mt Stromlo and Siding Spring Observatories.

Keywords: 2.3m Telescope, New Generation Telescopes, Australian National University, Siding Spring Observatory

1 INTRODUCTION

This is the story of a small team of engineers and technicians who rose to the challenge to build a New Generation Telescope at Siding Spring Observatory, (SSO), to fulfil the urgent need of the astronomers of Australia.

It is also the story of the visionary foresight of the members of the Chancellery[1] at The Australian National University who saw the enormous hurdles that Mt Stromlo and Siding Spring Observatories (MSSSO) faced but put their faith in the capabilities of the staff. They also realised the great technical, scientific and financial advantages of the proposed design and recognised the dire need of the Australian astronomers. The Chancellery could never formally fund the project because of the financial climate but it stood by the Observatories until the job was done.

Here is the story as told by Don Mathewson (Acting Director of MSSSO, 1977-1979, Director of MSSSO, 1979-1986), John Hart (Opto-Mechanical Engineer, Head of Opto-Mechanical Department), Hermann Wehner (Opto-Mechanical Engineer); Gary Hovey (Control Systems – Engineer) and Jan van Harmelen (Electronics Engineer, Head of Electronics). Figure 1 and Figure 2 show the four engineers who built the 2.3m Telescope.

2 THE CONCEPTION AND BIRTH OF THE 2.3m TELESCOPE

2.1 1977

By 1977 the need for a new Australian optical telescope had become urgent. The telescopes at Siding Spring Observatory were heavily oversubscribed, e.g. the Anglo-Australian Telescope was five times oversubscribed.

From 1970, funding for a conventional 60-in telescope from Boller and Chivens had been requested annually by Olin Eggen (who was Director of MSSSO from 1966 to 1977), but without success.

In June, Eggen asked Mathewson to take over the carriage of the project, which brought him into contact with Ian Ross, the newly-appointed Deputy Vice-Chancellor of The Australian National University. Mathewson made Ross aware of the urgent need of Australian astronomers for a new telescope.

In October Mathewson became Acting Director of MSSSO. It was the start of a new era of optical telescopes. Vince Reddish, Director of the UK Schmidt Telescope at Siding Spring Observatory was extolling to Mathewson the virtues of the UK Science Research Council's 3.8m thin mirror telescope on Mauna Kea. The light weight of the mirror meant that the whole telescope structure could be made much lighter, with considerable savings in construction of the telescope and mount.

The Multi-Mirror Telescope at Mt Hopkins in the USA had just been built and it had an alt-azimuth mount which was proving very successful (see Beckers et al., 1981). Alt-azimuth mounts provide a simple solution to problems associated with horse-shoe or fork flexures of a conventional equatorial mount and the changing loading on the declination bearings as the polar axis rotates. For alt-azimuth mounts the vertical loading is constant and symmetrical. Azimuth rotation causes no load changes, and tube flexure is in one plane. It allows massive instrumentation to be mounted at the two Nasmyth foci on a platform almost level with the elevation axis. Interchange of instruments at the two foci can be easily achieved by flipping a plane mirror. The instruments are easily accessible.

Figure 1 (above): (left to right), John Hart, Hermann Wehner, and Gary Hovey examining a model of the 2.3m Telescope (courtesy: Bob Cooper).
Figure 2 (right): Jan van Harmelen, Electronics Engineer.

A third development is a spin-off from using an alt-azimuth mount. If the building rotates in azimuth with the telescope its size over a conventional dome can be dramatically reduced. Also the building space can be used very effectively because of the rectangular cross-section. It is much easier to control the much smaller volume of air which now surrounds the telescope, and this leads to better seeing. The Multi-Mirror Telescope had a rotating building which clearly demonstrated these advantages.

2.2 1978

On 16 January 1978 Mathewson wrote to Reddish suggesting the UK Science Research Council and the Australian National University collaborate to build a 2.5m thin mirror telescope with an alt-azimuth mount and a rotating building at Siding Spring Observatory. However, Reddish did not think the Council could fund the project at that time.

On 20 January, a Working Party on New Generation Telescopes organised and chaired by Mathewson, was held at Mt Stromlo Observatory. Among the participants were Don Morton from the Anglo-Australian Observatory; John Bolton, Director of the CSIRO's Parkes Radio Telescope; and John Hart and Hermann Wehner from MSSSO. The meeting approved a 3m thin mirror, alt-azimuth mounted telescope with a rotating building to be built at Siding Spring Observatory and to be funded by all Australian universities. It was named the 'Universities Telescope'. Figure 3 shows Don Mathewson posing with a model of the Universities Telescope.

Figure 3: Don Mathewson with a model of the Universities Telescope (courtesy: Keith Smith).

On 10 February Donald Low, Vice-Chancellor of the Australian National University informed the Australian Science and Technology Council that it was withdrawing its 60-in telescope proposal in favour of the Universities Telescope. On 3 May Ian Ross, the Deputy Vice-Chancellor of the Australian National University, chaired a Universities Telescope meeting held at Mt Stromlo Observatory. All Australian universities were represented, and there was full support this proposed national facility. On 11 October, Mathewson wrote a formal proposal for the Universities Telescope, the cost of which was estimated at $3 million. The Universities Commission, the relevant funding body, was notified by the Australian Vice-Chancellor's Committee. This produced great interest around the astronomical world, and reports appeared in many international newspapers.

Figure 4: Norman Cole's Optical Shop. Norman is on the right. The blank being machined is that of the 2.3m primary mirror for the Wyoming Telescope (courtesy: R. Gehrz).

2.3 1979

During April-May in 1979 John Hart, Hermann Wehner and Ben Gascoigne visited Kitt Peak National Observatory in the USA and other centres to study recent developments in telescope design and construction, particularly the Multi-Mirror Telescope. In Tucson they also met Norman Cole, an optician who apart from earlier carrying out optical work at Kitt Peak National Observatory had recently made a 90-in thin and fast primary mirror for the University of Wyoming's telescope on Mt Jelm (Figure 4). This telescope had an equatorial mount and a conventional dome. The CerVit blank of their mirror had been purchased from Owens-Illinois of Toledo, Ohio.

Unfortunately on 11 May 1979 the Universities Telescope Project collapsed, as no funds were available from any source. As a last resort, Don Mathewson phoned Henry Cossitt of Owens-Illinois who located their last CerVit blank, 97 inches in diameter and 21 inches thick, under a tarpaulin in the backyard. CerVit was a revolutionary low expansion glass-ceramic that had been successfully used for telescope mirrors, including the Anglo-Australian Telescope. Unfortunately Owens-Illinois had stopped production because of environmental concerns. A few days later, John Hart, Larry Barr (from Kitt Peak National Observatory) and Norman Cole inspected the CerVit blank, which was too opaque for stress tests and was badly chipped. However on 17 May, Hart sent a report that the blank was satisfactory for slicing in two: from one blank, two mirrors 90 inches in diameter and 9 inches thick could be produced.

Mathewson put a formal proposal to the Australian National University that MSSSO should build a 90-in thin mirror alt-azimuth mounted tele-scope in a rotating building at Siding Spring Observatory for a cost of $1 million. On 21 May the University gave approval for the blank to be purchased on condition that it did not break in slicing and that they could sell it back to Owens-Illinois if the project collapsed. On 23 May, John Coleman, Bursar of the University, sent the order two hours before our option expired.

The blank was satisfactorily sliced into two by a surprisingly primitive process, witnessed by Hart, Barr and Cole. The mirror blank was mounted on a cart towed by a tractor in a yard at the back of the glassworks. A large and continuous loop of wire was driven around a series of wheels, with the mirror blank pulled against the wire to provide tension. A slurry of grinding grit was squirted onto the wire where it entered the advancing cut in the blank. Every now and then the tractor driver would start the tractor and nudge it forward to re-establish tension in the wire as the cut advanced. The overhanging upper slice of the blank was supported on the bed of grit accumulating behind the wire, protecting the blank from cantilever stress.

Norman Cole had made the 90-in thin mirror for the Wyoming telescope; L & F Industries had made the mirror housing and Boller and Chivens, the support system. Fortuitously our blank was just the right size to duplicate this mirror system. Hart successfully negotiated with the three parties to do this at a very attractive price.

In effect, this 'off the shelf' primary mirror cell purchase became the start of the project. We then designed and built our telescope around it, incorporating many new features to suit our needs and budget.

No funds were available for the project from the University Council, the funding body for such large projects to Universities. They also rejected Donald Low's request that the ANU's Large Equipment Grants would be assured for the next four years. The Chancellery told Mathewson that the project could never formally be funded but they would do their best to keep funds running but the project could be stopped at any time. At this point Mathewson sold the remaining blank to Robert Kirschner of McGraw-Hill Observatory, University of Michigan, at a profit —this helped considerably.

On 9 November Mathewson told the Chancellery that the cost had increased to $1.4 million. This increased to $3.2 million by the end of the project in 1984. Miraculously, the Chancellery, at all stages, managed to supply the funds.[2]

In June, the Design Study Group was set up. The group was Don Mathewson (chair), John Hart, Hermann Wehner, Gary Hovey, Jan van Harmelen, Ted Stapinski, Mark Downing, Alex Rodgers and Norman Stokes. Hilton Lewis joined the group later and Ted Stapinski left to become Engineer in charge of the Starlab Project. Detailed design of the telescope commenced.

3 SITE TESTING AND SELECTION

Van Harmelen started the site testing program using micro-thermal data obtained from sensors on three towers erected at SSO. Summer lightning activity and birds damaged the sensors and the data was unreliable.

David Griersmith who had recently completed his Ph.D. at MSSSO, made seeing observations at Siding Spring Observatory with two 8-inch Tinsley Telescopes used in site testing for the Anglo-Australian Telescope. He found no difference in seeing across the mountain. Vince Ford and Joanne Fisher compared images of stars taken with the Anglo-Australian Telescope, the UK Schmidt and the 40-in Boller and Chivens telescope and also found no difference in seeing between the three sites.

The area between the 40-in and 24-in Boller and Chivens telescopes and slightly below them was known amongst astronomers to be a low wind site. Vince Ford and Don Mathewson made wind flow measurements at this site. They tied smoke canisters to 4m-long poles and observed the smoke patterns whilst carefully avoiding the blobs of molten lead that cascaded around their heads! They put a dob of paint on the area with the smoothest flow. Later, core drilling found solid rock under this location. This site was selected for the 2.3m Telescope because it was also close to electricity and water supplies and was easily accessible from the road.

4 THE OPTICS

The chosen alti-azimuth mounting allows the use of Cassegrain and Nasmyth optical arrangements, both using the same primary mirror, but, of course, separate secondary mirrors. The latter are mounted in interchangeable telescope tube front ends. The use of the alt-azimuth arrangement results, however, in the rotation of the field in the focal plane—essentially, a third axis. To counteract this rotation, instrument rotators have to be fitted at each focal station.

The detailed optical design for the telescope was carried out at Mt Stromlo Observatory, with Ben Gascoigne as consultant. The choice was for conventional Cassegrain optics, i.e. a paraboloidal primary mirror combined with a hyperbolodial secondary mirror, with separate, matched secondaries for either focus. The Cassegrain optical arrangement has its focus just behind the primary mirror cell, with instruments attached to the instrument rotator on the mirror cell. In the Nasmyth optical arrangement the light, reflected by the secondary mirror, is further reflected by a flat mirror at the intersection of the azimuth and altitude axes, along the hollow altitude axis to a focus outside the telescope mounting. Hence rotation of this flat mirror creates two focal positions, where instruments can be mounted to the respective rotators.

As mentioned elsewhere, the material chosen for the blank of the primary mirror was CerVit, a vitreous ceramic manufactured by Owens-Illinois of Toledo, Ohio. The advantage of CerVit is its low coefficient of thermal expansion, of the order of $0 \pm 1 \times 10^{-7}$/ºC, which assures an almost unchanged optical figure within the range of normal telescope operation.

The size of the purchased blank permitted a finished mirror diameter of 2,337mm and an edge thickness of 220mm. The focal ratio of the primary is f/2.05. The achieved diameter to thickness ratio is 13:1 (equivalent flat plate), a substantial departure from the previously accepted ratio of about 6:1. The mass of the mirror is close to 2,000kg. The diameters of the secondary mirrors are 280mm (Cassegrain) and 355mm

(Nasmyth). Both optical systems have a focal ratio of f/18.

The contract for the optical work was let to Norman Cole of Tucson (Arizona) in mid-1979, who previously had converted his spacious garage into an optical laboratory. There he carried out all grinding and the initial polishing of the primary mirror. For final polishing and figuring to the required tolerances the primary mirror was transferred to the Optical Sciences Center of the University of Arizona in Tucson, where a vertical test facility (tower) was available. Here the mirror was supported at all times on a support system very similar to that designed for final use in the primary mirror cell of our telescope, i.e. an air-pressurised bladder supported the mirror such that only a very small, but constant contact pressure remained on the three mirror support points .

Tests of the optical adequacy of the mirror surface were carried out with the assistance of Optical Sciences Center staff, who produced computer-generated contour maps of the mirror surface after each polishing run to identify areas requiring further figuring work. Artificial double star tests were carried out to determine the mirror's resolving power. Wehner was present during some tests, but particularly the final ones. His presence assured that detailed findings from the test results could be implemented immediately and without time-consuming exchange of information over long distances. On 13 February 1983 Wehner recommended acceptance of the mirror to Mathewson. The primary mirror subsequently arrived at Siding Spring on 7 April 1983. During the final stages of polishing, Hermann Wehner, Norman Cole and the Optical Sciences Center formed a brilliant team of experts who complemented each other and produced an exceedingly high-quality mirror.

Both secondary mirrors were also produced by Norman Cole. After they arrived in Australia in early 1984 further acceptance tests were carried out by William James of Melbourne. The secondary mirrors are mounted in interchangeable telescope tube front ends. The Nasmyth flat which was made by Gabe Bloxham (of Mt Stromlo Observatory) can be removed from the tube centre for light to pass to the Cassegrain focus.

Since the Cassegrain optical arrangement was to be dedicated to infrared work, the secondary mirror was fitted to a 'chopping' mounting, with adjustable chopping frequency, amplitude and rotational position. This mounting was produced by the Physics Section of the RAAF Academy in Victoria. It was designed such that the telescope imaged only a minimum of 'locally'-produced infrared radiation, apart from the signal received by the telescope. Access to the Cassegrain focus for installation of instruments and access for observers, is via a hydraulically-operated platform, permanently located close to the telescope mounting.

At the time of the installation of the 2.3m Telescope the only facility for the aluminizing of mirrors available for the Australian National University telescopes was a 1.3m plant in the 24-in telescope building annex. After negotiations, we arranged to use the 4m aluminizing plant of the Anglo-Australian Telescope. Fortuitously, this plant had been fitted with a tank insert for a planned 2.4m Coudé mirror, but since it was no longer required the tank was modified for our primary mirror.

5 THE TELESCOPE STRUCTURE

5.1 The Scheme

For reasons of both economy and performance, it was decided at the outset of the project that the telescope would have an alt-azimuth configuration carrying a thin and fast primary mirror. This would facilitate a simple, compact and rigid structure as required for the highest possible pointing performance. Importantly, it would also allow the use of a compact rotating building that conformed closely to the telescope. Relative to this building, the only telescope motion would be nodding in altitude. In effect, the telescope can be contained within a slot in the building, with support facilities being thermally isolated in the surrounding space. Open areas on each side of the telescope would be used to accommodate two Nasmyth instruments, with rapid interchange achieved by flipping a flat tertiary mirror.

A Cassegrain focal station dedicated to infrared instruments would also be included by providing 1m of clearance between the base of the primary mirror cell and the throat of the telescope fork. The Cassegrain instrument would be deployed by removing the tertiary mirror and swapping the secondary mirror top end structure. The Cassegrain configuration would minimize thermal emission by having an unobstructed secondary mirror form the entrance pupil and having as little as possible structure within the beam. The support struts for the secondary mirror would be hidden behind glancing-incidence reflective masks to effectively replace structure with relatively darker sky background.

The upper level of the building would be used to accommodate the unused top end and the travelling crane used for the interchange. The crane would also be used to handle other instruments and equipment, as well as the primary mirror when re-aluminizing was needed.

The price paid for the alt-azimuth configurtion is that of field rotation. This would be dealt with by having identical instrument rotators at each of the three focal stations.

5.2 Mirror Support

The primary mirror has a mechanical diameter of 2,337mm and a vertex thickness of 160mm. This thickness is less than half the value that would be used for a traditional design. The difficulty in using a thin mirror is to prevent it from flexing significantly under its own weight. To isolate our mirror from bending stress, axial support is provided by an air bag and radial support by a mercury belt. The air bag supports almost all the axial component of mirror weight regardless of altitude angle. A small vane pump continually feeds air to the bag. The air then leaves the bag through a passive pressure regulator so that the pressure in the system is proportional to the sine of the altitude angle. Within the regulator, a weighted diaphragm simply blocks the open end of the exhaust tube to give very accurate pressure control. A hole in the centre of the bag is made larger than that in the mirror, so compensating for the radially-varying mirror thickness and load. The mirror position is accurately controlled by three defining points behind the mirror that carry a small proportion of the mirror weight.

The mercury belt used for radial support takes the form of a fabric-reinforced rubber tube, much like a bicycle tube, located in a 10mm radial gap between the mirror and the housing. So contained, it has a contact width of 37mm, and is almost filled with mercury. The ratio between the contact width of the belt and the average thickness of the mirror is arranged to be slightly greater than the ratio between the density of the mirror and that of mercury so that the mirror floats in the mercury. Neutral buoyancy is achieved by adjusting the amount of mercury in the belt so that there is no radial movement as altitude angle is changed.

5.3 Rolling Element Azimuth Bearing

An early consideration faced by the design team was the possibility of using a rolling element slew-ring bearing for the azimuth axis in place of the more conventional hydrostatic bearing. Such a passive system has the potential to be simpler, cheaper and maintenance-free, but friction torque must be very low in both its average value and its fluctuation to avoid compromise in pointing and tracking performance.

Our studies concluded that a conventional cylindrical roller slew-ring bearing would not be acceptable because of scuffing friction. An innovative means of substantially reducing friction, however, was to use an axial ball bearing. Such bearings use shallow raceway grooves in the opposing bearing faces to guide the balls. Usually, the radius of the groove profile is only slightly larger than that of the balls in order to increase contact area and load capacity, but this also increases scuffing friction to levels that would be unacceptable to us.

We were proposing to use a bearing with a pitch circle diameter of 1,400mm in order to have adequate stiffness and stability. The expected telescope load of 30 tonnes was very low for a bearing of this size, and this offered the possibility of substantially reducing friction torque by increasing the ratio between groove profile radius and ball radius (conformity factor). This approach was reinforced by the knowledge that bearings fail by fatigue, and our lifetime requirement was low when measured in terms of rotational travel.

Designing for a lifetime equivalent of 100 years, we concluded that very favourable performance could be achieved. An adverse consequence of increasing conformity factor was that lateral stiffness would be reduced considerably, but we planned to avoid this problem by adding a ring of cylindrical rollers arranged for radial support. This addition was normal in conventional slew-ring bearings anyway, and caused very little increase in friction.

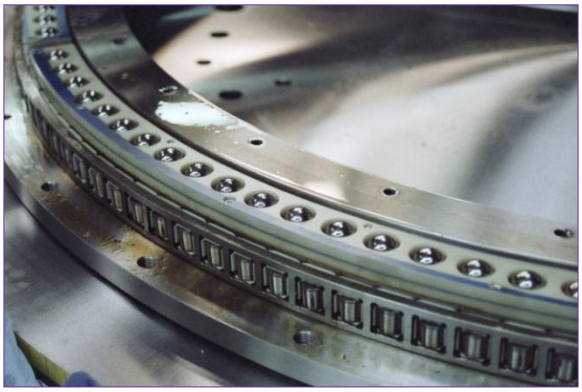


Figure 5: The modified azimuth bearing in the laboratory at Rothe Erde. The upper ring has been removed to show the ball race that provides axial support and the roller race that provides radial constraint.

We approached several slew-ring bearing manufacturers with this proposed design, but were unable to persuade any that this was the best solution. Our preferred supplier, German company Rothe Erde, was, however, prepared to design and manufacture a conventional cylindrical roller slew-ring that they were confident would meet our demanding torque requirement, and we proceeded with purchase.

Manufacture of this high-precision bearing was completed in June 1982, but testing showed that it fell well short of the required performance. After some discussion, Rothe Erde agreed to modify the new bearing by grinding raceway grooves into the flat thrust faces and fitting balls in place of rollers. The conformity factor was calculated to deliver the previously specified lifetime of 100 years.

Figure 6: A craftsman in the workshop of John Grout hand-scraping the azimuth-bearing flange of the telescope fork.

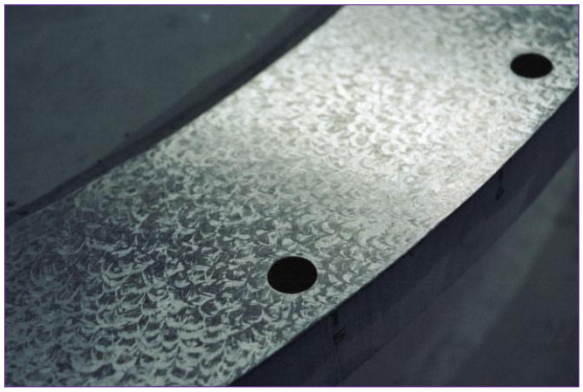


Figure 7: The finished azimuth-bearing flange of the fork, showing the characteristic pattern of hand-scraping. The surface is flat to 5 μm RMS.

The duly modified bearing was completed and re-tested in November 1982, and easily satisfied the torque requirements. Under the specified load of 30 tonnes, the required maximum torque at low speed was 250 Nm, with a maximum allowable fluctuation 60 Nm. The measured maximum starting torque was 95 Nm, and the measured mean running torque was 67 Nm, this being almost as low as the allowable fluctuation. Figure 5 shows a view of the modified azimuth bearing in the test laboratory at Rothe Erde. The news of this result was telephoned to Mathewson, who received it with great relief.[3]

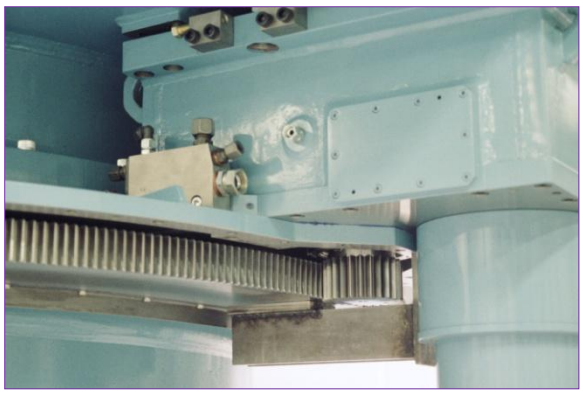


Figure 8: The main gearing of the azimuth drive showing one of the two gearboxes that apply torque in opposite directions. The gearbox is temporarily supported from a bracket attached to the underside of the ring gear to facilitate alignment.

5.4 Alt-azimuth Mount

The alt-azimuth mount was initially designed in-house to achieve a simple, rigid and compact structure with high natural frequencies, as required for good dynamic performance. This was checked and refined by consulting engineers MacDonald, Wagner and Priddle using finite slice computer analysis, who then produced the fabrication drawings. Machining drawings were produced at Mt Stromlo Observatory. Manufacture of the main structural components was contracted to the Newcastle State Dockyard, who did the machining after subcontracting fabrication in the Newcastle area. Smaller components were constructed within the Australian National University's precision workshops at Mt Stromlo and at the Research School of Physical Sciences in Canberra.

This type of work was unusual for the State Dockyard, but they were keen to diversify because their traditional heavy engineering work was waning. They had an old but comprehensive range of large machine tools that could easily accommodate the structural components of our telescope, and they were receptive to our involvement in using optical alignment methods to achieve high levels of layout precision.

An unusual requirement for the mount was that the azimuth bearings needed an exceptional level of flatness to ensure adequately even support the low-friction azimuth bearing that had been made by Rothe Erde. To achieve this, the newly-completed base and fork of the telescope were shipped to John Grout Machine Tool Reconditions in Sydney. Their staff include a European migrant who still had the largely-lost skill of hand-scraping flat surfaces. He applied this process to the bearing flanges, with precision flatness measurements being made by observatory staff along the way. The result was a flatness of 5 μm RMS over the 1,570mm diameter of the flanges. Views of the scraping process being applied to the flange on the telescope fork, and the finished surface, are shown in Figure 6 and Figure 7 respectively. The fork was inverted for this operation.

5.5 Precision Spur Gears

Drive for each axis is provided by two gearboxes applying torque in opposite directions to a common ring gear in order to eliminate backlash. Movement is produced by simultaneously increasing torque in one gearbox and decreasing it in the other. The preliminary design was done in-house, before seeking out a specialist gear drive supplier for detailed design and manufacture. One of the world's leading suppliers, Maag of Zurich (Switzerland) was contracted for this work. Hardened and precision-ground spurs gears of the type used in turbine powertrains

were adopted because, for reasons of speed rather than pointing accuracy, they also require the ultimate in bearing and gearing precision. A lubrication system that injected low viscosity turbo oil into all gear meshes and bearing (including the azimuth bearing) was utilised.

A view of the primary gearing in the azimuth drive is shown in Figure 8. The large ring gear has a pitch circle diameter of 2,000mm and a thickness of 50mm. The pitch circle diameter of the pinion is 100mm, providing a speed reduction ratio of 20:1. A further reduction of 5:1 within the gearbox provided a total reduction ratio of 100:1 from the drive motor to the telescope. The ring gear remains stationary as the two gearboxes move around it. Identical gearing is used for the altitude drive, except that the main gear there rotates between the two fixed gearboxes.

5.6 Superstructure

A classical Serurrier truss superstructure was used to support the primary and secondary mirrors, but with a twist. A Serurrier truss has a form that does not create rotational deflection under lateral load. Significant translational deflection is unavoidable, but the differential effect is annulled by making it equal for both mirrors.

For our telescope, an additional feature is that differential axial deflection is also annulled. The condition required to achieve this is the strut angles should be the same for the primary and secondary trusses. The primary and secondary trusses no longer share common anchor points on the centre ring, but the deflection that occurs between the separated anchor points is easily determined, and then compensated by slight changes to the truss geometry. This truss geometry is shown in Figure 9. This arrangement results in very compact lower truss units that can be easily changed for the purpose of tuning performance. The trusses that provide support in the azimuth direction were made lighter than those that provide support in the altitude direction because only the latter carry lateral load. The super-structure thereby has less lateral deflection. Mounts for all mirrors, including the Nasmyth tertiary, are also designed to annul rotational deflection by means of counter-flexure mechanisms.

Figure 9: The modified Serurrier truss geometry, showing the equal apex angles of the upper and lower trusses.

5.7 The Extended Support Network

An important part of the project was the enthusiastic and valuable support that came from people beyond the team itself.

Figure 10: Coonabarabran Shire Council workmen excavating the rock for the telescope pier foundations (courtesy: E.W. Simmonds).

Senior staff at the Multiple Mirror Telescope in Arizona were very generous in providing detailed design information about their telescope. They had recently commissioned their telescope, and like us, they had decided to use a rolling element azimuth bearing. They too had concluded that friction torque could be greatly reduced by using balls rolling in a raceway groove of relatively large section radius. Unfortunately for them, they did not adequately deal with the corresponding reduction in radial stiffness, and subsequently had to resort to a number of other compensations. The data they provided us with was very useful in our process of avoiding such problems. Likewise, information they provided about the bogie carriages under their rotating enclosure was very useful.

All the specialist contractors involved provided great cooperation and willingness to adapt their expertise to our unusual and niche requirements. The Newcastle State Dockyard allowed us free access to their facilities so that we could work directly with their staff to align their massive machine tools with precision optical measuring equipment. Machine tool reconditioners John Grout likewise allowed us to work with their staff to achieve exceptional levels of precision with the flatness of the bearing mounts, providing rare hand-scraping skills.

Figure 11: After positioning the rail segments and bolting them down, the running surfaces are being ground (courtesy: E.W. Simmonds).

German bearing manufacturer Rothe Erde engaged in a program of experimental manufacture and testing to achieve extraordinarily low friction in the rolling element azimuth bearing, largely out of interest in the outcome.

Swiss gear manufacturer Maag re-employed a retired designer with great experience and expertise in specialised gearing systems design, and then manufactured the system with great precision.

The Research School of Physical Sciences and Engineering made their precision workshop facilities available to supplement our own very capable workshop in construction of telescope components.

6 THE BUILDING

This concept of floor design is completely influenced by the fact that the building co-rotates with the telescope. This permits the provision of access space close to the instrumentation so the building can be made much smaller, thereby saving construction costs. The 2.3m Telescope building incorporates these facilities.

The design of the building commenced early 1979, since the building had to be completed in time for the installation of the telescope. The conceptual design of the building was produced at Mt Stromlo by Hermann Wehner. The detailed structural analysis of the entire structure, including the building bogies, any architectural work, and the preparation of the necessary contract documents for the various trades were carried out by our consultants, MacDonald, Wagner and Priddle of Sydney. They also produced the structural analysis of the telescope mounting.

The influence of wind-induced forces on the building was analysed initially at Mt Stromlo Observatory by Hermann Wehner and Bela Bodor. To assess the structural design of the building, wind tunnel tests were carried out by the CSIRO Division of Environmental Mechanics in Canberra. A model of the building (scale 1:100), mounted on a sensitive balancing system, was tested at various building attitudes and wind speeds to determine overturning and rotating moments. The test rig was manufactured at Mt Stromlo Observatory. The results were used by MacDonald, Wagner and Priddle to optimize the design. The adopted maximum wind speeds were 18m/sec (65km/h) operational and 45m/sec (162 km/h) survival. Resistance to over-turning was further aided by the use of 55 tonnes of reinforced concrete as floor material on level L2. The building has a square footprint of 14m side length, and a height of about 12.5m. Its steel frame rotates on a fixed rail with four two-wheel bogies, designed for a total load capacity of 200 tonnes, and placed one at each corner of the base frame.

In July 1981, Ed Simmonds (formerly of Building and Grounds at the Australian National University) was appointed site engineer to ensure close supervision of all site work. He played a very important role and proved invaluable to the project.

Simmonds suggested soon after taking up his appointment that it would be worthwhile to consider the addition of a partial floor space under the lowest stationary level L1 thereby making use of the natural surface slope, without having to fill the remaining cavity. This proposal was readily accepted and incorporated in the consultant's scope of work.

Figure 12: Having assembled the base of the building steel frame, the main structural columns are erected (courtesy: H.P. Wehner).

Core drilling at the selected site was carried out showing solid rock close to the original surface. At the same time holes for the lightning protection earthing rods were drilled in several places within the building footprint. Earthing mats were laid in this space and connected to the earthing rods.

Excavation of the pier foundation followed (Figure 10). Simmonds reported in late 1981 that excavation work for the installation had been completed. Framing up for and placing of the reinforced concrete foundations followed, being completed in March 1982.

Placing of the building rail segments immediately followed, since the building centre was still accessible for alignment measurements prior to the construction of the telescope pier. The rail segments, 43 of them, were cast in Sydney and machined at Mt Stromlo Observatory and at the workshop of the Australian National University's Research School of Physical Sciences. Once in place and grouted to the concrete base, the running surfaces of both the main, load carrying wheels and the side restraint rollers were ground using a bench grinder mounted to a radial, rotating frame, guided on the rail and swivelling about a bearing in the building centre (Figure 11). A major set-back occurred when it was found that the grout that initially was used broke up under the wheel loads and it was necessary to regrout the rail. Rail segments were removed in succession, cleaned of the old grout and re-bedded on a layer of epoxy grout. Precise alignment was maintained by accurate measurements to adjacent segments.

Next, the central telescope pier was formed up and cast. It is entirely independent from the surrounding building structure in order to avoid the transmission of external vibrations to the telescope.

The contract for the manufacture, corrosion protection and erection of the steel frame for the building went to the local firm of Coonabarabran Engineering in September 1981. Their workshop in Coonabarabran was not very spacious, so some of the structural steelwork spilled over onto the footpath and the access lane, very much to the amusement of the local residents. The contract required the inspection of all welds by X-ray. Ed Simmonds supervised this work, but only found two welds which had to be redone. All structural steel was painted with a zinc-rich compound to provide adequate corrosion protection. Figure 12 shows the erection of the steel framework.

The building design provides for six floors, four of which are in the rotating part of the building. Level L0, the lowest level, covers only about 40% of the building floor area and is used

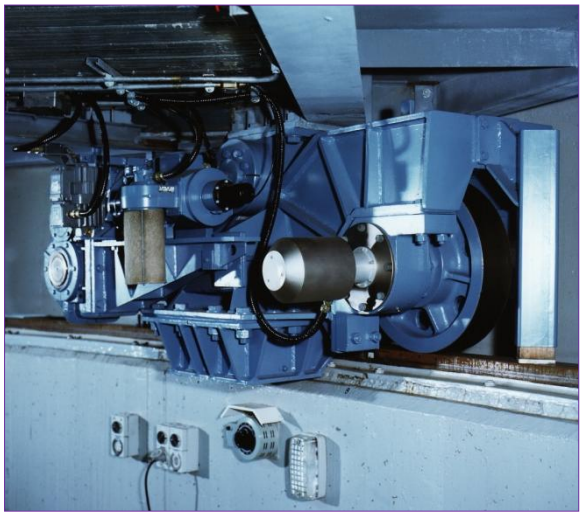


Figure 13: One of the four building bogies in position. The bogie shown is driving. It is fitted with gearbox and motor, on the left, and rotation-limiting switch unit, on the right (courtesy: R. Cooper).

for storage of spares, as well as containing the tea-room and toilet. Level L1 gives access to the building rotation bogies (Figure 13), the telescope cable wrap within the pier, the Cassegrain access platform mechanism, oil pumps, etc. Level L2 is the general entrance level. It gives access to the telescope mounting, and houses most of the control electronics cabinets. Level L3 is the Nasmyth observing level. An infrared instrument laboratory and instrument storage are also on this floor. Level L4 contains the telescope control console and the computers. Level L5 is for the telescope front end storage and houses the small crane used during front end inter-change, lifting instruments to the observing floor, level L3, and also primary mirror handling when the latter requires re-aluminising. Access to the wind-screens is possible from this floor.

Figure 14: The building steel frame is complete. The truck carrying the panels for the wall cladding has arrived (courtesy: H.P. Wehner).

The building is fitted with a side-opening, single-leaf shutter, which covers the slit through which the telescope observes during periods of use. The slit width is 3.5m. The design was shared between MacDonald, Wagner and Priddle (structural) and Mt Stromlo Observatory (operational). In order to prevent wind gusts from shaking the telescope two windscreens were provided, one vertical and the other horizontal. Both were controlled from the console, making it possible for the telescope to observe through a small aperture only.

In order to reduce costs, internal wall cladding was fitted only in the console and computer areas and the laboratories. The contractor for this work was Stramit Industries, who used their panels of compressed straw, treated with a fire retardant, and covered on both sides with a suitable architectural material (Figure 14). Someone thought that leaving an off-cut of Stramit outside in the rain and sun would awaken the forces of nature and produce sprouting of wheat, or whatever—and it did—fortunately not in the material fixed to the building walls. The cladding work was completed at the end of 1982.

Haden Engineering was awarded the contract for ventilation and air-conditioning, for completion by mid-1983. Ventilation required the installation of two fan units on the nearest building aprons, suitable ducting and air registers, blowing filtered, outside air into the telescope space. It was later found that exhausting air out of the building and replacing it with fresh, outside air, entering through the slit, gave better results in equalizing the air temperature around the telescope. Air-conditioning was only provided for the console and computer areas on level L4.

The building crane, supplied by Consolidated Lifting Services, was installed during early 1983.

Ed Simmonds left the site in February 1983, and Hermann Wehner took over supervision of the construction.

Barry Webb and Associates measured earth resistances around the building site and designed the lightning protection system, largely as proposed earlier by Gary Hovey and Hermann Wehner. Air terminals were installed, connected to the building steel frame. The building rail was connected to several earth terminations outside the building footprint. This system was also installed during 1983.

A major hitch occurred when it was found that cracks in the bogie wheels between the wheel webs and the rims had developed. The manufacturers, Schmidt and Muller of Sydney, were required to rectify these faults by replacing all wheels with cast ones, as was initially specified. This work involved removing one bogie at a time, shipping it to Sydney, having its wheels replaced, shipping it back to site and re-installing and re-aligning it. This work entailed a considerable time delay and extended involvement of site staff. The bogie wheels have been operating satisfactorily since.

The hydraulically-operated Cassegrain access platform was manufactured by a firm in Camden, NSW, which specialised in similar plat-

forms for trucks, etc. It is mounted as part of the building structure on level L2 and provides access to this focal position during instrument changes, instrument maintenance and, of course, observers.

On the whole, the building was essentially complete at the time of the official opening on 16 May 1984.

7 THE CONTROL SYSTEM OF THE TELESCOPE AND BUILDING

Control of the 2.3m Telescope and its building is best divided into the following areas: computer and data-communication systems, control software, time system, axis and rotator servos, auxiliary systems, building drive and meteorological system.

7.1 Computer and Data Communication Systems

Two prior developments at MSSSO provided legacies for the 2.3m project: in 1979 the Computer Section had taken delivery of the first digital Equipment VAX 11/780 computer in Australia. The VAX and its VMS real-time operating system were held in such high regard that Ted Stapinski decided that the telescope control computer would also be a VAX 11/780. This seemed somewhat excessive at the time but proved to be an inspired decision. The advanced machine firmly placed the computer as an integral part of the telescope control and banished decisively the notion that a telescope should be (at least partly) functional even if its control computer was inoperable. Much later the VAX 11/780 was replaced with a MicroVAX II. This had little impact upon the control code, however an arrangement whereby the VAX system clock was electrically phase-locked to the observatory time system had to be abandoned in favour of a software alternative.

The second legacy was a microprocessor-based data acquisition and communication system which had been developed for other smaller observatory telescope projects. Called the Microprocessor Time, Encoder and Control system (MTEC), it was designed largely by Michael Ellis (Ellis et al., 1980) and provided a data communication system needed to get data to and from control cubicles, windscreen and focuser drives and the meteorological system. It used a message-based asynchronous data transmission over RS-422 lines and proved extremely reliable. The MTEC system requires the control computer to issue a command or interrogation message to each remote station and await replies. With a cycle time of 20Hz, the MTEC system presents the computer with data from the telescope which is delayed by 100ms. Since this delay was deemed undesirably long for the servo loops which control the telescope axes and the instrument rotator, it was decided to implement a supplementary byte-serial, bit-parallel synchronous transmission system designated the Telescope Control Link (TCL).

The TCL also uses the RS-422 line standard but over a 9-pair cable. The design of the digital logic for the TCL and for many of the associated interface cards was carried out by Mark Downing who later became one of the senior detector engineers at Mt Stromlo Observatory. Both of these data transmission systems are still in use after three decades of use though they are now destined for replacement by an industrial Ethernet system.

7.2 Control Software

Design and coding of the telescope control software was commenced by project software engineer Hilton Lewis in early 1983. In early 1986 the position of software engineer was taken by David Hoadley. With the electronics and control systems now largely complete, Hovey and Hoadley had time for a more careful assessment of control algorithms and program structure. A new control system was written over the following two years. It is difficult now with the powerful graphical display systems of today to understand the problems we faced then: how to make ergonomic and customisable displays, how to create messages which could be dynamically removed from the display when no longer relevant, how to communicate everything needed by the observer without excessive complexity. Even though the VAX architecture, compilers and libraries were excellent for their time, graphic displays and integrated development environments were a luxury that still lay in the future (see Figure 15 and Figure 16).

By 1988 the revised VAX telescope control system was complete and met with wide acceptance from observers. Offsetting, rotator control, pointing error correction, accurate coordinate conversion, fast configuration from user files, and informative fault diagnosis were all efficiently and intuitively implemented. This system hosted several additions such as the oscillating secondary and an infrared tip-tilt seeing correction system and also survived the change of computer from the VAX 11/780 to the MicroVAX II without problems. The 2.3m Telescope saw two decades of VAX control.

During the 1990s, a paradigm shift away from VAX architecture towards less expensive and more capable UNIX-oriented systems together with the eventual demise of Digital Systems Corporation threatened the maintainability of VAX systems and precipitated yet another system redesign. Commenced by Gary Hovey and Mark Jarnyk in 2005, this incarnation of the

control system uses a compact PCI industrial machine and runs the QNX6 real-time operating system. Sadly, Mark died of cancer in early 2006 so the final control system was written by Jon Nielsen. Despite Hoadley's exceptionally well-commented code, Hovey chose to not to simply port the VAX software but to use it as a template to develop a new system incorporating TCSpk, a proprietary astrometric kernel (Wallace, 2002).

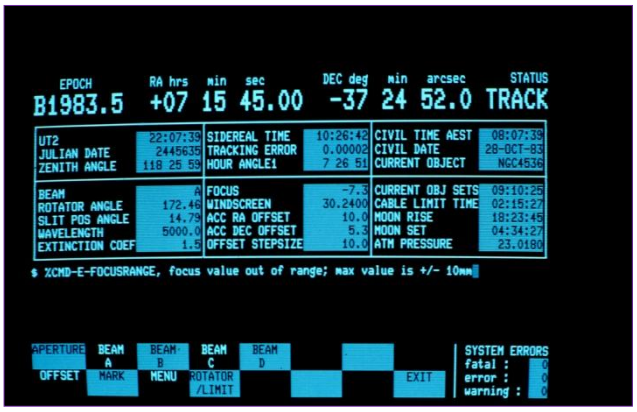


Figure 15: Original telescope display on an 80 character by 24 line VT52 terminal.

Named MSOTCS in the hope that it would be of use for other observatory projects, this new system was released to observers in late 2008. It preserves all of the functionality of the old VAX system but provides improved coordinate conversion accuracy, integrated pointing correction and engineering functions, and ease of maintainability (Nielsen and Hovey 2009). Nielsen's attractive and masterfully-written QNX control system should last for the remaining life of the telescope.

7.3 Time System

In the 1980s there was no computer network time, and observatories had to use autonomous sources of astronomical precise time. A Rohde & Schwarz time system based around a high-quality oven-controlled quartz oscillator was procured. This provided the control computer with precise UTC and stable pulses used to clock the data transmission systems.

The time was aligned to UTC (Australia) by a hierarchy of three methods: the Telecom speaking clock was dialled on the telephone to roughly align the time and to allow the second to be

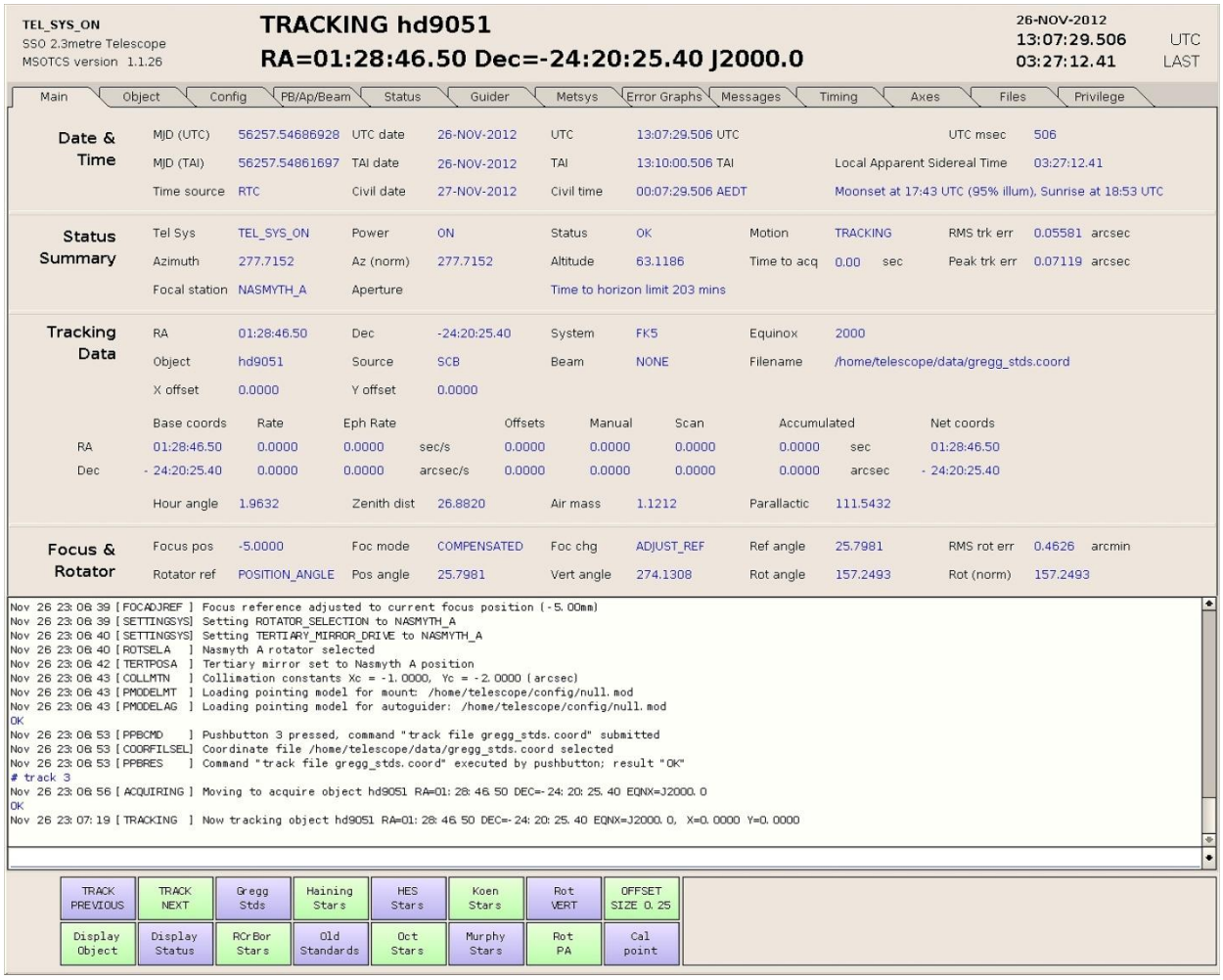


Figure 16: Current telescope display: MSOTCS running on QNX6 compact PC1 system.

identified; a HF time signal station was received using a Japan Radio NRD-515 communications receiver and the position of the time pips compared with the time system using a storage oscilloscope; finally the Sydney ABC TV signal was received via a satellite B-MAC receiver and a synchronizing pulse extracted to enable a digital counter to measure the offset to UTC to a precision of a few microseconds. The CSIRO National Measurement Laboratory facilitated this measurement by simultaneously measuring the same TV signal in Sydney and the system was calibrated using a Cesium-beam atomic clock belonging to the Department of National Mapping in Canberra (Figure 17).

Currently the control system relies on network time mediated via the NTP protocol which is thought to have an absolute accuracy of approximately 30ms. It is proposed to add a GPS timation receiver to regain a degree of autonomy. It is sobering to realise that after centuries during which astronomical observatories were the source of all precise time, we have become routine customers of the satellite and telecommunication industry!

7.4 The Axis and Rotator Servomechanisms

The two axes of an alt-azimuth telescope need to be driven at continuously variable rates to track a celestial object. Moreover, a 'third axis'—the instrument rotator—must be similarly controlled to counter the field rotation inherent in such a mount.

Early in the project Gary Hovey commenced the specification of the drive components and design of the servo electronics: frame-less, permanent-magnet, DC torque motors of INLAND manufacture were employed with velocity feedback provided by similar DC tachogenerators. The motors were driven in an anti-backlash 'virtual power loop' using INLAND linear servo amplifiers. The locked-rotor resonances of the telescope structure were explored by Hovey using an analogue frequency response analyser and found to be in the region of 8 to 10Hz.

Of particular help with the servo system design was a design study for the Multi-Mirror Telescope at Mt Hopkins, Arizona. Engineers at Ford Aero-Space provided considerable information and advice on that project. Servo modelling was done using a number of crude, in-house computer programs (this is before the era of MATLAB and similar applications) and the final adjustments were performed empirically during commissioning. The servos and their associated axis encoders were interfaced to the control computer via the synchronous TCL data communications system. The servos for the three rotator drives were of similar design but, because of the relaxed angular accuracy, did not require the two-motor anti-backlash system. The rotator circuitry was the last of the telescope electronics to be made and was able to take advantage of sub-racks, circuit card hardware and card connectors to the European DIN standard which was a substantial improvement over the older ISEP components used elsewhere.

As well as purpose-built electronics, the Servo and Rotator cubicles containing these systems required a complex array of electromechanical relays for control, sequencing and protection; this was designed by Jan van Harmelen who was able to standardize much of the design so as to allow it to be re-used in other cubicles.

Figure 17: Time-system in operation in 1984 with the time-pip from radio VNG clearly visible on the long-persistence oscilloscope.

Van Harmelen and Hovey supervised a small coterie of technical officers who constructed and wired the cubicles, wired circuit cards and manufactured the numerous interconnecting cables. The servo control aspects of telescopes such as the 2.3m are explored in Hovey 1986a and 1986b (Figure 18).

7.5 Auxiliary Systems

Many of the smaller sub-systems of the telescope are controlled from a cubicle called the Auxiliary Systems Cubicle (ASC). This comprises a mixture of electromechanical relays, dis-

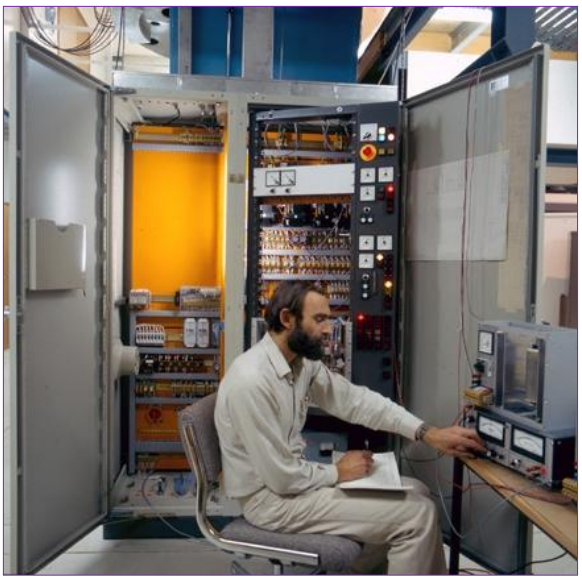


Figure 18: Servo cubicle during commissioning; Gary Hovey is measuring the driving point admittance of the azimuth axis.

crete component logic and microprocessor-based electronics. It was designed by Jan van Harmelen, and is interfaced to the control computer using the asynchronous message-based MTEC data transmission system.

The ASC is responsible for bearing/gear lubrication, primary mirror support air pressure, mirror cover and building shutter drives. Other minor systems such as the Cassegrain focus access platform, the gantry crane and the top-end clamping system are included with auxiliary systems but, apart from safety interlocks, are not involved with telescope control. The 2.3m Telescope has interchangeable top-ends which carry different secondary mirrors according to which of the Cassegrain or Nasmyth foci is in use. Control of the top-end clamping system involves electrical actuation of the clamps in sequence followed by crane operations to remove or install the top-end. The sequencing of these operations and the safety interlocking of the crane, clamping drives and the telescope is handled by a simple relay logic system. Commissioning such a plethora of sub-systems was quite a time-consuming process; the various status, signalling and safe-failure modes needed checking to confirm that the control computer was correctly seeing the telescope hardware and that generated error messages were valid and informative for the observer.

Figure 19: Senior Technical Officer John Findlay and Gary Hovey at the partially-completed control console.

The 2.3m Telescope was built in an era when the astronomer's control console was still considered to be the hub of the installation. Also designed by Jan van Harmelen, we include it here amongst the auxiliary systems. As well as the operating controls for the telescope and building systems it contains some of the relay circuitry needed to start up and shut down the telescope, and to signal faults. Even though remote observing was anticipated in the early stages of design, we failed to envisage operation of the telescope with no person present in the level L4 control room. Thus the console electronics were those most needing revision in May 2006 when some projects required completely unattended operation (Figure 19).

7.6 Building Drive

The building rotation drive was a major item which was deemed to be outside our in-house engineering capabilities. Hermann Wehner, who was responsible for the building design and building systems, initiated the basic design. Unlike the Multi Mirror Telescope building which used single-wheel bogies, our four bogies had two wheels each and the drive was through one wheel on each of two diagonally opposite bogies. The building drive does not receive commands from the control computer but instead is autonomous and simply regulates the angular offset between the telescope azimuth and that of the building direction.

Clearly high powers and large inertias were involved, but there were more subtle issues. Three firms were approached for proposals and quotations for a suitable building drive system. Of particular concern was the possibility of anti-phase oscillations where one of the diagonally opposite bogie motors unloads and the other makes up all of the torque until it decelerates and the two swap effort. ASEA indicated that they had experienced the problem on paper manufacturing web drives. Accordingly they were given a contract to produce a stand-alone building drive cubicle and to supply the shunt-wound DC drive motors. The installed system comprises a single Tyrak 8A thyristor converter driving two Thrige-Titan LAK112 DC motors; the

difference between the armature currents (motor loading) is used to control one of the motor fields providing the necessary torque stabilisation. The outermost servo loop comprises a PI controller which closes the loop around an LVDT which measures the building-to-telescope error. The system functions smoothly: there is an initial lag of up to 1.7° as the telescope accelerates but the building-to-telescope azimuth error when tracking is less than 0.1°.

To ensure that the building drive servo was stable, the torsional stiffness of the building needed to be as high as practicable. We also had the design challenge of how to prevent the rotating building from overturning in the event of a catastrophically high wind. Both problems were neatly solved by adding a 55 tonne concrete slab into the floor-plane of level L2.

7.7 Meteorological System

Meteorological measurements of wind speed and direction, temperature, humidity and barometric pressure are made using standard Weathertronics and Vaisala sensors mounted atop the building. The analogue voltages from the Weathertronics frame are digitized by purpose-built electronics and sent via the asynchronous MTEC system to the computer for display, logging and safety alarm purposes. The wind-speed, temperature and humidity are also displayed on analogue meters at the observer's control console. A rain detector is also installed and has an electrical interlock to the building shutter so that the latter is automatically closed upon the detection of rain. Meteorological data are logged, archived and made available via a web server. The meteorological system was designed by Gary Hovey who constantly had to explain to sceptics that, yes, the azimuth of the building *was* added to the wind direction measured with respect to the rotating building!

8 INTEGRATION OF THE TELESCOPE AND BUILDING AT SIDING SPRING OBSERVATORY

An obvious requirement for a telescope installation is the need to ensure that assembly problems are discovered and dealt with before the structure is transported to site. Prior trial assembly of the mount is essential. Fortuitously, the Research School of Physical Sciences had, in its early history, built a large machinery hall to allow the construction of the Homopolar generator during the 1950s. This cavernous building included an overhead crane that made it ideal for our trial assembly, and it was kindly made available for this purpose. Trial assembly commenced in mid-1983, and was completed a few months later. A party was held to mark the successful completion of the exercise, as shown in Figure 20.

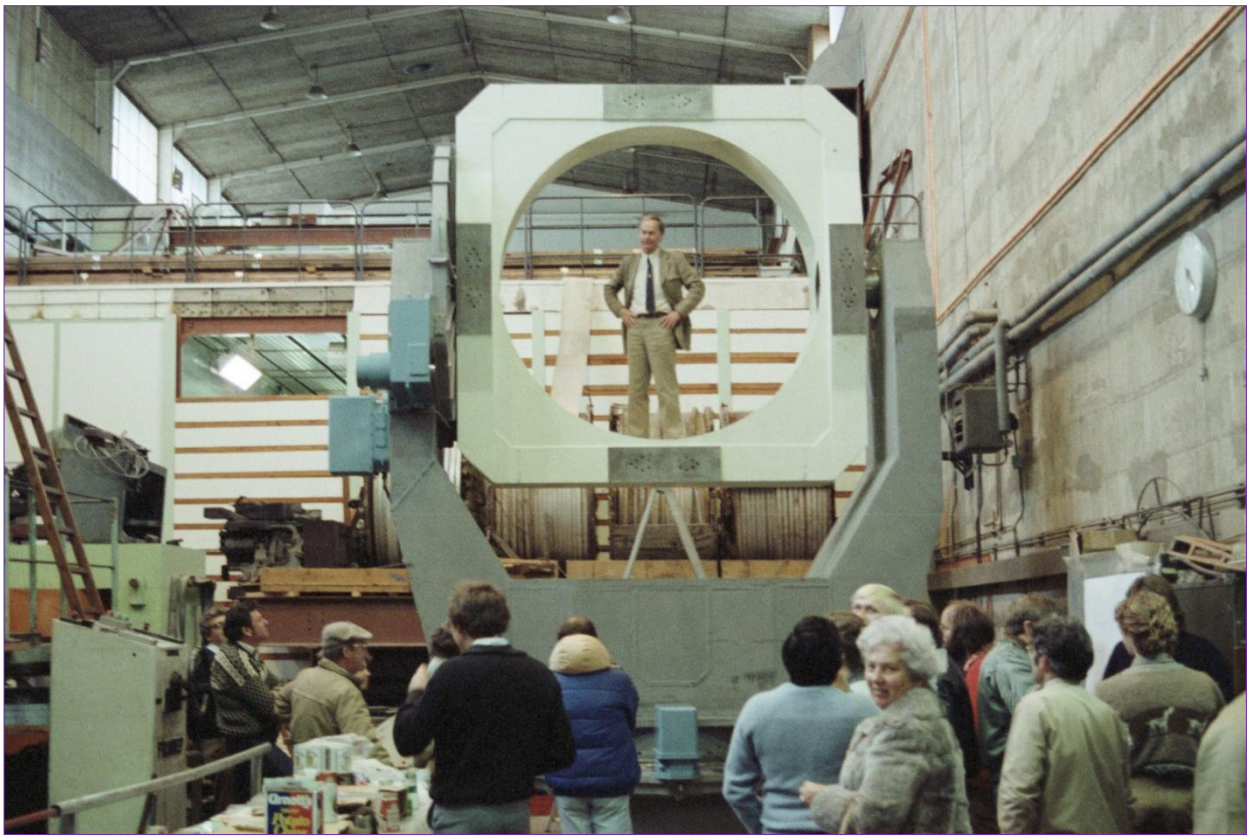


Figure 20: The telescope mount in the machinery hall at the ANU's Research School of Physical Sciences at completion of the trial assembly. Don Mathewson is standing in the centre ring of the mount.

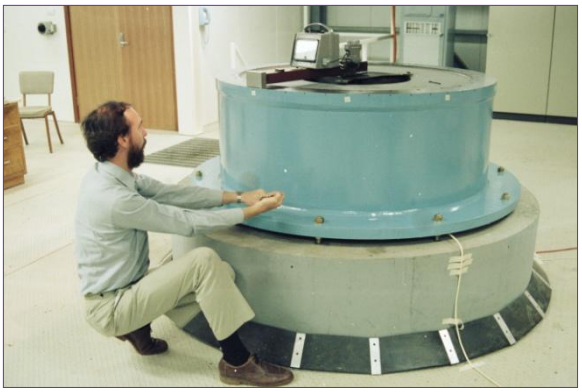


Figure 21: The telescope base being adjusted to accurately level the azimuth bearing mounting face. The measuring apparatus used was that previously devised to measure face flatness during the hand-scraping process.

After completion of the trial assembly, the mount was disassembled, loaded onto trucks and transported to Siding Spring Observatory over a period of a few weeks in November of 1983. The base and azimuth bearing system were installed first and adjusted so that the bearing flange was level to within one arc second. The adjustment process is shown in Figure 21. The mounting of the azimuth bearing and ring gear is shown in Figure 22.

Delivery of the telescope fork and altitude axis centre ring was synchronised with the arrival of a large mobile crane that had travelled from Brisbane. The crane was hired for several days in order to do a few hours of work because most of the time was consumed by travel. The major structure of the telescope mount was thus installed onto the newly prepared base. Figure 23 shows the telescope fork being lifted into the building, with a small crowd of spectators watching.

Detailed assembly work then continued for several months. Figure 24 shows its status in January 1984, when most components were in place. A dummy mirror is mounted in place of the real mirror, allowing the telescope to be balanced for drive testing. The primary mirror was kept in safe storage until assembly was otherwise

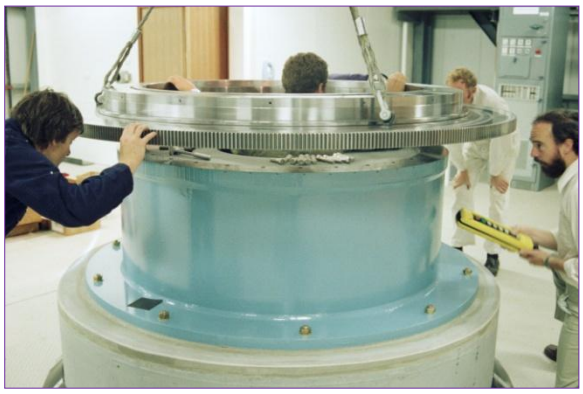


Figure 22: Mounting of the azimuth bearing and ring gear in preparation for installation of the telescope fork.

complete. Figure 25 shows it finally being installed. Figure 26 shows the final structure.

Necessary to the success of the 2.3m Telescope project was a major upgrade to the electric power distribution system at Siding Spring Observatory. The mountaintop which hosted the existing ANU 40-in, 24-in and 16-in Boller and Chivens telescopes was fed with three-phase power at a non-standard voltage of 1400V using autotransformers each end for step and step-down and would need augmenting. A scheme was devised by Gary Hovey and the chief engineer of Ulan County Council at Gulgong, NSW, to take the mountaintop feeder and re-insulate it for operation at 22kV. The Ulan engineer designed a system incorporating high voltage switchgear located in the utilities building which could feed the output of the existing 500kVA Petbow generator backwards through the existing step-down transformer and so feed energy at 22kV to the Australian National University's mountaintop area. A new step-down transformer was installed near the pump-house and an arrangement of 22kV regulators connected in open-delta fashion restored the voltage to LV (415V three-phase) to compensate for the feeder transformer being run in reverse. The new system potentially gave us 500kVA of power on the mountaintop and meant that we retained the back-up power capability of the site generator. It functioned well for 31 years until its recent replacement with a separate generator set and automatic LV changeover system.

The 2.3m Telescope was officially opened on 16 May 1984. The telescope was operational at that time, but commissioning work continued for many months as activity progressively transitioned to a full observing schedule. The Telescope has performed with great success over the 28 years since its opening. Changing technology has progressively revealed a problem, however, in that our diminishing supply of electronic spare parts is becoming difficult to replace. This led to the commencement of an upgrade program in 2011. For the most part, this involved modernization of drive system electronics and control systems. The original design team was re-assembled for the exercise, and they expect to complete the task in 2013.

9 INSTRUMENTATION

Limited resources meant that no permanent instruments were available for the telescope at the time of its opening. However, while the telescope was under construction, design and construction started on the Double Beam Spectrograph for one of the two Nasmyth focal stations

The design team for the Double Beam Spectrograph was led by Alex Rodgers, who was inspired by similar work done by his colleague

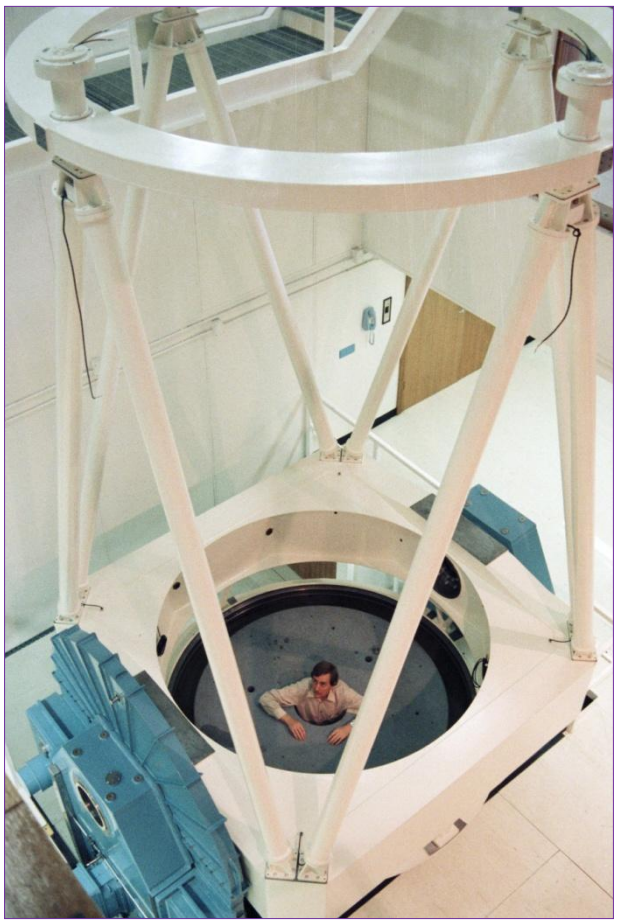


Figure 23 (top left): The telescope fork being lifted into the newly-completed building.
Figure 24 (top right): The newly-assembled telescope in drivable condition, with a dummy mirror in place of the real mirror.

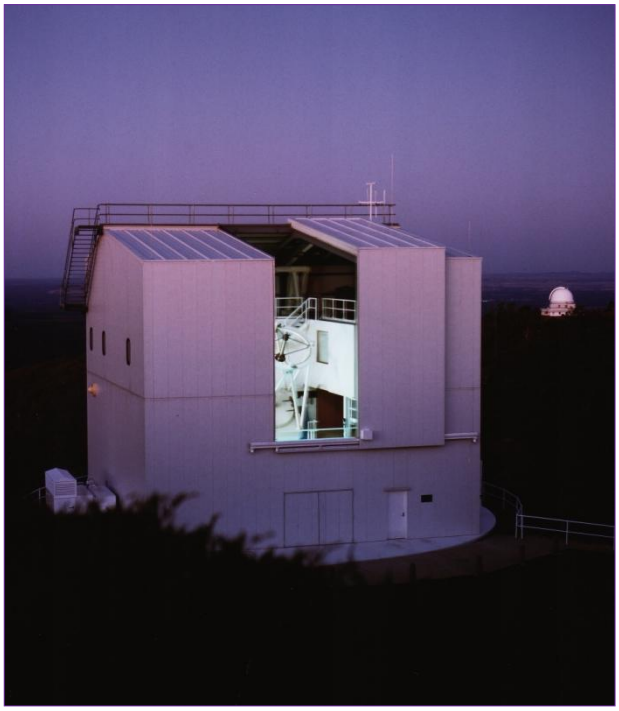


Figure 25 (bottom left): The primary mirror being installed in the completed telescope.
Figure 26 (bottom right): The 2.3m Telescope installed in the building.

from Hale Observatory, Bev Oke who visited Mt Stromlo Observatory to help with the design. It was designed as a state-of-the-art high-efficiency spectrograph providing intermediate resolutions ranging between 40 and 240km/s over a spectral range of 300-1000nm with a 1.5 arcsec slit. Interchangeable diffraction gratings are used in a collimated beam of 150mm diameter. To maximize efficiency, the beam is split into two bands at a wavelength of 580nm. Mirrors on the blue side are coated with aluminium, while those on the red side are coated with silver. The system is continually flushed with dry air to maintain high reflectivity, as is especially required by silver. Folded Schmidt cameras are used to achieve the required small focal ratio (f/1.1) with

high throughput. The original PCA detectors were replaced by Loral Fairchild CCD detectors in September 1984 and later by Tektronix CCDs which remained in use until the Double Beam Spectrograph was decommissioned.

Design of the second Nasmyth instrument, the Nasmyth B Imager, was commenced in 1985. Again, design of this instrument was led by Alex Rodgers, with advanced optical design done by Damien Jones of Prime Optics. It is a combined imaging system and low resolution spectrograph operating over the wavelength range 300-1100nm, accepting the whole 6.6 arcmin Nasmyth field without vignetting. The system uses exotic glasses to be achromatic across the whole wavelength range. Collimated and telecentric beams are provided in different sections of the instrument. The former accommodates diffractive prisms for spectroscopy. The latter accommodates narrow band interference filters, allowing uniform response across the field.

Given that the alt-azimuth configuration of the telescope causes field rotation, instrument rotators were required at all three focal stations. Design and construction of these commenced after the telescope opening. Indeed, considerable development and commission work continued on the telescope itself after its opening. A temporary instrument rotator was installed in 1984, and used to mount the Boller and Chivens Echelle Spectrograph that had been built for the 40-in telescope at Siding Spring Observatory in 1980.

The Cassegrain infrared system was installed in 1985. For the new installation, the system included a chopping secondary mirror mount built by the Physics RAAF Academy at the University of Melbourne.

The Cassegrain Echelle spectrograph continued to be used as the main Nasmyth instrument until it was joined in 1986 by the Double Beam Spectrograph. These instruments were made much more useful with the installation of the three new instrument rotators in mid-1988. This allowed the instrument suite to be properly tracked for field rotation.

The first generation of instrumentation was completed with the commissioning of the Nasmyth B Imager in October of 1991. Thereafter, it was interchanged with the Echelle spectrograph. The tertiary mirror of the telescope allowed rapid and remotely controlled switching between the two Nasmyth focal stations.

A major upgrade was made to the Cassegrain infrared instrument system in the early 1990s, with the building of CASPIR and a tip-tilt secondary mirror mount to allow correction of low-altitude seeing. CASPIR was a cryogenic near infrared imager with spectroscopic and polarimetric capabilities. Given its many operating modes, compact design was required to fit it within the restricted space available at the Cassegrain focus. The cryostat chamber is only 500mm long.

A variety of temporary instruments was installed through this period. A notable example was a Fairchild camera that was mounted at prime focus for the purpose of imaging Comet Halley during its 1986 appearance. The Nasmyth secondary mirror was removed to allow this, and the camera was mounted inside the focus carriage so that focus could be adjusted. Facilities for remote operation were also in place, allowing a number of publicity events to be conducted. On one occasion, the entire membership of the Federal Parliament attended an evening in the lecture theatre at Mt Stromlo Observatory, where they saw live images of the comet transmitted from the 2.3m Telescope at Siding Spring Observatory, which was remotely controlled from the lecture theatre.

More recently, a major modernization of the instrument suite was completed in March 2009 with the deployment of the Wide Field Spectrograph (WiFeS). This is a very successful example of a modern integral field spectrograph. An E2V detector upgrade is currently underway.

10 THE OPENING OF THE TELESCOPE

The day of the grand opening of the 2.3m Telescope had finally arrived, 16 May 1984, and Siding Spring Observatory turned on its best weather. The marquee where the guests would have lunch was erected near the Lodge. The first of nearly 200 guests were arriving and the place was a hive of excitement. Astronomers from around Australia were coming. The Astronomical Society of Australia held a special meeting in Coonabarabran to coincide with the opening of the telescope, so many astronomers were present.

Then disaster struck as the Chancellery's charter plane was still at Canberra, grounded because of a heavy fog which was not expected to clear for several hours. Meanwhile, the Prime Minister's Royal Australian Air Force plane had already taken off, because military planes were not grounded.

Bob Hawke, the Prime Minister, was scheduled to open the telescope in about an hour, and he arrived with his 'minders'. They told him he should continue with the opening as planned without waiting for the Chancellery members as he had very important meetings that afternoon back in Canberra. Don Mathewson then drew the Prime Minister aside and told him that for seven years the MSSSO and the Chancellery

had been working hard, crossing almost insurmountable barriers for this moment and it would be an unforgettable calamity to continue with the ceremony without members of the Chancellery. Bob Hawke thought for a moment and then told his minders to cancel the meetings.[4]

Don Mathewson then asked Peter Gillingham, the on-site engineer in charge of the Anglo-Australian Telescope, if he would show the Prime Minister over 'his' telescope. Peter leapt at the chance. Somebody then turned to Mathewson and commented that it may not be a wise move for the Prime Minister to see the bigger (3.9m) telescope, to which Mathewson replied,

> Bigger but not better! It's ideal because the PM has a chance to compare an older generation telescope with the new generation. He can see the vast AAT dome filled with unusable space and the huge, cumbersome equatorial mount.

The fog eventually cleared in Canberra and members of the Chancellery duly arrived. The ensuing tour of the telescope went smoothly, except that an over-zealous Boy Scout on guard on the lower floor tried to prevent the Prime Minister from using the toilet!

When the Prime Minister reached level L3 of the building he was shown the Double Beam Spectrograph, which was designed to be the main workhorse for use at one of the Nasmyth foci. This instrument had two prominent arms which housed the separate red and blue cameras, and Alex Rodgers, the left-leaning and mischievous team leader for this instrument, had labelled these "RED (LEFT) ARM" and "BLUE (CENTRE-LEFT) ARM". This sardonic allusion to the Australian Labor Party's factional groupings was not lost on an amused Bob Hawke.

In his opening address, the Prime Minister said:

> The ANU is to be congratulated for its initiative in developing this telescope which sets new international standards in astronomical engineering and is the most advanced optical telescope ever built.
>
> There are good reasons for Australians to be proud of this achievement.
>
> The design and development of the telescope is very much a co-operative Australian venture. Apart from several components which could not be manufactured in Australia, construction took place in the ANU's own workshops and involved a large number of Australian engineering firms, supply and service companies and consultants.
>
> The astronomers, engineers and technicians at Mount Stromlo and Siding Spring Observatories, with the support of the ANU and the co-operation of industry, have created a facility which clearly demonstrates Australia's capacity to contribute to the advancement of high technology.

Figure 27: In the foreground, from left to right, are Don Mathewson, Bob Hawke (the Australian Prime Minister) and Peter Karmel (Vice-Chancellor of the Australian National University), watching the opening of the 2.3m Telescope at Siding Spring Observatory on 16 May 1984.

As he finished, the 2.3m Telescope and its associated building rotated smoothly and noiselessly through 90º to present the Prime Minister with the commemorative plaque for him to unveil (Figures 27 and 28).

After this, the lunch went on for hours, and that night a Barn Dance was held down in Coonabarabran attended by more than 300 people.

It was a truly happy and memorable day!

11 SCIENCE OUTPUT

11.1 A Powerful Tool for Australian Astronomers

The combination of this easy to use, efficient large-aperture telescope with a suite of instrumentation unequalled in other observatories in Australia has produced a prolific science output and contributed greatly to the development of Australian astronomy. The 2.3m Telescope has been used by astronomers from all Australian universities (and many overseas ones) and has been a vital tool for the theses of a multitude of Ph.D. students.

Figure 28: The plaque which Bob Hawke unveiled to open the 2.3m Telescope.

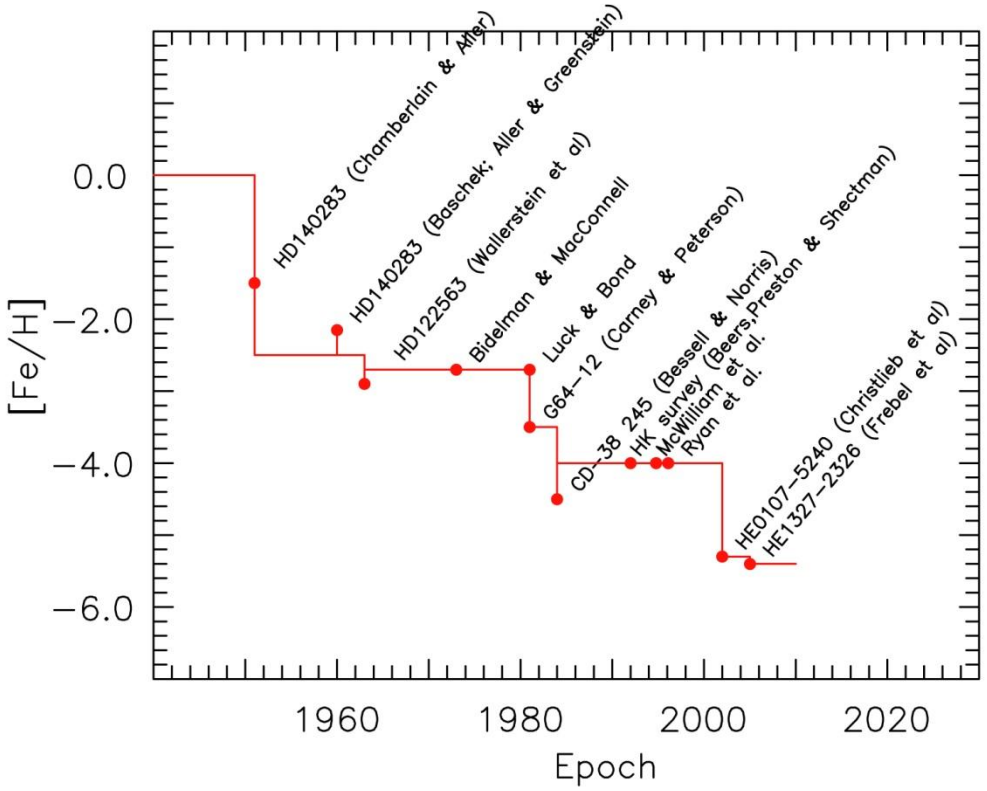


Figure 29: The diagram shows how the chemical abundance, [Fe/H], of the most metal-poor stars then known decreased as a function of the year of its discovery.

MSSSO allocates time on the 2.3m Telescope through a peer review process to the national and international community. Several astronomers from other Australian institutions are members of the Time Allocation Committee. On average about half of the time is given to external and collaborative projects involving MSSSO and external researchers.

11.2 The First Project

Shortly after the opening ceremony, even though the commissioning was not completely finished and the main instrumentation not yet built, the telescope was used to do I band photometry of 161 Cepheids in the Small Magellanic Cloud (Mathewson et al., 1986). These distance measurements yielded a major breakthrough, revealing that the Small Magellanic Cloud had been split into two by a recent collision with the Large Magellanic Cloud. These two galaxies were called the Mini-Magellanic Cloud and Small Magellanic Cloud Remnant.

It is impossible to detail all of the research projects that have been carried out using the 2.3m Telescope, but a few large programs have been selected to illustrate the types of research the telescope has contributed to.

11.3 Metal-Poor Stars in our Galaxy

During the first 25 years of 2.3m observations, the Double Beam Spectrograph was used extensively to discover the most metal-poor stars in our Galaxy. These stars are among the first to form in the Universe and tell us about the nature of the Big Bang and the conditions that existed at the earliest times. Mike Bessell, John Norris, and colleagues observed several thousand candidate metal-poor stars to discover objects containing less iron, by factors as large as 40, than were known when the 2.3m Telescope was commissioned. Indeed, the most iron-deficient of these are 400,000 more iron-poor than the Sun, and were most likely formed only 100,000,000 years after the Big Bang. The discovery of these objects has been followed up by high resolution, high signal-to-noise spectroscopy with the world's 6-10m telescopes, and has led to major advances in our knowledge of the nature of the first stars and the manner in which the first chemical elements heavier than lithium formed in the Universe. For reports on the two most iron-poor stars known, which were discovered during programs undertaken with the 2.3m Telescope, see Christlieb et al. (2002) and Frebel et al. (2005).

Figure 29 shows how the chemical abundance, [Fe/H], of the most metal-poor star then known decreased as a function of the year of its discovery (where [Fe/H] = 0, –2, –4, ... refers to Fe fraction of the star relative to the abundance of Fe in the Sun, of 1, 1/100, 1/10000, ..., respectively). The decrease of [Fe/H] since ~1980 results in very large part from discoveries made with the 2.3m Telescope.

11.4 Evolution of the Galactic Disk

Another very significant contribution to our understanding of how the galactic disk evolved since it began to form was made from observations with the 2.3m Telescope. We need to know how the chemical properties and velocities of the disk stars changed with cosmic time since the disk began to form.

We use the relatively rare subgiant stars for which it is possible to measure fairly accurate ages. Our stars come from the RAVE stellar survey of about 500,000 stars, which is large enough to generate a useful sample of nearby subgiants of all ages. We observed about a thousand subgiants with the echelle spectrograph modified to give a full multi-order echelle format with a CCD detector, and measured their velocities, temperatures, element abundances and surface gravities. Combined with proper motion data from other sources, this gives us all the data needed to derive observationally the age-velocity-metallicity relation in the solar neighbourhood.

We find that the average metallicity of the stars has gradually increased over the last 10 Gyr, from [Fe/H] = – 0.5 to solar. The random velocities of the stars appear to increase for the first 3 Gyr of their lives, as they interact with their environment, but then stay roughly constant. This makes sense. The higher velocities of the older stars mean that they spend only a small fraction of their orbits near the Galactic Plane, and this reduces their interaction with spiral arms and molecular clouds (Haywood, 2008).

11.5 The Final Stages of Stellar Evolution

A big, very successful project was the study of the turbulent final stages of stars in the Magellanic Clouds. The Large and Small Magellanic Clouds are the nearest galaxies to our own Galaxy and they are ideal places to study stars. Most importantly, individual stars can be readily resolved in the Clouds with ground-based telescopes, and the 2.3m Telescope is ideally suited for studying the final luminous stages of stellar evolution there. Highly evolved stars have turbulent lives: they pulsate with large amplitude; they undergo periodic nuclear burning episodes that lead to the contamination of the stellar surface with large amounts of carbon; and finally they eject their outer layers in a strong stellar wind leading to the formation of a planetary nebula. Particularly useful in studying these processes have been the near-infrared instruments on the 2.3m Telescope, especially the Cryogenic Array Spectrometer/Imager (or CASPIR). These instruments led to early calibrations of the pulsation period-luminosity relation for Mira variables (Hughes and Wood, 1990), the first detection of a second period-luminosity sequence obeyed by the semiregular variables (Wood and Sebo, 1996), and the first presentation of the now well-known multiple period-luminosity sequences for variable red giant stars in the near infrared (Wood, 2000) (see Figure 30). During the lifetime of the Spitzer Space Telescope, simultaneous observations made with both the Space Telescope and the 2.3m Telescope (and CASPIR) were crucial in determining the rates of mass loss in the final stages of red giant star lifetimes (Groenewegen et al., 2007).

11.6 Bulk Flows in our Local Universe

The advent of the 2.3m Telescope opened up a major area of research, observational cosmology, to investigate bulk flows of galaxies in our local Universe. For five years, the peculiar velocities of 1355 spiral galaxies were measured using the Tully-Fisher Relation. Five Ph.D. students (Figure 31) each worked on this project as part of their first year program. Rotation velocities were measured using long slit Hα spectroscopy with the Dual Beam Spectrograph on the 2.3m Telescope. The results showed that the 'Great Attractor' as postulated by UK and US observers to explain bulk flows, did not exist (Mathewson et al., 1992a). The bulk flow of some 600km/s extends well beyond the hypothetical Great Attractor at 4,400km/s to more than 8,000km/s (Mathewson et al., 1992b).

11.7 The Collision of Comet Shoemaker-Levy with Jupiter

There is no better way to finish this small sample of significant projects carried out with the 2.3m Telescope than to display one of the spectacular photographs taken by Peter McGregor and Mark Allen using the Cryogenic Array Spectrometer/Imager. The impact of Fragment K on Jupiter by Comet Shoemaker-Levy 9 is shown at 2.34 μm in Figure 32. Their photographs received international acclaim and were amongst the best taken of the collision (see McGregor et al., 1996).

12 CONCLUDING REMARKS

The factors that led to the construction of the telescope were an acute shortage of observing time, the need for a large telescope versatile enough to take full advantage of modern instrumentation, the lack of advanced facilities for the training of graduate students, and a desire to stimulate the development of astronomy in Australia.

The original specifications, as outlined by the astronomers and engineers at Mt Stromlo and Siding Springs Observatories (MSSSO), called for a versatile, precise and efficient telescope,

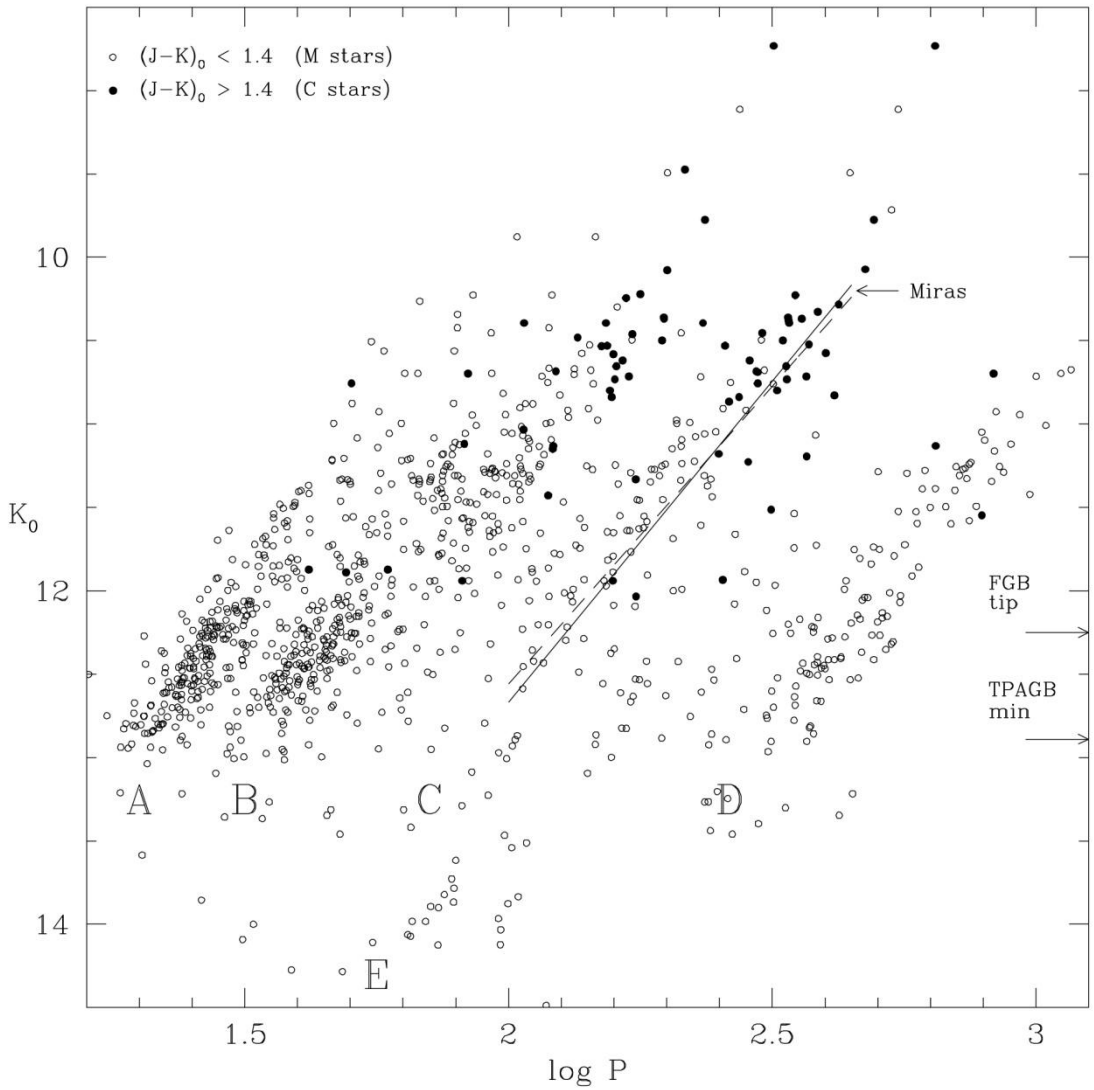


Figure 30: Variable LMC red giant stars plotted in the (K,log P) plane. The K magnitudes were obtained using CASPIR on the 2.3m Telescope, while the periods were obtained from the MACHO telescope at Mt Stromlo Observatory. Five period-luminosity sequences labelled A ... E can be seen. The positions of the tip of the first giant branch (FGB) and the minimum luminosity for thermally pulsing AGB stars with M ~ 1 Msun are indicated by arrows. The solid and dashed lines are the K-log P relations for Mira variables from Hughes and Wood (1990). Solid circles correspond to stars with J–K > 1.4 and they are assumed to be carbon stars. Other stars are assumed to be oxygen-rich stars. This figure is the first infrared version of the period-luminosity for variable red giants in the LMC.

Figure 31: Don Mathewson (centre) with Vince Ford (above Don) and Don's research group of Ph.D. students (clockwise from the left: Angela Samuel, Emmanuel Vassiliadis, Marcus Buchhorn, Carl Grillmair and Stuart Ryder) who studied the Large Scale Flow of Galaxies using the 2.3m Telescope in 1989.

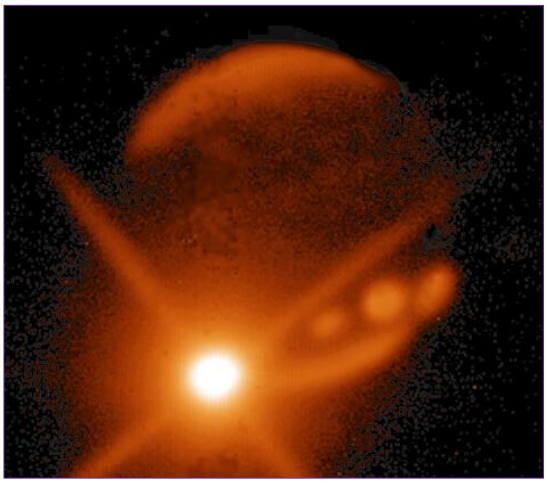


Figure 32: The impact of Fragment K of Comet Shoemaker-Levy on Jupiter, using CASPIR at 2.34 μm. The scars of three previous impacts can be seen on the planetary disk (image from Peter McGregor and Mark Allen).

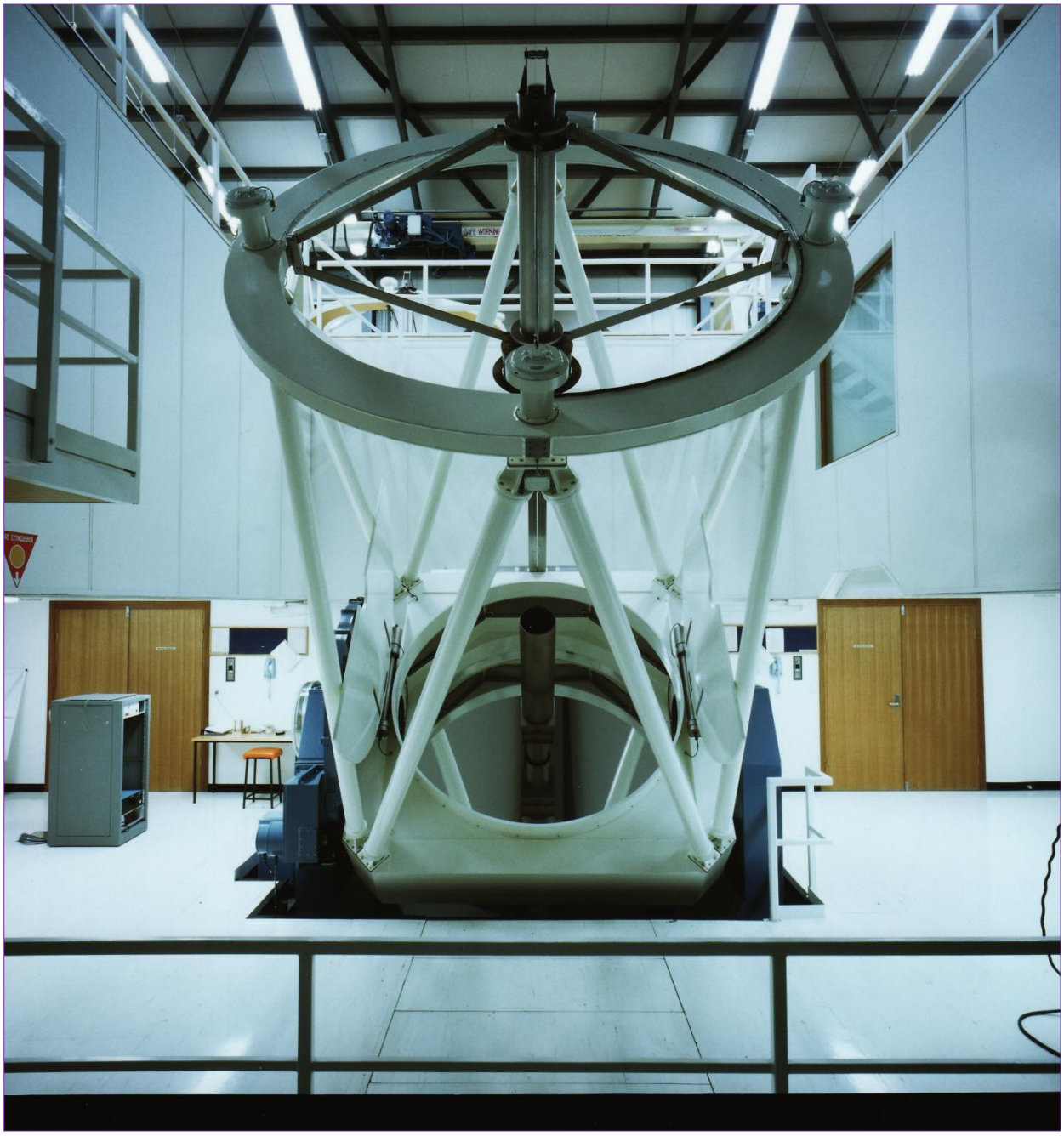


Figure 33: The rotating building places the 2.3m Telescope at the very centre of a laboratory where a variety of instruments can be mounted with ease.

equipped with advanced astronomical instrumentmentation, but costing a fraction of the price of a conventional telescope.

The final design is one of beautiful simplicity. An alt-azimuth mount and a thin primary-mirror keep the weight of the telescope to a minimum. A rotating building places the telescope at the very centre of a laboratory where a variety of experiments can be mounted with ease (see Figure 33).

A control-computer closely integrated into the operation of the building, the telescope and the astronomical instruments guarantees versatility, economy and efficiency because:

- the operational characteristics of the telescope can be altered easily, often simply by changing the telescope-control software;
- it is cheaper to implement and maintain complex control systems when the complexity resides in computer software rather than in specialised mechanical components; and
- the observer can exercise an unprecedented degree of control over the telescope, its environment, and its instruments.

Advanced astronomical instruments maximise the efficiency with which the collected light can be measured and analysed.

These instruments incorporate the photon-counting and infrared detectors already develop-

ed at MSSSO.

In all respects the new telescope met the original aims of its creators, and in many ways it surpassed those aims. The dream was translated into reality, a reality that was an inspiring example of the capabilities of Australian scientists, engineers and technicians—the concept was bold, the design was elegant, the implementation was professional.

In October 1985, the Institution of Engineers, Australia presented the 2.3m Telescope their Engineering Excellence Award and in September 1989 they also awarded it to the Dual Beam Spectrograph, the main instrument on the telescope.

The ingenuity and inventiveness of the engineers at MSSSO developed whilst building state-of-the-art instrumentation for the 2.3m Telescope was vital to the creation of the Advanced Instrumentation and Technology Centre which was opened in October 2006. This is now providing instruments for the world's largest telescopes.

13 NOTES

1. In the 1980s, 'the Chancellery' at the Australian National University comprised the Vice-Chancellor (Professor Donald Low and later Professor Peter Karmel), Deputy Vice-Chancellor (Professor Ian Ross) and the Bursar (John Coleman), and their support staff.
2. Professor Ian Ross, the Deputy Vice Chancellor, used to jokingly refer to Mt Stromlo as home to wild tribesmen who periodically raided the ANU to loot and pillage!
3. Indeed, the conversation was so protracted that Hart was presented with an $800 telephone bill when he checked out of his hotel the following morning!
4. At the time Don Mathewson thought: "Good old Bob, he's a real champion!"

14 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Chancellery of the Australian National University. They were superb. We don't know how they did it—but they did it! They provided $3.2 million (1980) out of University funds and we have a wonderful telescope. Also we thank the entire staff of MSSSO during this time. Everybody realized that it was an enormous challenge and everyone met and indeed, more than met, this challenge. In particular Norman Stokes and then Barry Newell, the Administration Officers, played a pivotal role. Thank you all very much.

15 REFERENCES

Beckers, J.M., Ulich, B., Shannon, R.R., Carleton, N.P., Geary, J.C., Latham, D.W., Hoffman, W.F., Low, F.J., Weymann, R.J., and Wolff, N.J., 1981. The Multiple Mirror Telescope. In *Telescopes for the 1980s*. Palo Alto, Annual Reviews Inc. Pp. 63-128.

Christlieb, N., Bessell, M.S., Beers, T.C., Gustafsson, B., Korn, A., Barklem, P.S., Karlsson, T., Mizuno-Wiedner, M., and Rossi, S., 2002. A stellar relic from the early Milky Way. *Nature*, 419, 904-906.

Ellis, J.J., Hovey, G.R., and Stapinsky, T.E., 1980. A microprocessor system for astronomical telescope and instrument control. *IEEE Journal of Solid-State Circuits*, SC-15, number 1, 144-147.

Frebel, A., Aoki, W., Christlieb, N., Ando, H., Asplund, M., Barklem, P.S., Beers, T.C., Fujimoto, M.Y., Minezaki, T., Norris, J.E., Ryan, S.G., Tsangarides, S., and Yoshii, Y., 2005. Nucleosynthetic signatures of the first stars. *Nature*, 434, 871-873.

Groenewegen, M.A.T., 20007. Luminosities and mass-loss rates of carbon stars in the Magellanic Clouds. *Monthly Notices of the Royal Astronomical Society*, 376, 313-337.

Haywood, M., 2008. Radial mixing and the transition between the thick and thin galactic discs. *Monthly Notices of the Royal Astronomical Society*, 388, 1175-1184.

Hovey, G.R. 1986a. Current trends in optical telescope control systems – part 1. *Australian Journal of Instrumentation and Control* Series 2, 1(3), 4-7.

Hovey, G.R. 1986b. Current trends in optical telescope control systems – Part 2. *Australian Journal of Instrumentation and Control* Series 2, 1(4), 4-7.

Hughes, S.M.G., and Wood, P.R., 1990. Long-period variables in the Large Magellanic Cloud. Cloud. II – Infrared photometry, spectral classification, AGB evolution, and spatial distribution. *Astronomical Journal*, 99, 784-816.

Mathewson, D.S., Ford, V.L., and Visvanathan, N., 1986. The structure of the SMC. *Astrophysical Journal*, 301, 664-670.

Mathewson, D.S., Ford, V.L., and Buchhorn, M.A., 1992a. No back-side infall into the Great Attractor. *Astrophysical Journal*, 389, L5-L8.

Mathewson, D.S., Ford, V.L., and Buchhorn, M.A., 1992b. Southern sky survey of the peculiar velocities of 1355 spiral galaxies. *Astrophysical Journal Supplement*, 81, 413-421.

McGregor, P.J., Nicholson, P.D., and Allen, M.G., 1996. CASPIR observations of the collision of Comet Shoemaker – Levy 9 with Jupiter. *Icarus*, 121, 361-366.

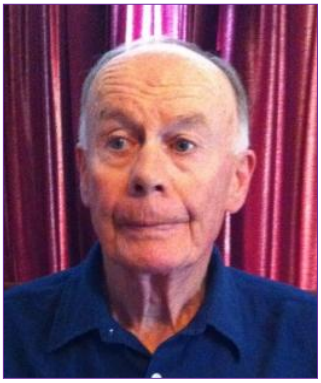
Nielsen, J.G. and Hovey, G.R. 2009. MSOTCS: A new telescope control system for the Australian National University's 2.3m telescope at Siding Spring. *Astronomical Society of the Pacific Conference Series 434, Astronomical Data Analysis Software and Systems*

XIX, 345-348.

Wallace, P.T., 2002. A rigorous algorithm for telescope pointing. *Proceedings of SPIE Advanced Telescope and Instrumentation Control II*, 4848, 125-136.

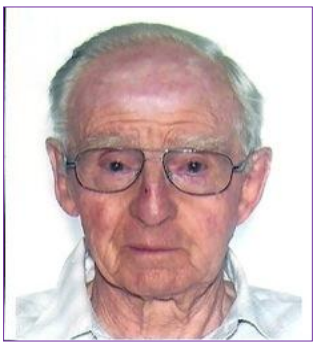
Wood, P.R., and Sebo, K.M., 1996. On the pulsation mode of Mira variables: evidence from the Large Magellanic Cloud. *Monthly Notices of the Royal Astronomical Society*, 282, 958-964.

Wood, P.R., 2000. Variable red giants in the LMC: Pulsating stars and binaries? *Proceedings of the Astronomical Society of Australia*, 17, 18-21.



Don Mathewson joined the Division of Radiophysics, CSIRO, in 1955. He helped Chris Christiansen build his 'Chris Cross' radio telescope at Fleurs Field Station. In 1958 he went to Jodrell Bank, University of Manchester, to observe with the newly-commissioned 250ft steerable dish. Don has held visiting Professorships at Ohio State University, the Sternewacht in Holland and the University of Bologna. Don was Director of MSSSO from 1977 to 1986. During this time, the 2.3m Telescope was built. He recalls the strong camaraderie that existed between staff and students during these challenging times. From 1984, the opening of the telescope, to his retirement in 1994, Don, together with his group of students and Vince Ford, was one of the main users of this telescope. They investigated the splitting of the Small Magellanic Cloud and Large Scale Bulk Flows in the Local Universe. He was farewelled at the international Workshop on Large Scale Motions in the Local Universe on Heron Island. Don is an Emeritus Professor of the Australian National University.

John Hart studied mechanical engineering at the University of New South Wales, graduating in 1967. John started his career in Adelaide, working for the car manufacturer Chrysler, where he was involved with the design of brake and suspension systems for a popular car of the time, the Chrysler Valiant. In 1969, he took up an engineering position with The Australian National University, working at Mt Stromlo Observatory on the opto-mechanical design of telescopes and their instrumentation. He has worked there ever since. His first task was the renovation of the historic 30-inch Reynolds Telescope. He later led the opto-mechanical design of the 2.3m Telescope. More recently, he played a central role in the opto-mechanical design of the large new-generation instruments NIFS and GSAOI for Gemini Observatories, and of the new WiFeS integral field spectrograph for the 2.3m Telescope. He is currently involved in the opto-mechanical design of GMTIFS instrument for the Giant Magellan Telescope being built in Chile. These new instruments include many novel features. John is very proud of the creation at MSO of the Advanced Instrumentation and Technology Centre for which the work for the 2.3m Telescope played a pivotal role



Hermann Wehner studied engineering (Precision Instrumentation and Optics) at Munich, Germany, working during vacation times at Göttingen Observatory, developing astronomical instrumentation. In 1952 he accepted the offer of an engineering position at Mt Stromlo Observatory. The initial project was the refurbishment of the 50-inch Great Melbourne Telescope, as well as the design and implementation of telescope instrumentation, particularly electronic photometers. In 1960 Hermann was put in charge of telescope development at Siding Spring Observatory, involving visits to manufacturers in the USA. From 1964 onwards he became involved in the initial technical planning for a large telescope of the 4m class, resulting in his secondment to the Anglo-Australian Telescope Project from 1967 to 1975. There he was the Australian senior engineer and later Project Manager (1973-1975). Returning to Mt Stromlo Hermann was engaged in various engineering projects, most importantly the design and implementation of the 2.3m Telescope facility. In mid-2011 he was re-employed by The Australian National University as one of the 2.3m Telescope engineering team to assess the serviceability of this facility.

Gary Hovey was educated in Maryborough, Victoria, and graduated with an honours degree in science from Monash University in 1969. In September 1974 Gary received a Ph.D. from the Australian National University for a thesis en-

titled “Software Correction of Telescope Pointing Errors”. From 1975 to late 2002 he was employed as an electronics engineer with Mt Stromlo Observatory where his main professional interests were instrument and telescope control, precise time and the mathematics of celestial co-ordinate systems and telescope pointing. In 1979 Gary became one of the principal designers for the 2.3m Telescope and was responsible for overall system design, control system, algorithms for astrometry and control, electric systems and commissioning tests. Later in the 1990s Gary was involved in other telescope refurbishment programs and contributed to site-testing work in the Flinders Ranges in South Australia. In 1995 he played a major role in the design of a low-powered, cold-climate telescope mount (GMOUNT) which was deployed in Antarctica, and he went to the South Pole on a repair mission in late 2000. Like others on the 2.3m Telescope project, Gary looks back on it as the high point of a diverse career in providing the engineering fabric needed by astronomers. This was not just challenging work, but it also provided opportunities (some unexpected) to meet and learn from others.

Jan van Harmelen grew up in Rotterdam and studied electronic engineering at Delft University in the Netherlands. Jan lectured in electronics at the Western Australian Institute of Technology, now Curtin University, for five years. His wish to do more hands-on engineering made him join the Australian National University at their Siding Spring Observatory near Coonabarabran in the Warrumbungle Mountains in New South Wales. After four years he moved to Mt Stromlo Observatory near Canberra to become Chief Electronics Engineer in 1983. His involvement in building the 2.3m Advanced Technology Telescope and its instrumentation and many more projects to modernise older telescopes prepared him for his appointment in 1999 as Project Manager for designing and building two multi-million dollar, highly specialised instruments for use with the 8m Gemini telescopes in Hawaii and Chile. Jan retired in 2006 after 27 years with the Australian National University and moved to Geelong, but he maintains a continuing involvement with Mt Stromlo and Gemini Observatories.

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ASPECTS OF GOND ASTRONOMY

M.N. Vahia
Tata Institute of Fundamental Research, Homi Bhaba Road,
Colaba, Mumbai 400 005, India.
Email: vahia@tifr.res.in

and

Ganesh Halkare
Indrayani Colony, Amravati, 444 607, India.

Abstact: The Gond community is considered to be one of the most ancient tribes of India with a continuing history of several thousand years. They are also known for their largely isolated history which they have retained through the millennia. Several of their intellectual traditions therefore are a record of parallel aspects of human intellectual growth, and still preserve their original flavour and have not been homogenised by the later traditions of India. In view of this, the Gonds provide a special window to the different currents that constitute contemporary India. In the present study, we summarise their mythology, genetics and script. We then investigate their astronomical traditions and try to understand this community through a survey of 15 Gond villages spread over Maharashtra, Andhra Pradesh and Madhya Pradesh. We show that they have a distinctly different view of the sky from the conventional astronomical ideas encountered elsewhere in India, which is both interesting and informative. We briefly comment on other aspects of their life as culled from our encounters with different members of the Gond community.

Keywords: India, Gonds, indigenous astronomy.

1 INTRODUCTION

The Gonds are the largest of the Indian tribes, with a population of between 4 and 5 million spread over northern Andhra Pradesh, eastern Maharashtra, eastern Madhya Pradesh, Jharkhand and western Orissa (Fürer-Haimendorf and Fürer-Haimendorf, 1979). While their precise history cannot be dated to a period earlier than AD 890 (Deogaonkar, 2007: 37), their roots are certainly older.

2 THE GONDS

2.1 The Origin of the Gonds

Mehta (1984: 105-215) has studied the Gonds from different perspectives, and also their history and mythology in detail. Based on linguistic and other data he considers them to be an ancient community, and one of the oldest tribes in India, with their roots going back to a pre-Dravidian arrival in south India around 2000 BC. He identifies later Brahman influences in their stories. Based on ideas of totem poles and other signs of early religion he makes a very strong case to consider them as one of the earliest inhabitants of central India, with the core in the Kalahadi region of Orissa. Interestingly however, the Gonds consider themselves to be later entrants into God's world through the penance of *Shiva's* son *Karta Subal* (Mehta, 1984: 177). It has also been suggested that they were descendants of *Ravan* (Mehta, 1984: 205). Aatram (1989: 141-143) has suggested a connection between the Gonds and the reference to the Kuyevo tribe in the *Rig Veda*.

The history of the Gonds suggests that they occupied large stretches of land in central India and were its primary rulers from AD 1300 to 1600 (Deogaonkar, 2007: 34-55). However, one of the conspicuous aspects of the Gond lifestyle has been that they did not transform from farmers using the simplest farming techniques to an urban, settled population until very recently. Moreover, they did not evolve into a formal civilisation, living in cities, with elaborate trading practices, and become a large non-agricultural population. This may have been due to a lack of any need to create surpluses, conserve resources and rationalise their population groups (e.g. see Vahia and Yadav, 2011). The reasons for this need to be studied separately.

Sociologically, the Gonds ruled large parts of central India before the rise of the Mughal Empire in Delhi. Several forts and other relics from the Gond Kingdom suggest their dominance over central India during this period. The fact that they built forts and not castles also suggests a lack of desire to move from agricultural roots to urbanisation. Their current lifestyle is also indicative of farming traditions rather than aggressive kingdom-building. The impact of acculturation since their original roots and their subsequent integration into respective state linguistic and religious traditions has resulted in a recent strong desire to revive their original traditions and preserve their group identity.

2.2 The Geographical Spread of the Gonds

The Gonds are mainly divided into four tribes: Raj Gonds, Madia (Maria) Gonds, Dhurve Gonds and Khatulwar (Khutwad) Gonds. Deogaonkar (2007: 15-16), quoting Mehta (1984), lists the major areas of the Gonds to be:

1. The Bastar region in Madhya Pradesh on the Godavari Basin
2. The Kalahandi region of Orissa
3. The Chandrapur region of Maharashtra
4. The Adilabad region of Andhra Pradesh
5. The Satpuda and Narmada regions of Madhya Pradesh
6. The Raipur region in Madhya Pradesh, including Sambalpur in Chattisgarh, and the Sagar region in Madhya Pradesh
7. The Ellichpur region in the Amravati District of Maharashtra

Their population size has increased from about 100,000 in the 1860s (Deogaonkar, 2007: 23) to about 3.2 million in the 1941 census (Agrawal, 2006: 35) and to 4.1 million in 1961 (Deogaonkar, 2007: 13). Their population as per the 1991 census was 9.1 million (after Wikipedia). Compared to this, the population of India as a whole rose from about 250 million (of undivided India) in 1870 to 360 million in 1950 and 490 million in 1965 (Maddison, 1989: 129). The population of India in 1991 was 850 million (after Wikipedia). The relatively steep increase in their population (which is rising faster than the general population of India) suggests that the Gonds originally lived in low-density population groups over large tracts of land and had a low life expectancy. However, there has been a change in this trend: integration into the larger Indian population, subsequent lifestyle changes and a significant improvement in their general well-being have resulted in increased longevity of the Gond population.

2.3 Genetic and Linguistic Data on the Gonds

Genetically the Gonds are a mix of Dravidian and Austro-Asian populations (Balgir, 2006; Gaikwad et al., 2006; Pingle, 1984, Pingle and Fürer-Haimendorf, 1987; Sahoo and Kashyap, 2005), while some genetic markers are unique to this population. In particular, two genetic markers, loci D3S1358 and FGA, show departure from the Hardy-Weinberg equilibrium in the Gond tribe. These are also markedly different from those of seven neighbouring populations (4 tribes and 3 castes—two middle castes and one Deshasth Brahmin caste) (Dubey et al., 2009) indicating that the Gonds have been able to maintain their genetic isolation, with little intermixing with neighbouring tribes.

Linguistic studies of the Gond language show that Gond tribes comprising the Madia-Gond, a hunter-gatherer population, harbour lower diversity than the Marathi tribal groups, which are culturally and genetically distinct. The Proto-Australoid tribal populations were genetically differentiated from castes of similar morphology, suggesting different evolutionary mechanisms operated within these populations. The populations showed genetic and linguistic similarity, barring a few groups with varied migratory histories. The microsatellite variation showed the interplay of socio-cultural factors (linguistic, geographical contiguity) and micro-evolutionary processes. Gond culture and language therefore can be considered isolated, and the level of contamination or modification by interaction with other tribes seems to be low. This is seen from the fact that while they use local names for the numbers 9 and 10, they continue to maintain their original number-name associations for the numbers 1 to 8. This is also reinforced by the fact that they continue to ignore the current Pole Star (Polaris), and do not seem to have a specific name for it (see further discussion on this point below). This evidence of isolation therefore permits us to study their indigenous beliefs without having to allow for cultural contamination.

2.4 The Religion and Customs of the Gonds

In religious terms, there are nine distinct groups of gods whose lineages are followed by all Gonds. Their primary god is *Bada Deo* or *Mahadev* (*Pen*) who is conventionally thought to be *Shiva* of the Hindu traditions. But at an operational level, there are nine groups of gods, and these are referred to by numbers (1 to 7, 12 and 16). However, references to twelve gods (from 1 to 12) named simply as *Undidev Saga*, *Randudev Saga* all the way to *Padvendev Saga* (the 10th God), *Pandunddev Saga* (the 11th God) and *Panderdev Saga* (the 12th God) can also be found, and they all have names. Each Gond is a follower of one of the numbered groups of gods. Members belonging to the lineage of the even-numbered group of gods were originally permitted to marry only those belonging to the odd-numbered group of gods, but this tradition is now changing. In addition, the Gonds have further subdivisions by surname and *gotra* (clan).[1] Conventionally there are believed to be 750 distinct *gotras*, a number that is marked on their flag (see Kangali, 1997: 183-185).

According to the 2007 Gondvana Kiran Calendar the Gonds have 24 major festivals, and these are listed in Table 1. The last column only gives the approximate Gregorian month, since synchronisation of solar and lunar months is only done periodically. Consequently, in a specific year, the New and Full Moon may fall in the previous or the following Gregorian month to the one mentioned here.

Gond customs also vary significantly from classical Hindu customs. Conventionally, Gonds bury their dead with the head of the body facing south in most regions, but to the west in some areas. They consider north to be a direction of ill omen that brings disaster. By contrast, south is considered to be a holy direction. This is the

Table 1: Festival Days of the Gonds.

No	Festival name in Gondi	Festival name	Lunar calendar date	Approximate Gregorian Month
1	Say Mutholi	Worship of Panch Pavli	Magha Full Moon	January – February
2	Sambhu Naraka	Shiv Jagran	2 days prior to Magh New Moon	January – February
3	Shivam Gavara	Worship of Shica (Shigma)	Fagun 5th day from New Moon	February – March
4	Khandera	Worship of Meghnath	Fagun 5th day from New Moon	February – March
5	Ravan Muri	Worship of Ravan	Fagun 5th day from Full Moon	February – March
6	Mand Amas	Worship of Mand	Fagun New Moon	February – March
7	Kuvara Bhimal Puja	Worship of Bhivsan	Chaitra Full Moon	March – April
8	Mata May Puja	Worship of Mata May	Chaitra 5th day from Full Moon	March – April
9	Nalenj Puja	Worship of the Moon	Chaitra New Moon	March – April
10	Naya Khana	Festival of new food	Vaishakh 5th day since New Moon	April – May
11	Budhadev Puja	Worship of Budhadev	Vaishakh Full Moon	April – May
12	Sajori Bidari		Jyeshtha Full Moon	May – June
13	Hariyommat	Worship of fruits and plants	Jyeshtha New Moon	May – June
14	Thakur Dev Puja	Time for sowing seeds	Akti	May – June
15	Khut Puja	Worship of Khut	Ashadh Full moon	June – July
16	Saag Pen Puja	Worship of Saag Pen	Ashadh New Moon	June – July
17	Naag Panchami	Worship of the Snake, particularly the King Cobra	Shravan 5th day from New Moon	July – August
18	Saila Puja	Worship through dance	Shravan Full Moon	July – August
19	Pola	Worship of Pola	Shravan New Moon	July – August
20	Naya hana	New Food Festival	Bhado 5th day from New Moon	August – September
21	Navaratra	9 day festival of worship of Durga	Ashvin 10th day from Full Moon	September – October
22	Jango – Lingo Lati Puja	Worship of *Jango* and *Lingo* (the Sun and Moon)	Kartik Purnima	October – November
23	Nagar Puja	Worship of the village	Kartik Purnima	October – November
24	Kalimay Puja	Worship of Kali Kankali	Paush New Moon	December – January

reverse of Hindu convention. A small stone marks the location of a burial. However, traditions of creating hero stones closer to home, and common community worship, are also known. In one community, we were also given reference to other gods, which included *Kali, Kankali*, *Maikali*, *Jango*, *Lingo*, *Jari-Mari*, *Maanko*, *Tadoba*, *Vagoba*, *Guru* and *Pahandi-Kupar* (Kangali, 1997). Their primary temples worship snakes and *Mahadeo*, but temples dedicated to weapons and other iron tools, and to memorials of *Rani Durgavati,* also can be found. The primary symbol of worship is a complex fertility symbol (Figure 1). It is interpreted as having a feminine representation at the bottom followed by the male *lingam*, and with Earth and the Sun on top, all interconnected in some representation and shown separately on flags etc.

2.5 The Gond Script

There is significant confusion about the existence of a Gond script and both Deogaonkar (2007: 123) and Mehta (1984: 173) suggest that there is no Gond script at all. However, we came across examples of Gond writing in several places. We found examples of a calendar written in the Gond language (i.e. in Gondi), with the first sheet (Figure 2) discussing the Gond script.[2] In line with the unique features of scripts of the Subcontinent, it also merges the vowels and consonants to create complex signs which require careful reading but can retain subtle aspects of pronunciation.

The page reproduced here in Figure 2, and the calendar, have the writing of names and numbers relating to the calendar in the original script, its transliteration and translation. As an example, we list the days of the week transliterated from Gondi in Table 2, and in Table 3 we list the names of the months. This is claimed to be the original text, but it is not clear when and how the present structure was finalised.

Figure 1: The religious symbol of the Gonds.

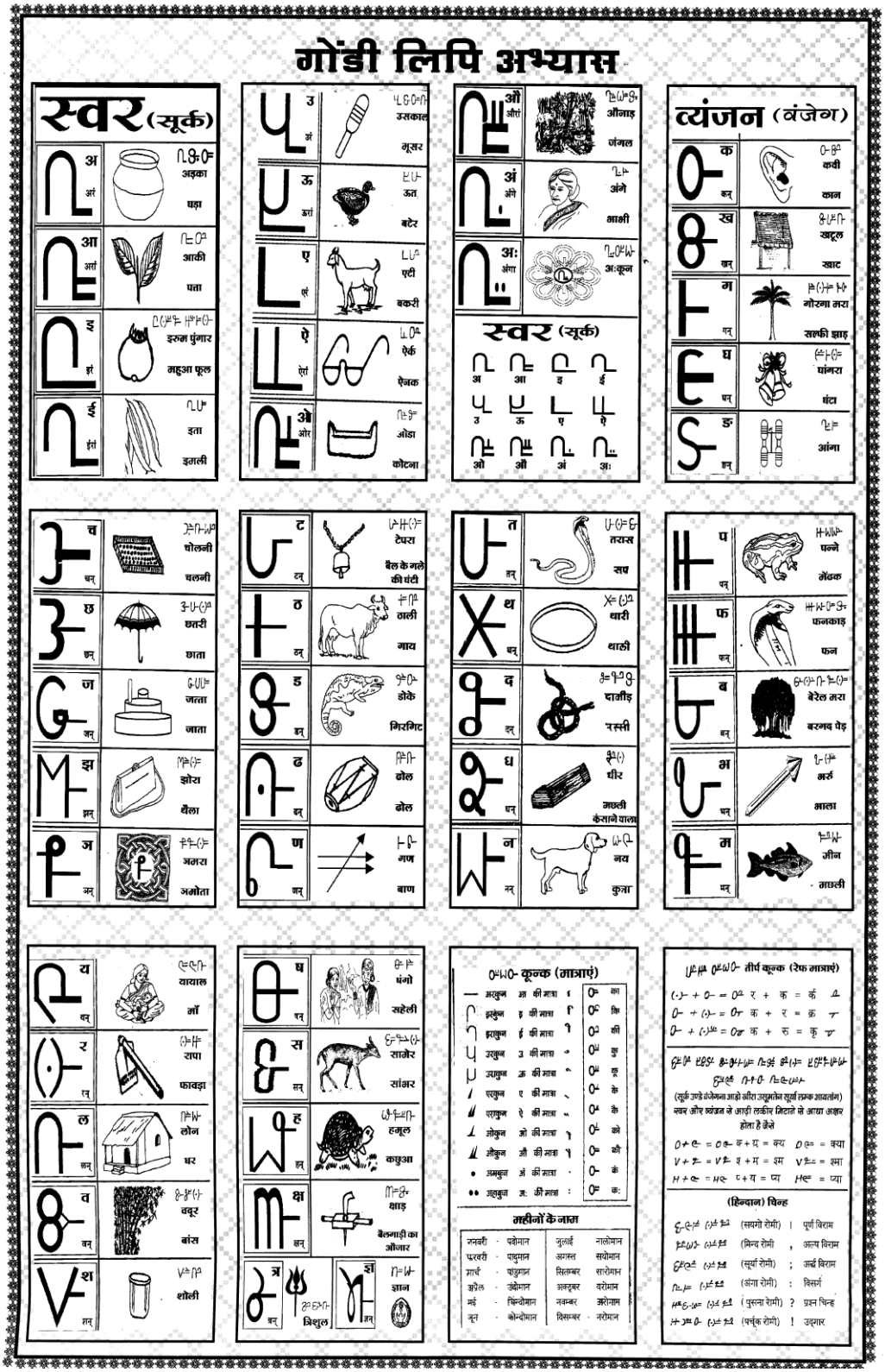

Figure 2: A description of the Gondi script.

Table 2: Days of the week in Gondi and in other languages.

Day of the week	Name in English	Name in Hindi	Name in Telugu	Name in Gondi
1	Sunday	Ravi vaar	Aadhi Vaaramu	Purva net
2	Monday	Som vaar	Soma Vaaramu	Nalla net
3	Tuesday	Mangal vaar	Mangala Vaaramu	Surka net
4	Wednesday	Budh vaar	Budha Vaaramu	Surva net
5	Thursday	Guru vaar	Guru Vaaramu	Mudha net
6	Friday	Shukra vaar	Sukra Vaaramu	Nilu net
7	Saturday	Shani vaar	Seni Vaaramu	Aaru net

Stylistically, the script differs significantly from other Indian scripts including Indus, Devnagari and the Dravidian group of languages, although it includes signs for consonants (such as a deep N)[3] which are no longer used in Hindi but are common in Marathi. We obtained three different calendars from the three different regions of Andhra Pradesh, Maharashtra and Madhya Pradesh. The calendar from Andhra Pradesh was wholly in Telugu while the one from Maharashtra was in Gondi and Marthi, and the one from Madhya Pradesh was in Hindi and Gondi. The numerals used in these calendars are given in Table 4. In the listing of months and days, the calendars of Madhya Pradesh and Maharashtra agree in detail (except for some obvious printing errors), but they differ significantly in the signs for the numbers 5 and 6. The Gonds have separate names for the numbers 1 to 10; after that they use the system of tens first followed by the numerals (i.e. 10 and 3 for 13, not 3 and 10 which is used in Hindi, for example).

2.6 The Myths of the Gonds

Deogaonkar (2007: 123-130) has briefly discussed the myths and folk literature of the Gonds, while Mehta (1984: 167-306) has discussed their myths and subtle regional differences in detail. Interestingly, all the recorded myths are related to terrestrial aspects, and stories of Great Floods and the virgin birth of the goddess are very common. Mehta (1984:181) considers the Gond hero *Lingo* to be the equivalent of Moses of the Jews who, with the mercy of the *Bada Deo*, his wife and *Gangudevi* the Great Goddess, freed them from the curse of captivity and led them to freedom. According to Mehta (1984: 37), the *Bada Deo* (also called *Pen*) is synonymous with *Mahadeo* and *Shiva*. Mehta (1984: 38) also refers to the *Bada Deo's* wife as *Parvati*, but this association is not obvious. The image of the *Bada Deo* differs from the conventional image of *Shiva* in many significant ways. For one, he is a creator who, after having initially banished the Gonds for bad behaviour turned around to assist them to the extent of taking on rivalry with *Indra* to create the Gonds (Mehta, 1984: 180). The *Bada Deo* also assists *Lingo* in a variety of ways.

It is interesting that in their analyses of Gond myths and beliefs neither Deogaonkar (2007) nor Mehta (1984) makes any reference to astronomical or cosmogonical ideas. The closest they come are in their discussions of the Great Floods, or the inability of the "… Sun, Moon and Stars to assist Lingo in locating the banished Gonds." (Mehta, 1984: 184). They take the terrestrial world to have been in existence forever, their land being the land of seven mountains and twelve hills (Mehta, 1984: 178). They also suggest that the Earth is held on the head

Table 3: Months of the year in English and in Gondi.

Day of the week	Name in English	Name in Gondi
1	January	Pado man
2	February	Padu man
3	March	Pandu man
4	April	Undo man
5	May	Chindo man
6	June	Kondo man
7	July	Naalo man
8	August	Sayo man
9	September	Saro man
10	October	Yero man
11	November	Aro man
12	December	Naro man

of *Patar Shek* (Mehta, 1984: 187). The Gond calendar from Andhra Pradesh (see Note 2) states that according to the Gonds

> The gift of nature, which gives astronomical, magnetic and gravitational pull makes the Earth move from right to left, that is, in an anticlockwise direction. (our English translation).

Beyond this, there are no records of Gond astronomical ideas.

However, since they held sway over large tracts of land and administered them, they must have had calendrical and other time-keeping systems. Such systems are most often rooted in astronomy, and hence observational astronomy must have been an important aspect of the science of the Gond people. Since they were never integrated into the dominant cultural and population groups of India until recently, their knowledge presumably contains the seeds of an

Table 4: Numerals in the Gond script, and in Maharashtra and Madhya Pradesh.

Number	Name	Style in Maharashtra	Style in Madhya Pradesh
1	Undi		
2	Rand		
3	Munda		
4	Nalung		
5	Sayyung		
6	Sarung		
7	Yerung		
8	Arung		
9	Narung		
10	Pad		

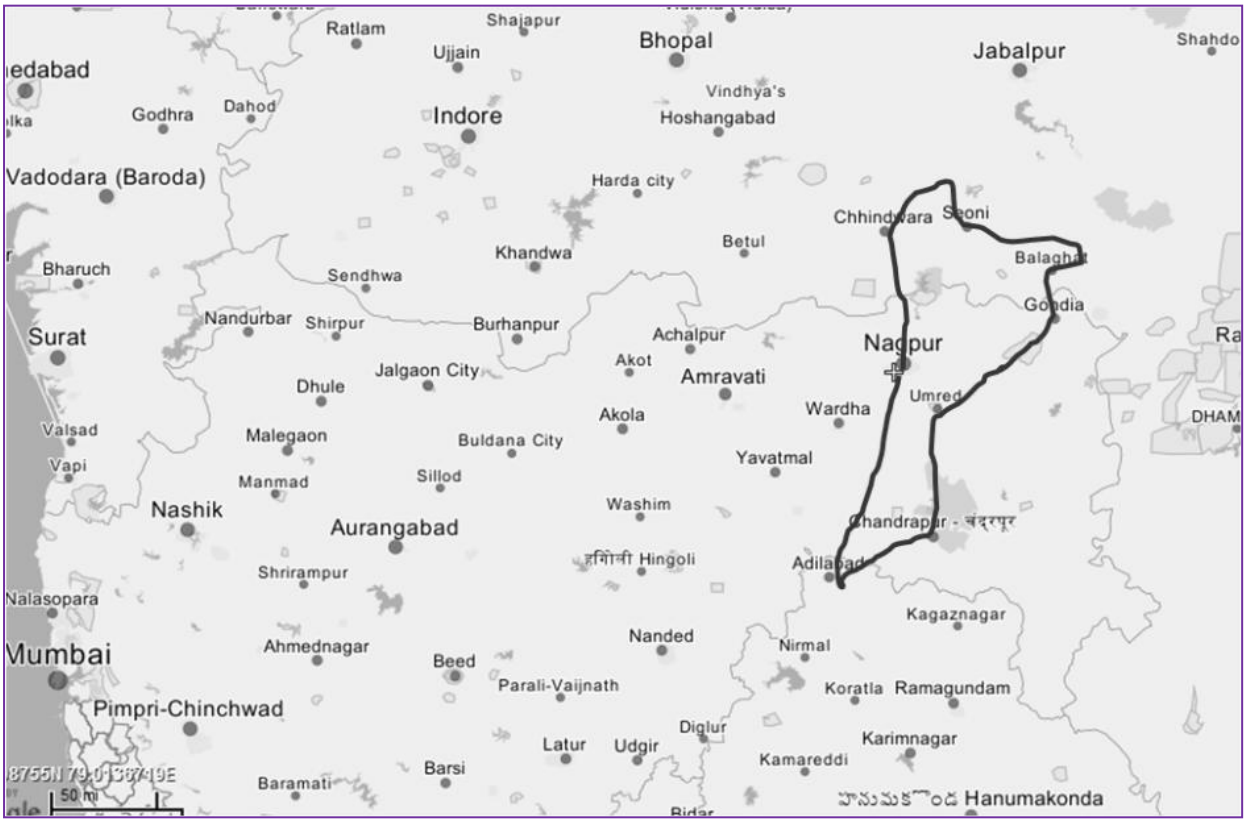

Figure 3: Map of our travels and villages visited by us.

independently-developed perspective of the Universe. In order to understand this, we studied the astronomical knowledge of the Gond people. In this study we focussed solely on understanding their astronomical traditions and ideas. As we have observed in our study, the limited description of Gond mythology is only a partial truth, and the skies form an integral part of their life—as would be expected.

3 THE PRESENT STUDY

From 25 to 31 March 2011 we visited 15 Gond villages spread over an area of 2000 km^2 around the Nagpur region in the states of Maharashtra, Andhra Pradesh and Madhya Pradesh, covering six of the seven regions mentioned in Section 2.2. In Figure 3 we show the area surveyed and the path that we followed. All 15 villages lay within the latitude range 19.5° and 21.8° North.

Details of the villages visited, persons contacted and the astronomical knowledge they supplied are given below. In order to ensure that all of us were talking about the same region of the sky, we carried a laptop and a LCD projector and whenever it was necessary we projected an image of the sky on the walls so that constellation identifications could be confirmed. While this approach was successful on most occasions, there were villages where the audience could not fully identify with the projected sky. The 15 villages visited by us are now discussed individually.

1: Karambi

State: Maharashtra

Location: About 22 km from the Shankarpur village of Chimur Tehsil in Chandrapur district, 100 km east of Nagpur, near Nagbhid.

Date of visit: 25 January 2011

Person contacted: Kirtivat Tivalsingh Atram.

Astronomical knowledge: They know the Belt of Orion as *Tipan* and the Pole Star as *Lagni Sukum* or 'the bright one'. *Sukum* means 'star' and *Lagni* means 'the one that shines'. The Sun and the Moon are called *Lingo* and *Jango* respectively.

2: Nimni

State: Maharashtra

Location: Post Jamkola, Taluka Zari, District Yeotmal. Via the Pandharkawada-Ghonsa-Wani road, 25 km from Pandharkawada. The village has 60 to 65 Gond houses. The other houses belong to Kolam tribesmen.

Date of visit: 25 March 2011

Persons contacted and their ages: Mahadeo Anandrao Kudmethe (56) and Sanjay Masram (28).

Astronomical knowledge: A star is called *Sukum*. *Saptarshi* (*Katul* and *Kalher*), *Samdur* (sea) a group of four stars in the shape of a quadrilateral (probably Auriga), comes overhead at 4 am, rains arrive and farming begins. They know the Belt of Orion as *Tipan*. 4 am, *pahili chandani*, heralds the beginning of the working day. Evening is known as *dohan chan-*

dani and is the time to milk the cows. The Sun is *Lingo* and the Moon is *Jango*. Comets are called *Jhadani* (in Marathi), which means a broom. Comets are the weapon of the Great God *Bhimal Pen* called *Bhimal-Saat*, and he uses them to cleanse the sins of the world so they are thought of as good omens. The prevailing burial practice is in the North-South direction, but a special undercut is made near the head so that top soil is not dug up near it and the head is slipped inside. Our informants know that the length of the day changes during the year. They also know the four cardinal directions as *Silalin* (East), *Farayin* (West), *Kalvada* (North) and *Talvada* (South). They are familiar with the southward and northward movement of the Sun in the course of the year and its relation to the seasons.

3: Matharjun

State: Maharashtra

Location: Post Matharjun, Taluka Zari Jamni, District Yeotmal. On the Pandharkawda-Shibla-Matharjun road, and the village is 28 km from Pandharkawda. There are about 170 Gond houses.

Date of visit: 25 March 2011

Persons contacted: Shyamrao Aatram (65), Gopalrao Maraskolhe (65), Punaji Madavi (70), Deorao Dongaru Madavi (70) and Karu Keshav Madavi (80).

Astronomical knowledge: *Shukra* (a canonical star that appears at sunset in the east) is called *Jevan-sukum*. They know *Tipan* (the Belt of Orion), and next to it are *Medi* (a star pattern where there is a bright star in the centre and other stars in a circle appearing like the set up for crush grains etc. using a bullock, locally known as *Khala*; but the constellation association is unclear) and *Tiva* (meaning a stool on which a farmer stands to thresh the grains by dropping them on the ground in the wind), which is identified with a constellation pattern just south of Sirius. They have rudimentary knowledge of how to predict the seasons by the presence of different star formations. They know a constellation called *Katul* (meaning a cot) as part of the constellation that we recognise as *Saptarshi* (or the Big Dipper). The first four stars that make the cup of *Saptarshi* are *Katul*, which is imagined as a cot with four legs made of the following precious metals: gold, silver, inferior silver and copper. The last three stars of *Saptarshi* are called *Kalher* (meaning thieves) and represent three thieves who want to steal the cot when the old lady falls asleep. Hence the old lady never sleeps (possibly indicating that the constellation never sets—as was the case in this region of India until 1000 BC, when *Saptarshi* was partly circumpolar). They know another constellation that they called *Samdur* (a quadrilateral, probably Auriga) which indicates the arrival of the monsoon season. A constellation they call *Kotela* (meaning the tool shaped like a cricket bat that is used to beat the grain out of the husk), most probably is the Pleiades (but it could be Taurus). They also identify *Koropadera* (a tool used to make buttermilk) but its modern equivalent was not identified by us. The constellation of *Koropadera* is a good omen. They also know *Michu* (the Scorpion) which is the same as the modern constellation of Scorpius. They know the names of the four cardinal directions: East is *Shilain*, West is *Farain*, North is *Kalwada* and South is *Talwada*. While visiting here we spotted a rainbow and they called it *Kamarpatta*. The Milky Way is *Sagur*, or a road. They were aware of Gondi numbers from 1 to 7 (8 onwards is Marathi). They buried the dead in a North-South direction, with the head to the north. A comet is called *Bhimalsaat*, and a shooting star is *Sukum Pelkta* (star excreta).

4: Kesalapur

State: Andhra Pradesh

Location: Post Kesalapur, Mandal Inderveli, Taluka Utanoor, District Adilabad. Via Adilabad, Gudi Hatnoor and Mutnoor. About 35 km from Adilabad.

Date of visit: 26 March 2011

Persons contacted: Urvetta Chinnu (100), Mesram Laxman (45), Mesram Venkatrao (45, the *Patel* of the village) and Todsam Ghanshyam (60).

Astronomical knowledge: This village had the most detailed memory of astronomy. They gave us the names of the 12 months of the year and the *adhika maas* (intercalary month). They know *Saptarshi* as *Katul* (old lady's cot) and *Kalir* (thieves), and the Milky Way as the 'Path of the Animals' (*Dhor Sari Marg*). The location of *Saptarshi* at sunset is used for calendrical purposes. They know that there are three star combinations for three seasons. Season 1 has the constellation of *Murda* in which they identify not only the body, but also the complete funeral procession of stars in this order: *Duf* (the drum bearer), *Shika* (the procession leader), *Murda* (the dead body) and a group of 4 *Ladavya* (weeping women). *Murda* rises around 11 pm early in this season. This star combination is to the north (east?) of Scorpius (whose bite produces the *Murda*) and extends across the sky. They know a constellation *Purad* or *Hola*, a bird and its two eggs, probably stars below Sirius. They know *Pahat sukum* (meaning 'morning star'), which they identified as Alpha Aquila when they saw the projected star chart. Season 2 has the months of *Budbhavai*, *Akhadi* and *Divali*. During this time you see *Samdur* (Sagittarius?), *Tipan* (Orion) and *Topali* (Lepus). Season 3 is

from *Kartik* to *Maho* and the prevailing constellations are *Medi* (rising between 9 and 10 pm), the central star of *Khala* (a grain-crushing device), *Tiva* (a stool) and *Kotela* (a bat). In June at sunrise they can see *Tipan* (the Belt of Orion), *Topli* (Gamma and Beta Orionis), *Samudar* (Alpha, Beta, Gamma and Kappa Cassiopeia), *Medi* (Taurus) and *Tiva* (Canis Major) —confirmed by our projection of the night sky. They know that the monsoon arrives when *Tipan* appears at sunset. They know the Orion sequence with *Kotela* (a bat for thrashing grain) identified with modern-day *Lepus,* and can identify a basket (*tokali*). They know of comets as *Kayshar* (a broom—the Pleiades) and shooting stars as star excreta (*Sukir Pelkta*). A month is called *Vata*, and extends from New Moon to New Moon. The northern direction is considered inauspicious.

5: Kharmat

State: Maharashtra

Location: Post Kharmat, taluka Pombhurana, District Chandrapur, via Rajura, Kothari, Gondpimpari, Kharmat, 57 km from Rajura (GPS location 19° 48′ 6.5″ N and 79° 39′ 1.3″E).

Date of visit: 26 March 2011

Persons contacted: Sitaram Kisan Madavi (75), Sambhashiv Shivarama Madavi (62) and eleven other members of the Gond tribe.

Astronomical knowledge: They know *Katul*, *Jevan Sukum* (the first star seen in the east at night, indicating dinner time). Similarly there is *Pahat Sukum* (the last star to be seen in the west at sunrise), *Naagarda* (Orion), *Sagur* (the Milky Way) seen at midnight, *Irukmara* (a star seen at 3 am) which indicates the season for collecting *Mahua* (*Madhuca longifolia)*. They know a constellation *Kutpari* or *Mogari* which they identify with the modern Pleiades, and refer to a comet as *Kayshar* (a broom) and a shooting star as *Chandani Pelkta*. They know the 12 months of a year; the intercalary month after completing three years; and can count to 7 in Gondi and after that in Marathi. They call the Sun *Purbaal* and the Moon *Nalend*, and East is *Sukra*l. Their burials are in a North-South direction. They still remember a major flood that occurred about 3,500 years ago. At the end of the flood crows brought soil to create the Earth, and hence the crow is worshipped. They 'predict' the arrival of the monsoon by seeing clouds in the west. New Year *Punal (Nava) Saal* starts at *Gudi Padwa.*

6: Wamanpalli

State: Maharashtra

Location: Post Lathi, Taluqa Gondpimpari, District Chandrapur. Via Gondpimpri, Dhaba, Sonapur. 35 km from Gondpimpri on the banks of the Vardha (across the river from Andhra).

Date of visit: 27 March 2011

Persons contacted: Sainath Kodape (28, the Village *Sarpanch*), Kawdu Raju Gadaam (70), Urkudabai Sukru Veladi (65), Bhiva Kondu Talandi (66), Ganpat Dharma Sedmake (78), Urkuda Paika Sedmake (60) and Gopala Tanu Madavi.

Astronomical knowledge: They know that stars are called *Sukum*. They know the constellation termed *Tipan* by others by a different name, and call it *Naagarada* (which means 'plough') and identify it with the modern-day Belt of Orion. They know *Saptarshi* with an imagery and mythology that is similar to other regions namely, the cot is called *Sedona Katul*, and the three thieves are called *Muvir Kaler*. They correctly identify the legs of the cot. In the sky they can also see *Irukna Mara* (the tree of *Mahua*, *Madhuca longifolia*), *Pahat Sukir* (the Morning Star), *Jevan Sukir* (the Evening Star), *Dhruva* (clearly an after-thought and addition since the Gonds have no word or reference to it, and many other villages denied its existence), *Kutpari* (the Pleiades), *Kayshar* (the broom = comet) and the Milky Way as *Pandhan* or *Sagur* or *Murana Sagur* (the path of animals). Their list of months is the same as the generic list. The Moon is called *Nalen*. From New Moon to Full Moon is called *Avas*, and from Full Moon to New Moon is *Punvi*. The lunar calendar is followed, and they recognise the intercalary month. A shooting star is *Sukir Pelkta* (star excreta). Human burial is North-South. The burial itself should be far from home, but a memorial stone can be set close to home, with a terracota or wooden horse that is worshipped for generations when convenient. None of these memorial stones we saw were more than a hundred years old, indicating that ancestor worship is forgotten after a generation or so.

7: Khadaki

State: Maharashtra

Location: Post Mendha, Taluka Nagbhid, District Chandrapur. Via Nagbhid, on the Nagbhid-Mendha-Khadaki path. On the Nagpur-Brahmapuri Road about 12 km from Brahmapuri.

Date of visit: 27 March 2011

Persons contacted: Sheshrao Mansaran Naitam (38, *Up-sarpanch*), Narayan Bisan Madavi (70) and Barikrao Sitaram Naitam (65).

Astronomical knowledge: They know *Shukra* as a generic evening star, *Tipan* (Orion), *Mongari* (the bat = Pleiades), *Jevan Chandani* (the first star of evening), *Saptarshi*, Scorpius (*Vinchu*), a comet as *Kayshar* (which is vaguely regarded as a portender of bad luck), the Milky Way (*aakash ganga*) and a meteor shower (*ulka*). They believe that the world moves counter-clockwise as do the planets, whirlwinds and whirlpools, and the oil-extracting bull-run grinding device common in India. Their burials are in the North-South direction to the East of the

village (but this latter choice seems to have been made more out of local geographical necessity rather than some custom). Burials include personal utensils and other belongings. Now-a-days they include dolls made from edible flour. The grave of an old man is marked by a vertical stone, while other graves are left unmarked. They worship their ancestors in the form of horses. They recognise the intercalary month.

8: Yelodi

State: Maharashtra

Location: Post Dhabe Pawani, Taluka Arjuni Morgaon District Gondia. Via Brahmapuri-Wadse, Arjuni Morgaon-Navegaon Bhandh and Dhabepawani, on the Dabepawani-Chikalgad Road, 5 km from Dhabe Pawani and 28 km from Arjuni.

Date of visit: 28 March 2011

Persons contacted: Jairam Manku Salame (75), Kaaru Devsu Duge (65), Charandas Nagaru Kumare (60), Pandhani Istari Walke (70), Jagan Mansaram Walke (70), Baliram Dhondu Ghumake (70), Sadashiv Laxman Kokote (65), Govinda Bakshi Uike (80), Tukaram Madku Karpate (67) and Goma Ghegu Alone (60).

Astronomical knowledge: They have a vague idea of *Jevan Chadani* (the Evening Star), *Pahat Tara* (the Morning Star), *Saptarshi* (*Katul* and *Kalher*), Orion (*Nangal*, visible in the east every day), *Thengari* (the bat = the Pleiades) and *Topli* (Lepus). They know *Sagar* (the Milky Way), and the Moon as *Nanleg* and the Sun as *Bera*. Their burials are oriented East-West, with the head to the East.

9: Zashinagar

State: Maharashtra

Location: Post Palasgaon chutia, Taluka Arjuni Morgaon, District Gondia via Navegaon bandha and the Dhabepaulani-Chichgad Road, 16 km from Navegaon.

Date of visit: 28 March 2011

Persons contacted: Antaram Modu Bhogare (78) and Sitaram Chamru Hodi.

Astronomical knowledge: They know the Moon as *Nalen* and the Sun and *Vera*. They know *Saptashi* as *Sedona Katul* and *Kaler*. They know that the first leg of *Katul* is made of gold. They know the early morning star as *Viya Huko* ('Huko' means 'star'). They know the first star of the night as *Jevan Sakun*. They know *Nangal*, and they refer to the Milky Way as *Hari*, or the 'road'. They know about *Bohari* (*Kayasur*) or *Jhadani* (but they could not point one out). A shooting star is called *Huko Pelkta*. They know the names of each month. They have heard about the Gondi *lipi* (script) but have no idea what it is like. They know of the equinox, and they bury the dead East-West with head to the East.

10: Mohagaon

State: Maharashtra

Location: Post Supalipa, Taluka Aamgaon, District Gondia via Gondia, Dohegaon, Adasi, Gudma, Sitepar and Mohogaon.

Date of visit: 28 March 2011

Persons contacted: Ramlalji Uikey (69), Beniram Yadu Uikey (55) and Nimalabai Uiley (50).

Astronomical knowledge: They know *Nangar* (Orion's Belt) and can point it out. They know *Pahat Sukir* (a Morning Star that rises every morning at 4 am). They know *Saptarshi*. They do not know the Pole Star, Polaris. They know *Kotela* (*Taurus* or the Pleaides) and *Topli* (Lepus). They call the Milky Way *Sagarpath*. The Sun is *Din* and the Moon is *Chandal*. They know names of the months. A comet is called *Kaysaar*. They know that a glow called *Kondor* appears around the Moon, and if it is close to the Moon the rain is far away but if it is far from the Moon then the rain is nearby. They bury the dead in a North-South direction, and they sometimes include burial goods such as clay pots for use in the afterlife.

11: Kaweli

State: Madhya Pradesh

Location: Post Chalisbodi, Block Parswada, Tehsil Baihar, District Balaghat. Via Balaghat-Banjari-Kanatola-Kaweli. Banjari is 21 km from Balaghat on the Baihar Road. From Banjeri to Kaweri is 9 km.

Date of visit: 29 March 2011

Persons contacted: Sohansingh Bilaising Uiykey (41), Munnalal Zarusing Bhalavi (70) and Himmatsing Mohan Uikey (40).

Astronomical knowledge: They know the Morning Star rising at 4 am and the Evening Star. They say that *Nangar* (the plough) rises every evening. They know *Katul* and *Kalhad* (*Saptarshi*). They know the Pleaides as *Kayshar* (*Bahari*), the broom. They know *Jewan Tara* (a late evening star). They think the Pole Star rises at 4 am. They know *Nangar* but think it rises every evening or morning. They know *Saptarshi*. They refer to a shooting star (meteor) as star excreta, and have heard of comets but do not know much about them. They can identify the months of the year. They know that one month runs from New Moon to New Moon and every third year is a '*Dhonda*' year when an intercalary month is added; no marriage can occur during this month. They know of the glow around the Moon and can identify it. The Sun is *Din* and the Moon is *Chandal*. They have not heard of eclipses. They count from one to seven in Gondi, and they bury their dead with the body aligned North-South.

12: Chalisbodi

State: Madhya Pradesh

Location: Post Chalisbodi, Block Parswada,

Thesil Baihar, District Balaghat. Via Balaghat-Banjari-Kanatola-Kaweli. Banjari is 25 km from Balaghat on the Baihar Road, and the distance to Kaweli is 4 km. It is 35 km from Balaghat and 13 km from Banjari.

Date of visit: 29 March 2011

Persons contacted: Gorelal Madavi (60), Mohanlal Tekam (55), Radheshyam Warkale (52), Mohparsingh Markam (35) and Ramsing Tekam (34).

Astronomical knowledge: They know of the Pole Star that is seen every day. They know *Sedona* (old woman's) *katul* (cot) and *Kalhad* (*Mund kalhed*, i.e. thieves). They know *Nangar*, that is like a plough, and *Kotela*. In addition, they know of *Purad* and *Mes* (a bird and its egg) as stars east of Sirius. The story goes that the man in Orion throws stones in the form of the Pleiades so that they will fall on the bird and kill it. What the story does not record is if he was successful. They know the Evening and Morning Stars. They can count to 7 in Gondi, and they claim that *Aimdi* is 10 and *Padi* or *Padivakati* is 100. They count 12 months of a year, and the leap month. They bury their dead facing North-South. They know of comets as *Jhadu* and shooting stars as stellar excreta. They refer to a rainbow as *Gulel*, the bow of a bow and arrow. They know of the glow around the Moon. They know *Pada din* (increasing day), and *Chirdur din* (decreasing day). To them the Milky Way is *Sadak*, and they have heard of the Gondi script.

13: Kopariya

State: Madhya Pradesh

Location: Post Ramnagar, Block Mohagaon, Thesil Mandala, Julla Mandala.

Date of visit: 30 March 2011

Person contacted: Shivsingh Charusing Parateti (70).

Astronomical knowledge: They know *Nangir* (Orion), can point it out and know that it rises around 8 pm in April and brings rain. They know *Dhruva Tara*. They know *Mangal Tara*, which is the morning star. They know *Poyi* (a noble man), his wife (*poyatar*) and his *kotwal* as the three stars that form the tail of *Saptarshi*. The *Kutil* is the path of *salveshan* and the three approach it for their personal salvation after doing good deeds on Earth. They know the Morning and Evening Star. They have heard of Scorpius, and know of the Pleiades as *Kotela*. They refer to the Sun and the Moon as *Dinad* and *Chandal* respectively. They know comets as *Baahari* (the broom) and shooting stars as *Tara Uruganta*. They know of the glow around the Moon and its interpretation. A month goes from New Moon to New Moon, but in contrast they claim that each month has exactly 30 days; they do not know that an intercalary month is added after three years. They bury their dead oriented North-South.

14: Sailakota

State: Madhya Pradesh

Location: Post Kanhiwada, Block Seoni and district Seoni. Salaikota is 26 km from Sivani.

Date of visit: 31 March 2011

Person contacted: Sabalsingh Kaureti (72).

Astronomical knowledge: They know about *Saptarshi* but are confused about the story. They know *Bahri* and pointed it out in the sky as the Pleiades. They know of the Sun as *Din* and the Moon as *Chandal*. They know the Milky Way, and believe that shooting stars occur when souls fall back to Earth. They refer to a comet as a broom (*bahari*). They know of the glow around the Moon and can interpret it correctly in terms of its relation to rain. They do not know about eclipses. They can count a little in Gondi and can recite the months. They know that the Gondi script probably exists. They bury their dead in a North-South direction.

15: Lodha

State: Maharashtra

Location: Post Karwahi, Tehsil Ramtek, District Nagpur. Via Manegaon tek, Karwahi, Lodha, Pindkepar. 11 km from Manegaontek.

Date of visit: 31 March

Persons contacted: Munsi Saddi Bhalavi (75) and Parasram Munsi Bhalavi (45).

Astronomical knowledge: They know the Morning Star and the Evening Star, *Saptarshi*, *Kaysar* (the Pleiades), Scorpius (?), *Purad* and the glow around the Moon. They refer to shooting stars as stellar excreta, the Moon as *Chandal*, the Sun as *Suryal* or *Din* and the Milky Way as *Sari*. They know the months of the year, about leap years and about the numbering system. They bury their dead North-South (where South is termed *Rakshas Disha*).

4 ANALYSIS OF THE OBSERVATIONS

In Table 5 we list major aspects of astronomy known to the Gonds. In most cases, the information was corroborated from more than one village, although in some cases the precise detail of the name varied as a result of local linguistic differences. In April 2012 a select group of 23 villagers from the three districts of Adilabad, Yeotmal and Chandrapur were invited to the Raman Science Centre in Nagpur, and asked to explain the night sky in the planetarium.[4] The associations discussed below therefore represent accurate identifications.

In Table 6 we list the villages in which we were told the same or largely similar stories or identification names of various objects.

Table 5: A list of the major astronomical ideas of the Gonds.

	Standard Terms	Local Names	Description
		Sun, Moon, etc.	
1	Sun	*Lingo*, *Purbaal*, *Bera*, *Vera*, *Din*, *Dinad*, *Suryal*	There is no knowledge of solar eclipses.
2	Moon	*Jango*, *Chandal, Nalend* or *Nalen*. New Moon to Full Moon is *Avas*, and Full Moon to New Moon is *Punvi*.	There is no knowledge of lunar eclipses.
3	Glow around the Moon	*Kondor*	Often a glow is seen around the Moon. If the glow is close to the Moon, the rain is far away while if it is far from the Moon the rain is expected.
4	Duration of the month	The month runs from New Moon to New Moon.	There is no long-term calendar. Every 3rd year has a 13th month for solar-lunar synchronisation. New Year begins at *Gudi Padwa* though in earlier times the dates were probably different.
5	Months of the year, and the leap month	*Vata* (month), *Punal (Nava) Saal* (New Year) is on *Gudi Padwa* though older practice was different. A leap month is called *Dhonda*. Increasing length of the day is called *Pada din* and decreasing length of the day is called *Chirdur din*.	January = *Pus*, February = *Maho*, March = *Ghuradi* (*Umadi Amavasya* marks the New Year), April = *Chaita*, May = *Bhaavai*, June = *Bud Bhaaavi*, July = *Aakhadi*, August = *Pora*, September = *Akarpur*, October = *Divali*, November = *Kaartika*, December = *Sati*. At the end of every three years the New Year is delayed by 1 month by adding a *Ghoda*. A month runs from New Moon to New Moon and no calculations are done. Sometimes a *tithi*, (Lunar Mansion) particularly *Amavasya*, can extend to 2 days. Long-term memory does not go beyond 3 years.
6	Directions	*Silalin* (East), *Farayin* (West), *Kalvada* (North) and *Talvada* (South)..	Directions are important to the Gonds largely for burial rituals. We did not come across any evidence where they use the stars for navigation. In one village they knew of the northward and southward movement of Sun and its relation to the seasons.
7	Burial practices		Burials are most often aligned North-South, with the head to the South, since "… bad people live in and come from the North." Some people practised equinoctial East-West burial, with the head to the East. In the village of Nimani we were told that while the body is laid straight, the head is put under the solid earth by scooping out more earth on that side. There were few reports of burial of goods with the body. A grave was typically about 3 feet deep, i.e waist deep.
8	A rainbow	*Kamarpatta*, *Gulel*	It is also called the bow of a bow and arrow.
		Stars	
9	A star	*Sukum*, *Sukir*, *Huko*, *Tara*, the adjective *Lagni* ('bright') is also used. *Sukra* is also used.	These are generic names for all stars. These terms are also used to describe diffuse moonlight or starlight. *Chandani* is also a generic name for starlight or moonlight
10	The Morning and Evening Stars (The planet Venus).	*Jevan Tara* ('dinner star', is also called *Shukra Tara* or *Pahili* [first] *chandani*), and *pahat sukom* (*sukur*), (star of early morning), *Shukra*, *Mangal Tara*. The Evening Star is also called *Dohan Chandani* and indicates the time to milk the cow. One group (from the Matar-jun region) was categorical that this star rose with the Sun either in the morning or the evening.	*Jevan* (meal) is a generic star that rises every evening in the east, indicating dinner time. *Javen*/*Pahili* etc. *tara* is a generic early morning star that is overhead at 4 am(!) indicating the time to start working. The recognition that *Jevan Sukum*, the Evening Star, and *Pahat Sukum*, the Morning Star, is the same *Sukum* indicates a knowledge of planets, or transient stars. However, with the exception of Venus, the Gonds are not aware of any other transient stars.
11	Comets	*Jhadani*, *Bhimal Saat*, *Kay-shar*, *Jhadu*, *Bahari*	A comet is believed to be the sword-like weapon of the gods, and is considered a good omen in that the gods are protecting humans by cleaning up the mess that was created by bad events, either by killing evil (using the sword) or sweeping away the evil (with a broom).
12	Shooting stars	*Ulka*, *Sukum Pelkta*, *Sukir Pelkta*, *Huko Pelkat*, *Tara Urungta*.	In general shooting stars (meteors) are called excreta of stars, or are thought of as souls that are falling from their holy places in the sky.
13	Milky Way	*Dhor Sari*, *Rasta*, *Sagur*, *Murana Sagur*, *Marg*, *Pandhan*, *Hari* ('the road'), *Sadak*	The Milky Way is known as the great path of animal migration.
14	The Pole Star	*Dhruva Tara*, *Mout Tara*	Polaris was reported in three villages, using a Sanskrit name, which suggests that it is a later addition. *Mout Tara* is the umbilical star.
		Constellations	
15	*Saptarshi*	*Sedona* (old lady's) *Katul* (cot) and *Kalher* or *Kalhed* (thieves), [*muvir* = three] *Kal-hed*, *Kalir*. *Buddhi chi khat* and *chor*. In another story the	It is believed that the first four stars of the *Saptarhi* form the bed of an old lady and that the legs of this bed consist of gold, silver, inferior silver and copper, in an anti-clockwise direction from the star of contact to the trailing three that form the three thieves who are trying to steal the bed. In turn they keep the old lady from falling

		three thieves are replaced by *Poyi* (a noble man), *poy-atar* (his wife) and *Kotwal* (his assistant) going towards their salvation.	asleep. It is believed that if the old lady sleeps, i.e. if *Saptarshi* sets, the Earth will come to an end. This refers to the circumpolar nature of *Saptarshi*. *Saptarshi* is the primary reference point from which all constellations are located.
16	Auriga	*Samdur*	This is visible in the last week of May at 4 am indicates the arrival of the monsoon season. The constellation is overhead in early July at 4 am in the morning. If Auriga is bright at that time, it is assumed that the monsoon will be good and the Gonds sow water-demanding crops like cotton, but if Auriga is dull they assume that the monsoon will be weak and as a result they sow crops that will need less water.
17	Orion and its Belt	*Tipan*, *Naagarda*, *Nangar*, *Nangir*, *Nangal*.	The Belt of Orion is called *Tipan* (3 stars) while along with the sword of Orion, it is called *Naagarda*, which is like a plough. With Taurus, the eastern shoulder of Orion, Lepus and Sirius, it refers to farming activities. The arrival of *Tipan* in the early night sky therefore is an indication of the arrival of the farming season.
18	Sirius region	*Topli*	The basket is indicative of the basket of seeds which is used for sowing in the fields ploughed by *Tipan*.
19	Taurus	*Medi, Kotela*	
20	The Pleiades	*Mogari*, *Mongari*, *Kutpari*, *Thengari*, *Mundari.*	In one village (Karambi) it was pointed out at night.
21		*Tiva*, *Purad*, *Hola*, *Purad* and *Mes*	These are stars west of Sirius in Canis Minor. This implement is used to drop the husk and seeds in the wind so that the husk flies away and the seeds are collected at the bottom of the implement. The myth of *Purad* (a bird) with *Mes* (two eggs) was recorded in only one village. Orion throws a stone which will hit the bird, so that the hunter can steal the eggs. Note that *Pudar* is to the east of Orion so the stone must follow a curved trajectory.
22	Scorpius	*Michu*	*Michu* is responsible for producing the dead body, *Murda*, mentioned in 23 below.
23	Leo	*Murda* (the dead body), *Duf* (the drum bearer), *Shika* (the procession leader), *Ladavya* (the procession of crying women)	The body of Leo is considered the body of a dead person with the head located at Eta Leonis and one hand indicated by Algieba. The other hand is Regulus. The legs are formed by Delta Leonis and Theta Leonis. Delta Leonis (*Asellus Australis*) is the pall bearer. Stars in Virgo form the funeral procession. The procession moves from west to east. The whole procession of death is found in the sky.
24	The tail of the Scorpion	*Khala*	This constellation has a bright star in the centre of a circular pattern with faint stars surrounding it. It represents the animal-powered large grinding circles used in villages.
25		*Irukmara*, *Irukna Mara*	This star is seen at 3 am, indicating the season to pick *Mahua* (*Madhuca longifolia)* flowers (i.e. March-April).
26	Centaurus	*Khayan,*	

Table 6: Concepts encountered in Gond villages listed according to their frequency of occurrence.

Village (see pages 34-38).																
Serial No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Burial practices	E W	S N	S N	E W	S N	S N	S N	E W	E W	S N	S N	S N	S N	S N	S N	15
Referances to stars	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	15
Orion and *Tipan*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		14
The *Saptarshi* Story		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	14
Venus		Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y		Y	12
Comets		Y	Y	Y	Y	Y	Y		Y	Y		Y	Y	Y		11
The Milky Way			Y	Y	Y	Y	Y	Y	Y	Y		Y		Y	Y	11
Names of the Sun and Moon	Y	Y		Y	Y	Y		Y	Y	Y			Y	Y	Y	11
The Pleaides			Y	Y	Y	Y	Y	Y		Y	Y		Y	Y	Y	11
Shooting stars			Y	Y	Y	Y	Y		Y		Y	Y	Y	Y	Y	11
Duration of the month, and Leap years					Y						Y	Y	Y		Y	5
Purad or *Hola* (Canis Major)			Y	Y		Y						Y			Y	5
A glow around the Moon										Y			Y	Y	Y	4
Names of the months				Y	Y	Y										3
Samdur		Y	Y	Y												3
Scorpius				Y			Y						Y			3
Topli				Y				Y		Y						3
The Pole Star						Y				Y			Y			3
Bohari									Y		Y					2
Medi			Y	Y												2
Names of cardinal directions		Y	Y													2
Irukna Mara						Y										1
Khala				Y												1
Khayan (Centaurus)										Y						1

Village (see pages 34-38).																
Serial No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
Koropadera			Y													1
Mrug		Y														1
Murda and its companions				Y												1
Nangel									Y							1
Rainbow			Y													1

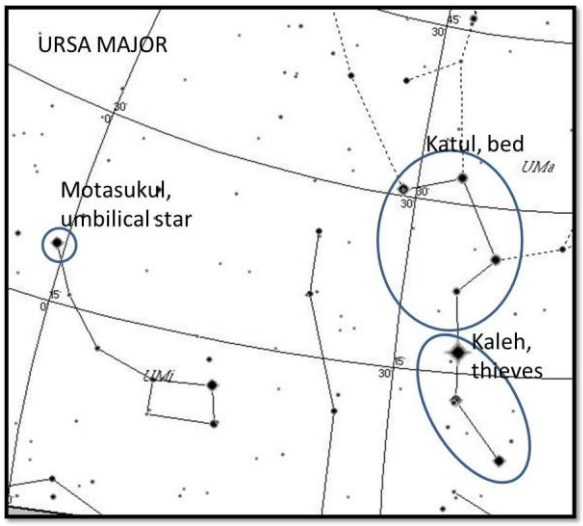

Figure 4: The region of Ursa Major.

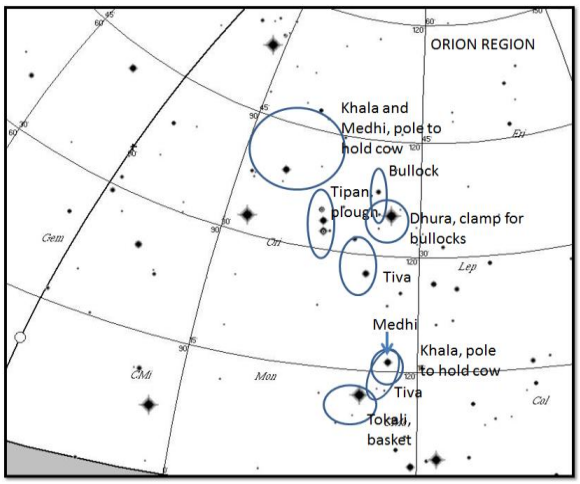

Figure 5: The region of Orion.

In Figures 4 to 9, we present maps of the sky with the Gond constellations marked on them.

5 CONCLUSIONS

The Gond community is clearly an ancient civilisation in its own right dating to a period well before the arrival of Dravidians in south India. Their genetics, lifestyle and mythologies all confirm this. In the present study we have analysed their astronomical beliefs and knowledge. Even our brief survey confirms that their astronomical beliefs were not influenced by later developments that occurred in India, and are sustained by various ancient ideas.

The stories and other astronomical information we collected can be divided into the following categories:

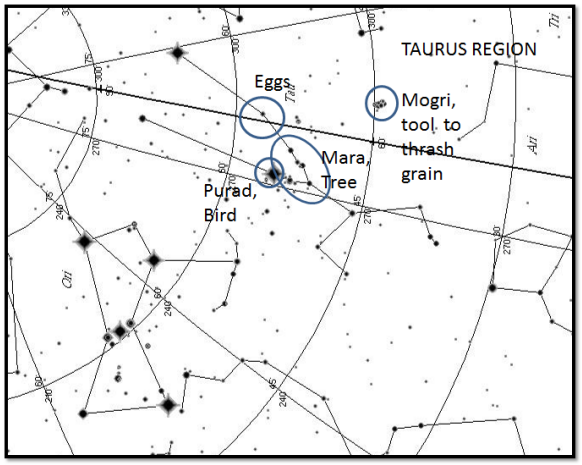

Figure 6: The region of Taurus.

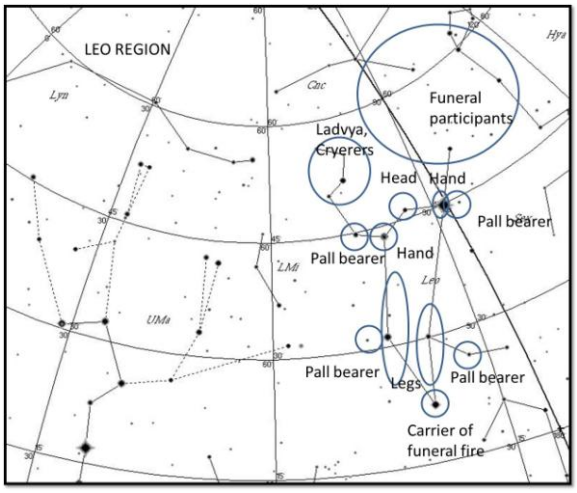

Figure 7: The region of Leo.

- Daily time-keepers – the Sun, the Moon, *Jevan Tara, Pahat Sukum,* the glow around the Moon
- Calendrical – constellation rise times, seasons
- Expression of human activities – *Tipan* and related star groups, *Murda*
- Mythological – comets, the Milky Way, shooting stars
- Cosmogonical – *Saptarshi*

It is clear that the Gond people used astronomy for a variety of purposes from simple daily and annual time-keeping to projecting their life in the skies and cosmogony. Note that all their festivals are based on the lunar calendar (Table 1). However, they do not seem to have used it for navigation. We also did not find a single instance where they numbered their calendars beyond the three years needed to add the intercalary month. Clearly, given the scope of Gond

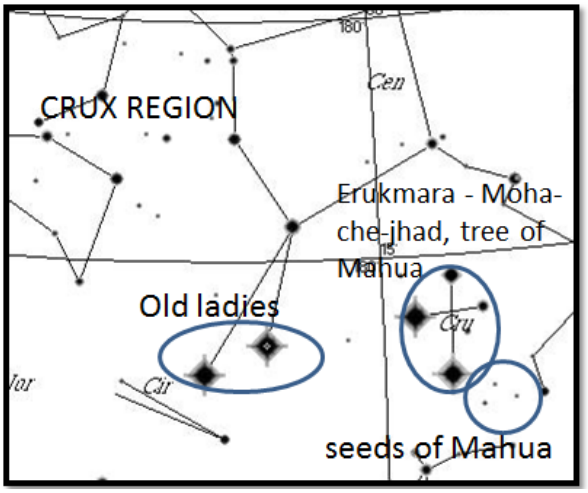

Figure 8: The region of Crux.

culture, this must be more of a memory loss rather than a tradition. Together, therefore, even this sample study indicates Gond interest and perception of astronomy with underlying mythologies and practical ideas. That they had a very well-pursued idea of the intercalary month suggests sensitivity to the seasons and synchronisation of solar and lunar calendars. Their firm and commonly-held belief and knowledge of comets which typically appear only a few times in a century also indicates a continuing tradition of astronomical and other observations. However, they clearly lacked any knowledge of eclipses, which are a relatively common (and periodic) phenomenon, indicating either an absence of very keen observations, or equally likely, a conscious decision to ignore information that did not easily fit their world view.

Another marked feature of their astronomy is the absence of gods or super-humans, except for *Saptarshi*. This again suggests that in spite of having an agrarian lifestyle, the Gonds were not given to grandiose speculations about the heavens and events occurring in the sky.

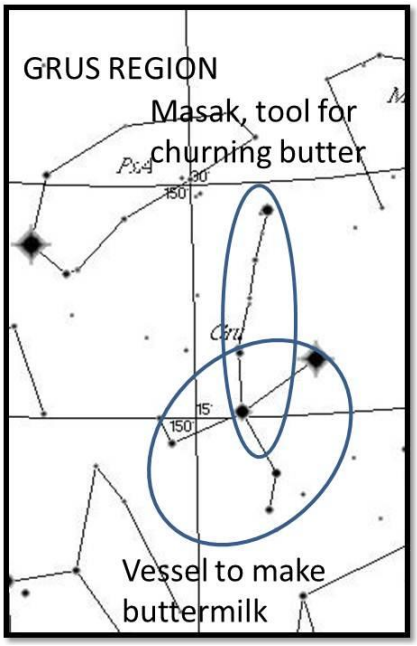

Figure 9: The region of Grus.

Another aspect of the observations is the Gonds' lack of interest in constellations such as Cassiopeia, Aquila, Gemini, Bootes, Cygnus and Sagittarius. These contain bright stars yet the villagers could not even identify them in the planetarium. It is significant that apart from Sagittarius, all of these constellations lie in the northern sky, north of the northern-most point of sunrise (Mahendra Wagh, private communication), which suggests a lack of interest in northern constellations where the Sun does not travel.

The naming of Polaris as the umbilical star suggests cosmogonical ideas based on the Pole Star as the centre of the Universe and humans. Such an interpretation of the heavens is also found in the *Surya Siddhanta*.

One more interesting feature of Gond astronomy is that their observations extended all the way down to Crux and Grus, confirming that the Gonds were keen observers of their own local sky and did not import astronomical ideas from people living elsewhere.

As regards planets, they seem to have noticed only Venus and identified it as both the Morning and the Evening Star.

All in all therefore, it seems that Gond astronomy had its roots in early farming needs and was designed several thousand years ago when Polaris was not yet the Pole Star and *Saptarshi* was circumpolar, which happened around 1000 BC. This reinforces the general consensus that the origin of the Gonds is much older than previously thought. There also seems to have been little later modification of this basically utilitarian approach to life and environment which is a hallmark of Gond traditions.

It would be useful to follow up this study in greater detail, and also endeavour to compare the astronomical views of the Gonds with those of other Indian tribes.

6 NOTES

1. In Hindu society, the term *Gotra* means clan. It broadly refers to people who are descendants in an unbroken male line from a common male ancestor (after Wikipedia).
2. In Madhya Pradesh the Gond calendar is designed by Chaitanya Kumar Sinha of Rajanandgaon. In Maharashtra it is published by Tiru Moreshwar Tukaramji Kumare and Tiru Sampatji Kannake Ballarshah and is printed by Ohmkar Graphics in Chandrapur.
3. This is a deep N, produced by using the soft (back) of the palate rather than the 'normal' N that is produced by using the hard (front) of the palate.

4. A short film about this April 2012 visit of the Gonds to the planetarium at the Raman Science Centre in Nagpur can be viewed at: www.tifr.res.in/~archaeo

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8 REFERENCES

Aatram, V., 1989. *Gondi Sanskrutiche Sandarbha, Srimati Yashodabai Aatrma*. Aarvi, District Vardha (in Marathi).

Agrawal, R., 2006. *Gond Jati ka Samajik Adhyayan.* Mandala, Gondi Public Trust (in Hindi).

Balgir, R.., 2006. Genetic heterogeneity of population structure in 15 major scheduled tribes in central-eastern India: a study of immunohematological disorders. *Indian Journal of Human Genetics*, 12, 86-92.

Deogaonkar, S.G., 2007. *The Gonds of Vidarbha*. Concept Publishing Company, New Delhi.

Dubey, B., Meganathan, P.R., Eaaswarkhanth, M., Vasulu, T.S., and Haque I., 2009. Forensic STR profile of two endogamous populations of Madhya Pradesh, India. *Legal Medicine*, 11, 41-44.

Fürer-Haimendorf, C. von, and Fürer-Haimendorf, E. von, 1979. *The Gonds of Andhra Pradesh: Tradition and Change in an Indian Tribe*. London, George Allen & Unwin.

Gaikwad, S., Vasulu, T.S., and Kashyap, V.K., 2006. Microsatellite diversity reveals the interplay of language and geography in shaping genetic differentiation of diverse Proto-Australoid populations of West-Central India. *American Journal of Physical Anthropology*, 129, 260-267.

Gondvana Kiran Calendar for 2007. Bhopal, Gondvana Kiran (newspaper).

Kangali, M., 1997. *Pari Kupar Lingo koya Punem: Gondi Dharma Darshan*. Nagpur, Gondwana Vikas Mandal (in Hindi).

Maddison, A., 1989. *The World Economy in 20th Century*. Paris, OECD.

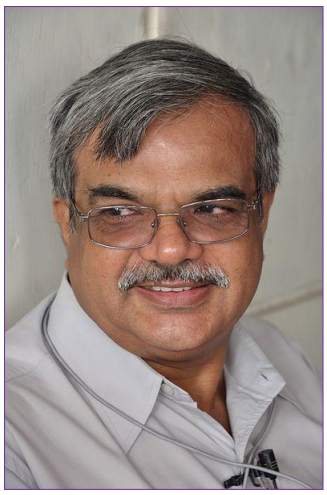
Mehta, B.H., 1984. *The Gonds of Central Indian Highlands. Volumes 1 and 2*. New Delhi, Concept Publishing Company (all references in this paper are to Volume 1).

Pingle U., 1984. Anthropometric and genetic distance between Gonds of Central India. *American Journal of Physical Anthropology*, 65, 291-304.

Pingle, U., and Fürer-Haimendorf, C. von, 1987. *Gonds and Their Neighbours: A Study in Genetic Diversity*. Lucknow, Ethnographic & Folk Culture Society.

Sahoo, S., and Kashyap, V.K., 2005. Influence of language and ancestry on genetic structure of contiguous populations: a microsatellite based study on populations of Orissa, *BMC Genetics*, 6(4) doi:10.1186/1471-2156-6-4.

Vahia, M.N., and Yadav N., 2011. Reconstructing the history of Harappan civilisation. *Journal of Social Evolution and History*, 10, 67-86.



Mayank Vahia is a Professor in the Department of Astronomy and Astrophysics at the Tata Institute of Fundamental Research in Mumbai. He began his career making satellite-based astronomical instruments for high energy astrophysics. He was the Director of the Nehru Planetarium in Mumbai for a year in 2000-2001. He is currently the National Coordinator of the Astronomy Olympiad in India. In recent years he has become interested in the origin and growth of astronomy in the Indian subcontinent. He has been working on prehistoric records of astronomy in India and is deeply interested in documenting astronomical beliefs amongst Indian tribes. Mayank has published more 200 papers in research journals, about 35 of which are in history of astronomy.

Ganesh Halkare is an advocate in Amravati, a town in Maharashtra. He is also a post-graduate degree holder in Archaeology and Anthropology from Nagpur University. He has a deep interest in tribal education, particularly in the removal of superstition among the tribe members. He is also deeply interested in tribal anthropology and is highly respected amongst the tribesmen for his work in ensuring that they are aware of and can exercise their rights within the nation state. He also has been a regular columnist on constitutional rights. Ganesh has published more than a dozen research papers on the archaeology of the Nagpur region in Indian journals and conference proceedings. He is now working on the astronomy of other tribes in the Nagpur region.

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CHINESE RECORDS OF THE 1874 TRANSIT OF VENUS

Lingfeng Lu and Huifang Li
Department of History of Science and Scientific Archaeology, University of Science and Technology of China, Hefei, People's Republic of China.
E-mails: lingfeng@ustc.edu.cn; huifang@ustc.edu.cn

Abstract: Before the advent of radar, transits of Venus were very important for measuring the distance between the Earth and the Sun. A transit occurred in 1874, and was visible from China, other parts of east and southeast Asia and from India, Australia and New Zealand and certain islands in the Indian and Pacific Oceans. As a result, many astronomers from Western countries came to China to observe it. According to traditional Chinese astrology, the Sun represented the Emperor, and if the Sun was invaded by other astronomical bodies it meant that the Emperor and the country faced some ominous disaster. In the late nineteenth century, Western astronomical knowledge was widely translated into Chinese and spread among Chinese intellectuals, so the 1874 transit supposedly was easily understood by Chinese intellectuals. Before the transit took place, various Chinese publications introduced this kind of celestial event as science news, but at the same time other influential newspapers and journals discussed the astrological connection between the transit and the fortunes of the nation. In this paper we review these interesting Chinese records and discuss the different attitudes towards the transit exhibited by Chinese intellectuals and officials, during a period when Western learning was being widely disseminated throughout China.

Keywords: 1874 transit of Venus transit, China, the *Peking Magazine*, W.A.P. Martin, James Craig Watson

1 INTRODUCTION

Once Edmund Halley demonstrated that transits of Venus could be used to address that fundamental challenge of astronomy, determining the distance from the Earth to the Sun (i.e. the 'astronomical unit'), these rare events assumed immense international importance. The 1761 and 1769 transits produced discordant results (see Woolf, 1959), which directed attention to the two nineteenth century transits, in 1874 and 1882 (e.g. see Sheehan and Westfall, 2004).

As shown in Figure 1, the entire 1874 transit was visible from China, India and Japan in the Northern Hemisphere; from Australia New Zealand and isolated islands in the Indian Ocean in the Southern Hemisphere; and from islands in the Pacific Ocean in both Hemispheres. Consequently, eclipse expeditions from England, France, Germany and the USA were attracted to these nations and to various islands in the Indian and Pacific Oceans (e.g. see Chauvin, 2003; Dick et al., 1998; Duerbeck, 2007; Lauga, 2004; Launay, 2012; Orchiston, 2004; Pigatto and Zanini, 2001; Ratcliff, 2008).

Astronomers from many countries, including England, France and the USA, enthusiastically came to China and other East Asian countries in order to observe the transit, and they established observing stations in cities such as Peking (present day Beijing), Tianjin and Qingdao. Britain even sent a team to observe from the Himalayas. The USA invested a great deal of money in the transit observations, and began their preparations ten years before the event (see Dick et al., 1998). The Americans also invented new types of instruments with which to carry out the observations, especially ones that relied on newly-invented photographic technology.

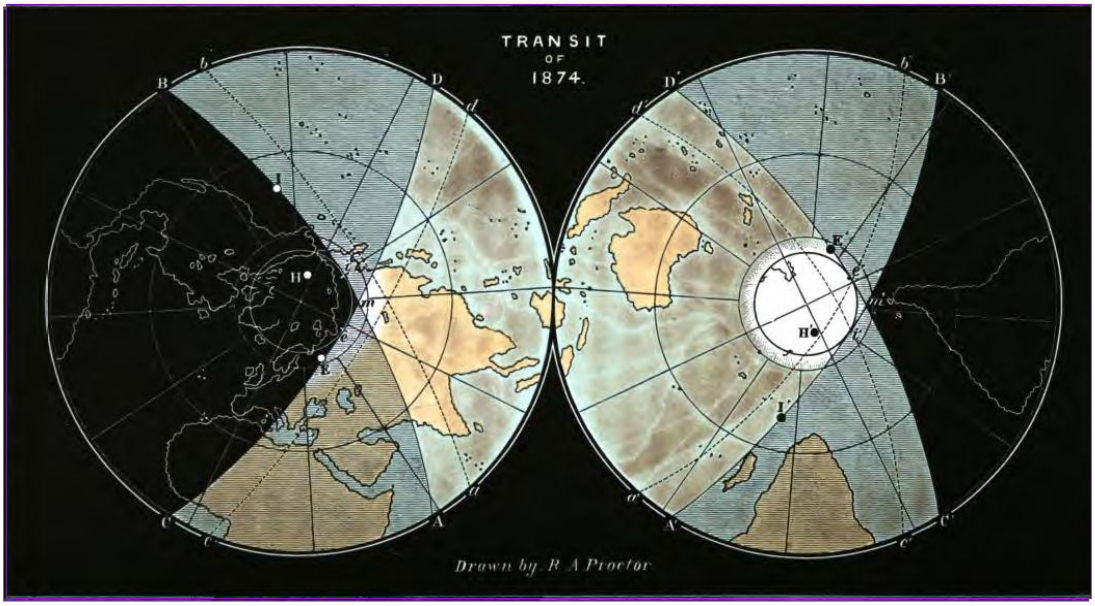

Figure 1: Map showing those areas of the globe (in pale blue and mottled brown) where all of the 1874 transit of Venus would be visible (after Proctor, 1874: Plate VI).

Unfortunately, officials from the Qing Dynasty did not make any records of the transit (wrongly believing that it would occur at night), but some local newspapers and magazines produced by Western cultural and religious institutions and controlled by missionaries published detailed useful information for those who wished to observe the transit. These same newspapers also reported some interesting responses from the visiting Western astronomers, from intellectuals and from common people, both before and after the transit.

In recent years, historians of astronomy have conducted considerable research on the historic transits of Venus (e.g. see the Bibliography in Sheehan and Westfall, 2004), but transit observations from China have not featured in this research. It is hoped that this paper will be viewed as a first step in this direction.

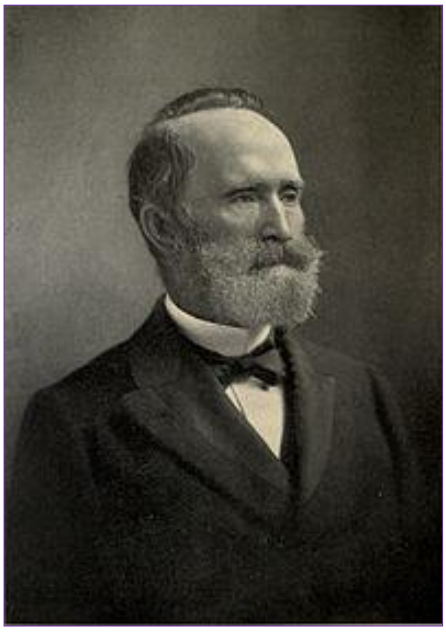

Figure 2: William Alexander Parsons Martin (en.wikipedia.org).

2 PUBLICISING THE TRANSIT

One year before the 1874 transit of Venus, the *Peking Magazine*[1] provided background knowledge of this rare astronomical event. The October 1873 issue of the *Peking Magazine* included the following article titled "Transit of Venus" by William Alexander Parsons Martin (1827–1916; Figure 2), a co-founder of the *Magazine*:

> Venus will cross the Sun on the 30th day of the 10th month next year in the Chinese lunisolar calendar. The phenomenon will be seen again in 8 years time but will never be observed thereafter [during our lifetime]. Western countries are sending professional astronomers to observe in various places. The Russians are going to the north. The British are going to the south. These kinds of expeditions also occurred in ancient China. For instance, Emperor Yao sent his minister to western and southern China to make accurate observations and measurements of astronomical phenomenon for a time service. Western astronomers are going to places with harsh climates to observe the transit. If you think their purpose is for astrology and the prediction of disasters and fortune, you are totally wrong. Westerners don't use astronomical phenomena to predict the future. The reason why they carry out these observations is so that they can use the data to calculate the distance between the Sun and the Earth. First, during the reign of Hongzhi in the Ming Dynasty Copernicus demonstrated the Heliocentric Theory and declared that the distance between the Sun and the Earth was only 600 times the diameter of the Earth. Then in the reign of Tianqi, Kepler stated that the distance was more than 1700 times the diameter of the Earth. During the reign of Kangxi, Newton proclaimed that the distance was 8000 times the diameter of the Earth. Nowadays we believe it is 11000 times or 12000 times the diameter of the Earth. The diameter of the Earth is 8000 miles … It seems like the distance between the Earth and the Sun is getting larger. Actually it is because technology and calculations are more advanced nowadays. Astronomers believe that the distance is between these two values and that up-coming observations of the transit of Venus will provide a more precise figure. If the distance between the Earth and the Sun can be calculated, the distance between the Earth and other planets can then be determined. As a result, the distance between the Earth and the Sun is a basic yardstick for all astronomical determination. And the calculation of the distance between the Earth and the Sun relies on observations of the transit of Venus … (Martin, 1873; our translation).

This article discussed the preparations being made by observing teams from other countries and acknowledged the importance of the transit to Western science. It introduced the means of calculating the distance between the Sun and the Earth. And the "… method of taking photographs …" (ibid.), the technique that would be used during the transit, also was discussed in the magazine. The use of photography during the 1874 transit was an important innovation (see Lankford, 1987).

Over the following months, the *Peking Magazine* provided more news about the transit of Venus. The 21st issue, in April 1874, and the 24th issue, in July 1874, reported on the preparations by France (Martin, 1874d) and the United States. For instance, the article "Another item of news on America" reported that the United States would invest a significant amount of money in the observations and would send professional astronomers and photographers to the Eastern Hemisphere:

> The news of the transit of Venus has been reported in earlier issues. And now it is said that the Americans will send people to eight places. Five of them are located to the south of

> the Equator. The names of the places are unknown. Three of them are located to the north of the Equator. The locations are Nagasaki in Japan, a Russian site to the north of North Korea and the capital of China. It is planned that to each location will be sent one chief professor and five assistants. And the instruments used to make the observations have been produced. To equip the expeditions, the American National Treasury intends to invest 1.5 million [dollars] on these expeditions. Now all the professionals are in training with their equipment and they will soon leave the USA. (Martin, 1874b; our translation).

In the 25th issue, in August 1874, the *Peking Magazine* reported more news about the transit, including the forecast from the American astronomer James Craig Watson (1838–1880), who was Professor of Astronomy at the University of Michigan (Comstock, 1895) and leader of the U.S. transit expedition based in Peking:

> The transit of Venus [of 1874] is a significant event for astronomy and will be the only one seen from China within a hundred years. A transit is related to the calculation of the distance between the Sun and the Earth. As a result, Western countries pay a lot of money to go to various places to observe it. One reason why they go to different places that are far away from each other is because the further the distance is, the larger the angle is [see Figure 3]. Another reason is that they can observe in other places and compare the data if the weather in an area is bad and they encounter a cloudy day when observing. The method of calculating [the Sun-Earth distance] has been briefly discussed in the 15th [October 1873] issue. And now three French astronomers and six American astronomers have arrived in the capital, including three who will take charge of the photography. Because the transit of Venus is difficult to record accurately while making visual observations, using photography can help astronomers to record the whole transit, which will be convenient for future use. The application of photography has had a profound influence on the development of astronomy. American astronomer James Craig Watson has described the transit in detail. Here is a brief translation of his opinions:
>
> The transit of Venus will happen on the 11th month of the Chinese lunisolar calendar.
>
> It will begin at 9:32. Mid-transit will be at 12:01. It will end at 2:18. When Venus enters the Sun, the angle will be 51° northeast. When it exits the Sun, the angle will be 22° northwest.
>
> Because Venus will pass in front of the Sun, it will be seen that the radius of Venus is one thirtieth the radius of the Sun. (Seen from the Earth, Venus is like a bean. When it passes across the face of the Sun, people can use sunglasses or stained glass to observe it. These devices will be described later.) (Martin, 1874f; our translation).

People who were curious about the phenomenon would be able to observe it on the day because of the detailed description provided by Professor Watson. He predicted that the transit of Venus would begin at 9:32 and end at 14:18 on 9 December 1874. The whole event would take 4 hours and 46 minutes. Watson also identified the locations where Venus would enter and exit the Sun, the route it would take in crossing the disk of the Sun, and its size relative to the Sun.

The transit of Venus was not only reported in the *Peking Magazine,* but it also was covered by the newspaper *Shen* Bao,[2] which had a large circulation. Before it took place, there were a few reports on the transit published in this newspaper (Shen Bao, 1874(a); 1874(b); 1874(d)). The interesting thing was that the *Shen Bao* used the opportunity to publish advertisements for telescopes one month before the transit (e.g. see Shen Bao, 1874(c)). Interest in the transit among common people really stimulated business.

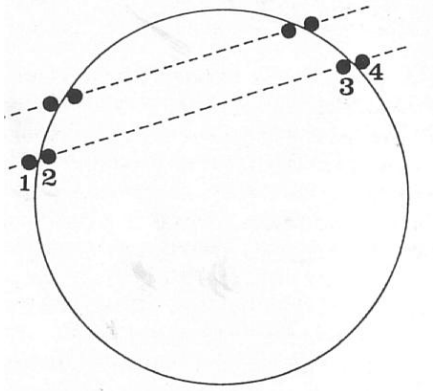

Figure 3: Ingress contacts (1 and 2) and egress contacts (3 and 4) during a transit of Venus. The two transects show the different paths of Venus across the Sun's disk viewed from observing stations that are widely separated in latitude (but for the purposes of illustration we have inserted *considerable* vertical exaggeration) (courtesy: Wayne Orchiston).

On 8 December, the day before the transit, the *Shen Bao* published the specific time schedule for the event in Shanghai on the first page:

> At 9:50:30, Venus will touch the edge of the Sun. At 12:14:6, Venus will reach the center of the Sun. At 14:10:30, Venus will first touch the inside edge of the Sun. At 14:37:48, Venus will leave the Sun altogether [and the transit will be over—see Figure 3][3] … the times mentioned above are quoted from the appendix in the *Wan Guo gong bao*. (*Shen Bao*, 1874(d); our translation).

The report explained that the information was from the *Wan guo gong* bao,[4] in Shanghai. Furthermore, the *Universal Circulation Herald*[5] in Hong Kong also covered the news. Due to the large circulation of the *Shen bao,* the *Wan guo gong bao* and the *Universal Circulating Herald* at that time, the transit of Venus should have been popular with the public.

An official of the Qing Dynasty also provided a description of the phenomenon. However, it differed significantly from the account provided by the Western people. It predicted that the event would happen at night, which was obviously incorrect. It turned out that some people wrote to the *Peking Magazine* to ask about the true situation, and the *Peking Magazine* was forced to deny the accuracy of the official account published in the 27th issue and iterated that the data in the 25th issue (Martin, 1874f) were correct:

> A reader asked about the difference between the accounts from Western countries and the official version. The letter said that according to our magazine, Western countries predicted the transit of Venus would occur on the first day of the 11th month of the Chinese lunisolar calendar and it would begin at 9:32 and end at 14:18. However, the official astrological almanac Qizheng said that it would happen on the second day of the 11th month of the Chinese lunisolar Calendar and would begin at 0:14. Accordingly, the phenomenon will happen at night and can only be observed from the Western Hemisphere. So why are Western scientists so eager to come to the Eastern Hemisphere? Astronomers from five countries, namely Britain, the United States, France, Germany and Russia have come here, and those from France, the United States and Russia have even come to the capital. It can't be a coincidence that they all came here at the same time. It seems like there's a mistake in the official account. We only have to wait for a few days to find out the truth. If the weather is good on that day, we will see it right away. If it is a cloudy day, we only will be able to see it in some other places. And after the transit, we can make the previous calculations of the distance between the Sun and other planets more accurately. The method of calculation has been introduced at the 15th issue. It seems that there are differences in the predicted dates of the transit, that we say the 30th of the 10th month rather than the 1st of the 11th month but this is because Western astronomers start the date from noon while the Chinese lunar calendar calculates the date from midnight. So, there is no difference. And the time schedule of the transit of Venus has been published in the 25th issue. (Martin, 1874c; our translation).

The officials did not ignore the transit but we have yet to find any of their accounts or records. However, there is some indirect evidence that indicates that they did carry out observations. For example, on page 22 in Volume 11 in the local chronicles of Zhejiang Provence there is a report that on the first day of the 11th month of the Chinese lunar calendar during the 13th year of the reign of the Emperor Tongzhi, there was a black spot on the Sun (Yan Zhenheng, 1879). That was 9 December 1874, the exact date of the transit, and because people lacked knowledge of the transit Venus was referred to as a 'black spot'.

3 OBSERVATIONS OF THE TRANSIT

The accounts of the up-coming transit stimulated public interest, and detailed information on the planned observations was covered in the November 1874 issue of the *Peking Magazine* (Martin, 1874a; 1874c). In addition, a student named Zuo Binglong from Tongwen College, a foreign language school, wrote an informative article titled "The Record of the Observation" which introduced the equipment that he saw in Professor Watson's apartment:

> It was said that the Western astronomical instruments were sophisticated. And I was so eager to see them for myself. Yesterday when I passed the apartment of James Craig Watson, I got the chance to see the equipment that they will use to observe the transit of Venus. I was so excited to see such a sophisticated instrument. I recorded the main features of the observing system immediately after I returned home and translated them into English. Then I presented this account to my supervisor Mr. William Alexander Parsons Martin. Mister [Martin] was impressed with the article and sent it to Mr. Watson, expecting me to translate it into Chinese. And now there must be a lot of newspapers that want to publish it. I can't describe the instruments very well because of their complexity. (Zuo, 1874).

Not long after the transit of Venus, the results of the observations made by the American, French and Russian parties were published in the December 1874 issue of the *Peking Magazine*:

> On 9 December, Venus transited the Sun. Astronomers from the United States, France and Russia had readied their equipment early in the morning for the observation. At the time predicted, Venus appeared. Although Venus is about the same size as the Earth, it only looked like a little ball when seen from the Earth because of its great distance from us. When it entered the Sun, there were clouds in the sky. After 12:00, the clouds moved away and we could see it again. The transit began at 9:33 and ended at 14:17 which were quite in accordance with the prediction.[6] American and French astronomers also took photographs of the Sun. The Americans used glass plates and got more than ninety pictures. The French … got tens of pictures, each of which accurately recorded the position of Venus on the Sun's disk ... Western countries paid a lot of money to come here to observe the transit of Venus and in the end they were successful. However, had they only observed from Peking and not at other places, because of clouds their observations would have been useless. If they were able to observe at other places, the distance between the Earth and the Sun could be calculated … Successful observations were made at more than forty locations. Therefore, the data can be used to compute an accurate value for the distance. In about one year the results will be known to the public. The illustration [shown here in Figure 4] was drawn by James Craig

Watson.

> We heard that the German astronomers observed the transit from Yantai. And the Japanese media reported that some Americans saw the transit from Nagasaki. In eight years time, the next transit of Venus will only be visible from America and some other countries. It is unknown whether China will send astronomers there to conduct observations. (Martin, 1874e; our translation).

In the meantime, the *Shen Bao* also reported observations made at various locations. According to the 12 December 1874 issue,

> Shanghai received a telegram from Nagasaki yesterday. This said that it was a little foggy in Nagasaki although the weather was generally good enough to observe the transit. A telegram from Yokohama said that the weather there was perfect for the observations. And the weather in other places also was suitable.
>
> Astronomers in Shanghai had prepared for the observation for so long. But because the day was foggy, they did not observe it as well as they wanted to. Fortunately, the fog faded away for a moment and the astronomers were able to take some photographs of the transit. The weather in Yantai was perfect, and the astronomers took advantage of this for their observations. (*Shen Bao*, 1874(e); our translation).

On 19 December1874 the *Shen Bao* reported:

> A message from Yokohama said that an astronomer used the telescope to observe the transit and the image was pretty clear. And it had been hypothesized that there was a "hot atmosphere" around the Sun and the observation this time really proved it ... Venus moves at 40,000 kilometers an hour. The rotation period of Venus is 23 hours and 21 minutes, which is 39 minutes less than that of the Earth. The new figures are more accurate than before due to the observations. (*Shen Bao*, 1874(f); our translation).

Public interest in the transit did not fade away quickly. One month after the transit, Watson delivered a lecture in Shanghai about the transit and its relation to the problems in astronomy, and this was reported in the 14 January 1875 issue of the *North China Herald*.[7] Watson displayed 3 of the 99 photographs of the transit taken in Peking, and diagrams to illustrate the subject in a popular manner. Notwithstanding unfavourable weather, an audience of nearly 200—including a large proportion of ladies—was present and received a rare intellectual treat.

Additional information was in the February 1875 issue of the *Peking Magazine*, including a report on the transit observations of the French astronomer Frégate Fleuriais written by the French Ambassador in Wuhan, F. Scherzer (1875).

Furthermore, news of the transit observations made in Japan was also covered in the same issue of the *Peking Magazine*:

> In the middle of the observation, the sky was clear enough to take more than ten clear photographs. However, there were clouds in the sky at the beginning and the end so that the pictures taken in those periods were not clear. The Emperor of Japan heard that the transit of Venus was a rare phenomenon. He really admired the courage and efforts of the Western astronomers. Therefore, a telescope was placed in the Palace for the Emperor to use. The whole of the transit was visible. And there was an American and a Japanese astronomer in the Palace to explain the transit to the Emperor.

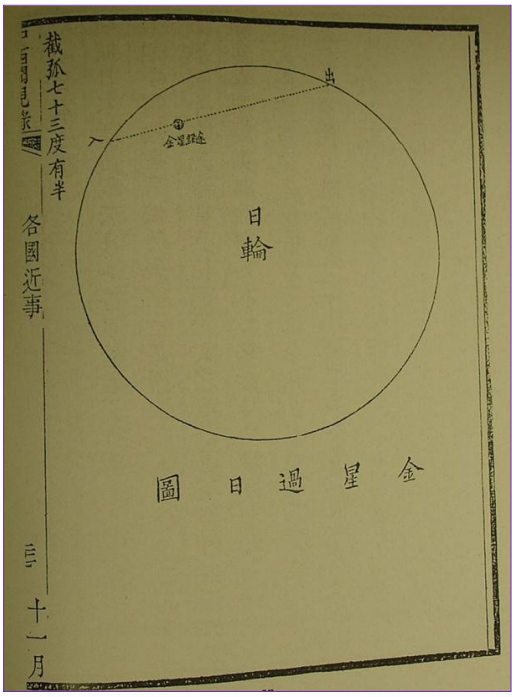

Figure 4: The drawing of the transit made by James Craig Watson (after Martin, 1874e).

> One French astronomer [with the Chinese name Ransun] who was in Japan for the observation of the transit of Venus now lives in Nagasaki. He plans to observe the eclipse of the Sun in Siam in March.[8] Scientists are eager to discover more about the structure of the Sun which is normally too dazzling to observe … However, the sky will be dark when the eclipse of the Sun occurs. Ransun plans to go to Siam because it is predicted that this total eclipse of the Sun can only be seen from Siam (Scherzer, 1875; our translation).

It is also important to mention that before the transit occurred, Professor Watson regularly used his telescope to observe the sky, and in the process he accidentally discovered a new asteroid. Because he made the discovery while in China, Watson invited Prince Gong to name it. News about this discovery was published in the 27th issue of the *Peking Magazine* (Martin, 1874a). Prince Gong approved the suggestion and he named the asteroid Ruihua, which means 'lucky China'. This news was also included in the 20 December, 1874 issue of the *Shen Bao* (1874(g)).

4 THE TRANSIT AND ASTROLOGY

In traditional Chinese astrology, the Sun represented the Emperor. If the Sun was interfered with by other celestial bodies, the reign of the Emperor would be challenged or the nation would be in danger. Therefore, the transit of a celestial body across the Sun was generally translated as inauspicious. During the late Qing Dynasty, although plenty of overseas scientific works had been translated into Chinese and basic knowledge had been circulated among the public, it was impossible for the authorities, who still used traditional astrology, to interpret these types of phenomena in a scientific way. So each report of an abnormal astronomical event was followed by an astrological interpretation.

The attitude of the non-official scholars was the opposite. Before the 1874 transit of Venus, the Editor of the *Peking Magazine*, William Martin, had predicted the superstitious reactions of the public, and so the magazine published a scientific article titled "Debate on Astrology" by Li Shanlan, a very famous Chinese mathematician in nineteenth century China, which demonstrated that ancient astrology was ridiculous:

> The theory of astrology is a kind of cheating and has a bad effect on society. People who preached astrology would be sent to the guillotine in ancient China. So a man of insight should be careful and not be deceived by these people. (Li, 1873).

Supporting Li Shanlan was one of his colleagues, Gui Lin, who wrote an article "Sequel of the Debate on Astrology" which was published in the October 1873 issue of the *Peking Magazine* (Gui, 1873). This article used various examples to prove that astrology was harmful to the public.

However, the influence of the *Peking Magazine* was limited, and superstitions could hardly be changed in so short a time. Only a few days after the transit, the astrological explanation of the event was being circulated among the public. It was stated that Emperor Tongzhi's smallpox was related to the transit. And the following message was published on the *Shen Bao* (1874(h)):

> The Emperor has been ill … [He] got smallpox at the beginning of this month … [and] has suffered from the illness for seven days. The doctor said that the Emperor will recover soon …

Although the newspaper said that the Emperor's situation was not critical, he passed away on 12 January 1875, and rumors quickly circulated:

> The news from Tianjin: the rumors said that people were intimidated by the illness of the Emperor. And the transit of Venus was the sign of this sickness … (*Shen Bao*, 1875).

William Martin then wrote an article titled "Argument on Astrology" arguing against the rumors, and this was published in the January 1875 (29th) issue of the *Peking Magazine*:

> In ancient times, when language did not exist, people observed the sky and invented astrology. One star represented the Emperor. Other stars represented the officials. Their fates were determined by celestial phenomena. Western and Eastern cultures both agreed with this … However, Western countries soon abandoned the ancient idea and believed in scientific explanations. People laughed at those who still believed in astrology. And two astronomical events have confused the public this year in China. The first was the comet that appeared in the northwestern sky.[9] Rumors circulated because Japan began competing with China over Taiwan. People recognized the comet as a sign and did not understand that it had its orbit and showed up periodically. Besides, a comet is a universal phenomenon for all the countries around the world, not just China. How could the appearance of a comet be a sign for all international affairs? The second event was the transit of Venus which was recognized as a sign of the illness of the Emperor. People did not know that these transits had happened before. A transit of Venus was visible from China one hundred and five years ago, in the reign of Qianlong. At that time Qing China was enjoying prosperity, so nobody worried about this inauspicious omen. Two hundred and thirty-five years ago, astronomers in Western countries also saw a transit of Venus, but no evidence exists to show that any of the Emperors reacted to that event. Those in America will see the next transit in eight years time, but Western people do not express concern about the future. Therefore, using astrology to divine the future is ridiculous. If public opinion is misled by such absurd theories, society may descend into chaos. Compared with traditional astrology, Western learning seems more realistic and practical due to its calculated scientific approach. (Martin, 1875).

These kinds of articles were quite effective at that time. For example, an article, "After Reading the Argument of Astrology" by a reader, Yin Ruichang from Tianjin, was published in the August 1875 issue of the *Peking Magazine* (Yin, 1875). The article criticized traditional astrology, which Yin viewed as absurd, and he supported the statements of Li Shanlan and William Martin. He also discussed in depth the historical reasons for the belief of Chinese officials in astrology.

Indeed, we can see the relationship between astronomical phenomena and the fate of an Empire from the official documents of the late Qing Dynasty. For instance, the teacher of the Emperor, Weng Tonghe, paid close attention to the appearance of Coggia's Comet. During that period, Weng observed the sky every night, and became worried about a sudden change in the Empire (Chen, 2006). We can understand his attitude towards astronomical phenomena as he represented the conservatives in China.

However, the attitude of a reformer, Chen Chi, was inexplicable. He mentioned the transit of Venus in a letter to his friends Wen Tingshi and Li Shengduo:

> Though having a good command of calculation, I am convinced of astrology. Venus transited the Sun in the 13th year of the reign of Tongzhi, and then the Emperor died, which made me have increased faith in astrology. Westerners claim that there is no relationship between celestial phenomenon and the fortunes of a country because nothing particular happened as a result of the transit. (Chen, 1875).

Chen Chi was fond of Western literature and promoted Western culture, so it was surprising that he still stated that the transit of Venus and the death of Emperor Tongzhi were related.

5 DISCUSSION AND CONCLUDING REMARKS

From the various newspaper accounts cited above we know that the transit of Venus was not only significant scientific news, but also was an event that was considered relevant to the death of the Emperor.[10] Ten years later, the drawing reproduced here in Figure 5 appeared in the *Dian shi zhai hua bao*,[11] a magazine that was established in 1884. This drawing relates to observations of a transit of Venus made at Tongwen College. The following is an English translation of the script that appears on this drawing:

> It is said that mathematics is the basis of science in the West. By using calculus, astronomers predict astronomical phenomena and verify their predictions. Tian Wensheng (students majoring in astronomy) from Tongwen College predicted the transit of Venus would happen at 15 o'clock on the 8th day of the 10th month of the Chinese lunisolar calendar. So they set up an observatory and prepared instruments in the general administration office, and ministers of the office were invited to carry out the observations together with the astronomy teachers and the students. Whether this astronomical event had a direct correlation with the fortunes of the country aroused more heated debate than it deserves, but what was more important was to make the observations and provide a scientific interpretation.

From the date of the record it would appear that the transit of Venus mentioned in the *Dian shi zhai hua bao* occurred in 1882. However, the 1882 transit was not visible from China (see Sheehan and Westfall, 2004), so we can be certain that the record relates to the 1874 transit, but the script in the picture records that the transit began at 15 o'clock on the 8th day of the 10th month of the Chinese lunisolar calendar, whereas the 1874 transit began at 9:33 and ended at 14:17

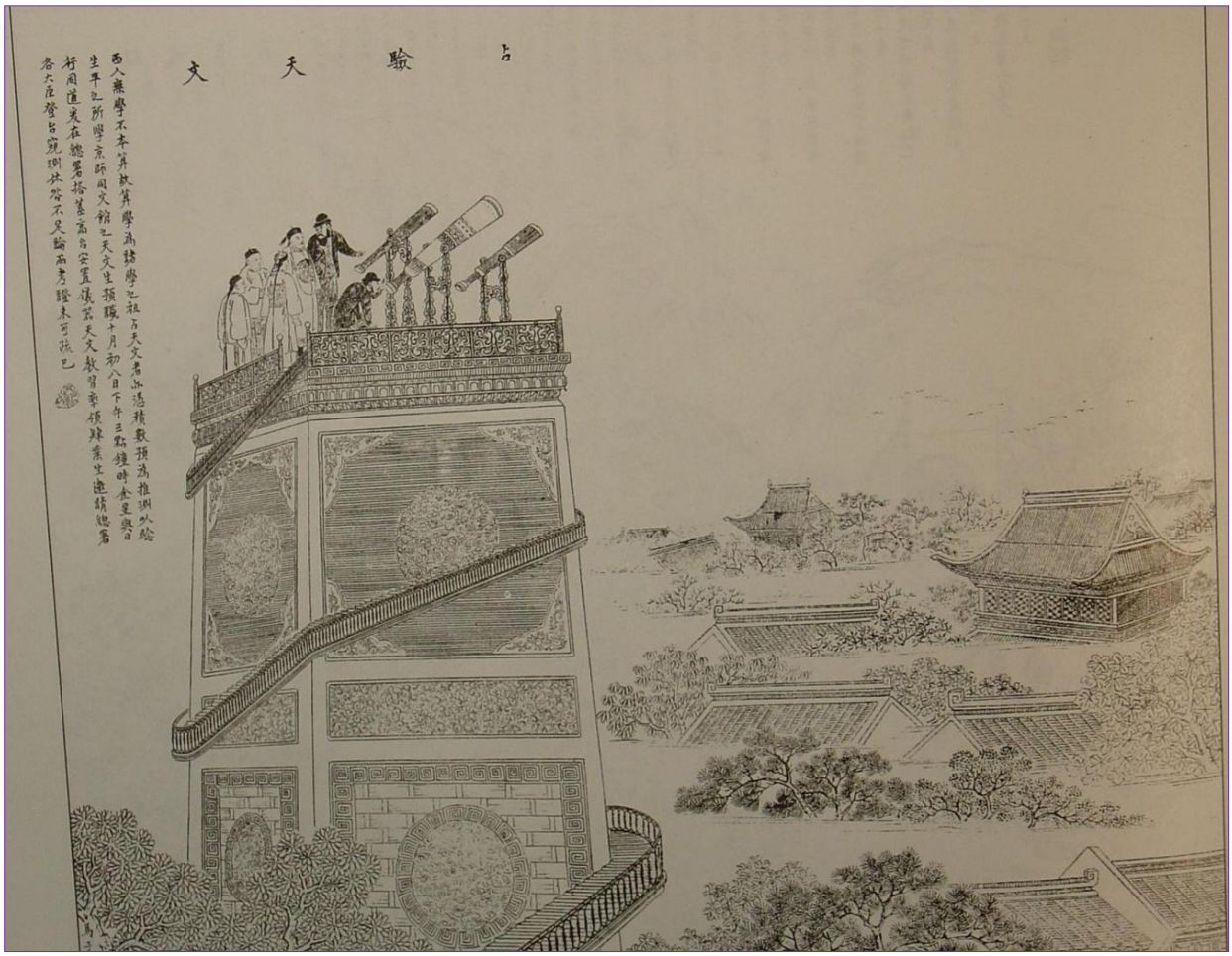

Figure 5: Observing the 1874 transit of Venus (after the *Dian shi zhai hua bao*, 1884).

on the first day of the 11th month of the Chinese lunisolar calendar. So the account in the *Dian shi zhai hua baol* is incorrect. But this record reflects people's memories of the 1874 transit after many years, and from this viewpoint we can see the significance of these phenomena to the Chinese people. This especially demonstrates that the efforts of William Alexander Parsons Martin and some Chinese intellectuals to try to eliminate traditional astrology was not futile. The Chinese public had begun to appreciate the scientific meaning of these kinds of astronomical events.

It is a pity that we did not find any reports of Chinese officials making observations of the 1882 transit of Venus, and it seems that some time still had to pass before Chinese astronomers would begin to participate actively in international astronomy.

6 NOTES

1. The *Peking Magazine*, a monthly journal that was established by William Alexander Parsons Martin and Joseph Edkins in August 1872, was devoted to Western and international news, but it also included articles on astronomy, geography and science in general (see Zhang, 1995).
2. The *Shen Bao*, formerly transliterated as the *Shun Pao* or the *Shen-pao*, and known in English as the *Shanghai News*, was a newspaper that was published in Shanghai from 30 April 1872 to 27 May 1949. The name is short for *Shenjiang Xinbao*, Shenjiang being a short form of Chunsheng jiang, the old name for the Huangpu River. This newspaper was founded by English businessman Ernest Major, and was one of the first modern Chinese newspapers. It played a pivotal role in the formation of public opinion in the late nineteenth century.
3. Astronomers recognize four distinct contacts that occur during a transit of Venus, and these are shown in Figure 3. There are two ingress contacts (1 and 2, in this Figure) and two egress contacts (3 and 4). Most critical in determining a value for the astronomical unit are the precise times of contacts 2 and 3. Observers widely spaced in latitude will see Venus cross the Sun on different (parallel) transects, as shown in Figure 3, and the angular separation of these transects is also critical in calculating the solar parallax and ultimately the astronomical unit.
4. The *Wan guo gong bao,* originally established as the *Church News* by the American Methodist missionary the Reverend Young John Allen of Georgia (Lin Lezhi), changed its name to *Wan Guo Gong Bao* (in English, *The Global Magazine or A Review of the Time)* with the 301st issue. Its subject matter ranged from discussions on the politics of Western nation-states to the virtues and advantages of Christianity.
5. The *Universal Circulating Herald* was established in Hong Kong on 4 February 1874 by Wang Tao, a famous political commentator of the time. The aim of this daily newspaper was to introduce early reformists' views.
6. In fact the start of the transit in Peking was just 1 minute later than predicted and the end just one minute earlier than predicted.
7. The *North China Herald* was also the gazette (official record) of the British Supreme Court for China and Japan, and the British Consulate. This newspaper was an influential force in Shanghai and throughout China.
8. The 6 April 1875 total solar eclipse was visible from Thailand (then referred to as Siam), and British and French expeditions led by Professor Arthur Schuster and Professor Jules Janssen respectively came to Thailand and successfully observed it (see Hutawarakorn-Kramer and Kramer, 2006; Launay, 2012). The presence of these eclipse expeditions was due to the enlightened views of King Rama V, who had a personal interest in astronomy, and he and other members of the Thai Royal Family also carried out systematic observations of this eclipse (see Soonthornthum, 2013). However, from an international perspective, this eclipse did not have the same importance as the 16 August 1868 total solar eclipse. Because of the introduction of spectroscopic observations, this earlier eclipse was a 'watershed event' in our understanding of prominences and of the solar corona (see Clerke, 1893; Orchiston et al., 2006). By good fortune, this total solar eclipse also was visible from Thailand (see Orchiston et al, 2013).
9. Comet C/1874 H1 (Coggia), popularly known as 'Coggia's Comet', was one of the Great Comets of the nineteen the century. It was a prominent naked eye object, and at its prime exhibited a spectacular head and tail whose changes helped to further our knowledge of cometary structure (see Guillemin, 1877).
10. These Chinese accounts of the 1874 transit of Venus are in marked contrast to the ways in which the 1874 and 1882 transits were depicted and promoted in most Western newspapers and magazines where the focus was very much on their scientific attributes and importance (see Cottam, 2012). For example, see Cottam et al., 2011 and 2012 for the ways in which these two transits were discussed in the *New York Times*.
11. The *Dian shi zhai hua bao*, an illustrated magazine, was established in 1884. It was attached to the *Shen Bao*, and was published every ten days. Every issue had 8 pages containing

recent news and associated pictures. In order to appeal to readers, some of the pictures and text tended to be exaggerated.

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8 REFERENCES

Chauvin, M., 2003. *Hōkūloa: The British 1874 Transit of Venus Expedition to Hawai'i*. Honolulu, Bishop Museum Press.

Chen chi, 1875. Unpublished letter to Wen Tingshi and Li Shengduo. Cited by Kong Xiangji, 2007. Discussion of Ronghong's promotion of American experience: taking the 1898 reform movement as a focus. *Social Science in Guangdong*, 1, 91-99 (in Chinese).

Chen Yijie, 2006. *The Diary of Weng Tonghe, Volume 3*. Beijing, Zhonghua Shuju (In Chinese).

Clerke, A.M., 1893. *A Popular History of Astronomy During the Nineteenth Century*. London, Adam and Charles Black.

Comstock, G.C., 1895. *Biographical Memoir of James Craig Watson*. Washington, National Academy of Sciences (*Biographical Memoirs*, III, 43-57).

Cottam, S., 2012. The Popularization of Astronomy in America Subsequent to the Events of the Transits of Venus of 1874 and 1882 and the Total Solar Eclipses of 1868, 1869 and 1878. Unpublished Ph.D. Thesis, Centre for Astronomy, James Cook University, Townsville, Australia.

Cottam, S., Orchiston, W., and Stephenson, F.R., 2011. The 1874 transit of Venus and the popularisation of astronomy in the USA as reflected in *The New York Times*. In Orchiston, W., Nakamura, T., and Strom, R.G. (eds.). *Highlighting the History of Astronomy in the Asia-Pacific Region. Proceedings of the ICOA-6 Conference*. New York, Springer. Pp. 225-241.

Cottam, S., Orchiston, W., and Stephenson, F.R., 2012. The 1882 transit of Venus and the popularisation of astronomy in the USA as reflected in *The New York Times*. *Journal of Astronomical History and Heritage*, 15, 183-199.

Dick, S., Orchiston, W., and Love, T., 1998. Simon Newcomb, William Harkness and the nineteenth century American transit of Venus expeditions. *Journal for the History of Astronomy*, 29, 221-255.

Duerbeck, H., 2007. De Photographen des Venusdurchgangs von 1874. *Acta Historica Astronomiae*, 33, 358-397.

Gui Lin, 1873. Sequel to the debate on astrology. *Peking Magazine*, October, pages 6-8 (in Chinese).

Guillemin, A., 1877. *The World of Comets*. London, Sampson Low, Marston, Searle and Rivington.

Hutawarakorn-Kramer, B., and Kramer, M., 2006. The King Rama V total solar eclipse of 1875: Schuster's expedition to Siam. In Chen, K.-Y., Orchiston, W., Soonthornthum, B., and Strom, R. (eds.). *Proceedings of the Fifth International Conference on Oriental Astronomy*. Chiang Mai, Chiang Mai University. Pp. 19-22.

Lankford, J., 1987. Photography and the 19th-century transits of Venus. *Technology and Culture*, 28, 648-657.

Lauga, J., 2004. Les missions Françaises pour le passage de Vénus de 1874. *L'Astronomie*, 118, 296-305.

Launay, F., 2012. *The Astronomer Jules Janssen*: *A Globetrotter of Celestial Physics*. New York, Springer.

Li Shanlan, 1873. Debate on astrology. *Peking Magazine*, July, page 3 (in Chinese).

Martin, W.A.P., 1873. Transit of Venus. *Peking Magazine*, October, pages 1-4 (in Chinese).

Martin, W.A.P., 1874a. A new star observed. *Peking Magazine*, November, page 49 (in Chinese).

Martin, W.A.P., 1874b. Another item of news from America. *Peking Magazine*, July, page 25 (in Chinese).

Martin, W.A.P., 1874c. Answer to the question of the time of the transit of Venus. *Peking Magazine*, November, page 50 (in Chinese).

Martin, W.A.P., 1874d. News from France – overseas observations of the transit of Venus. *Peking Magazine*, April, page 22 (in Chinese).

Martin, W.A.P., 1874e. News from Kyoto – observation of the transit of Venus. *Peking Magazine*, December, page 55 (in Chinese).

Martin, W.A.P., 1874f. Sequel to the transit of Venus. *Peking Magazine*, September, pages 11-12 (in Chinese).

Martin, W.A.P., 1875. Argument on astrology. *Peking Magazine*, January, pages 1-2 (in Chinese).

North China Herald, 14 January 1875, page 23 (in Chinese).

Orchiston, W., 2004. The nineteenth centry transits of Venus: an Australian and New Zealand overview. *Journal of Astronomical Data*, 10(7), 219-308.

Orchiston, W., Soonthornthuum, B., and Komonjinda, S., 2013. French observations of the 18 August 1868 total solar eclipse from Wah-Koa, Thailand. In Nakamura, T., and Orchiston, W. (eds.). *The Development of Astronomy and Emergence of Astrophysics in Asia*. New York, Springer (in press).

Orchiston, W., Chen, K.-Y., Lee, E.-H., and Ahn, Y.-S., 2006. British observations of the 1868 total solar eclipse from Guntoor, India. In Chen,

K.-Y., Orchiston, W., Soonthornthum, B., and Strom, R. (eds.). *Proceedings of the Fifth International Conference on Oriental Astronomy*. Chiang Mai, Chiang Mai University. Pp. 23-34.

Pigatto, L., and Zanini, V., 2001. Spectroscopic observations of the 1874 transit of Venus: the Italian party at Muddapur, eastern India. *Journal of Astronomical History and Heritage*, 4, 43-58.

Proctor, R., 1874. *Transit of Venus: A Popular Account of Past and Coming Transits*. London, Longmans, Green

Ratcliff, J., 2008. *The Transit of Venus Enterprise in Victorian Britain*. Pickering and Chatto.

Scherzer, F., 1875. A brief description of the transit of Venus observations by French astronomers. *Peking Magazine*, February, page 26 (In Chinese).

Sheehan, W., and Westfall, J., 2004. *The Transits of Venus*. New York, Prometheus Books.

Shen Bao, 30 July 1874(a), page 1 (in Chinese).

Shen Bao, 3 September 1874(b), page 1 (in Chinese).

Shen Bao, 18 November 1874(c), page 3 (in Chinese).

Shen Bao, 8 December 1874(d), page 1 (in Chinese).

Shen Bao, 12 December 1874(e), page 1 (in Chinese).

Shen Bao, 19 December 1874(f), page 1 (in Chinese).

Shen Bao, 20 December 1874(g), page 1 (in Chinese).

Shen Bao, 28 December 1874(h), page 1 (in Chinese).

Shen Bao, 7 February 1875, page 1 (in Chinese).

Soonthumthorn, B., 2013. The development of astronomy and emergence of astrophysics in Thailand. In Nakamura, T., and Orchiston, W. (eds.). *The Development of Astronomy and Emergence of Astrophysics in Asia*. New York, Springer (in press).

Woolf, H., 1959. *The Transits of Venus: A Study of Eighteenth Century Science.* Princeton, Princeton University Press.

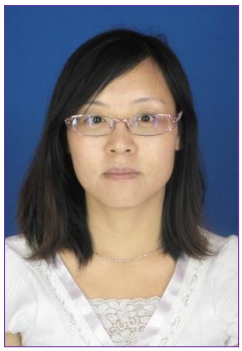
Yan Zhenheng, 1879. *Local Chronicles of Shimen County, Volume 11.* Shimen, Government of Shimen County (in Chinese).

Yiu Ruichang, 1875. After reading the article on astrology. *Peking Magazine*, August, page 20 (in Chinese).

Zhang Jian, 1995. A brief introduction of the *Peking Magazine*: evaluating its influence on the research of western Science and technology. *Journal of Fudan University (Social Science)*, 4, 57-62 (in Chinese).

Zuo Binglong, 1874. A brief description of the observation site. *Peking Magazine*, November, pages 14-16 (in Chinese).

Dr Lingfeng Lu is an Associate Professor of History of Science at the University of Science and Technology of China in Hefei, but for much of 2013 is a Visiting Professor at The Cluster of Excellence “Asia and Europe in a Global Context: The Dynamics of Transculturality” at Heidelberg University in Germany. His primary interest is in European astronomy in China and the history of Chinese astronomical observations.



Dr Huifang Li is a Postdoctoral Fellow in History of Science at the University of Science and Technology of China in Hefei. She received her Ph.D. in the history of science from Shanxi University (Taiyuan, China). Her main research field is astronomy in modern China.

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THE LIFE AND TIMES OF THE PARKES-TIDBINBILLA INTERFEROMETER

Ray P. Norris and M.J. Kesteven
CSIRO Astronomy & Space Science, PO Box 76, Epping,
N.S.W. 1710, Australia.
Emails: Ray.Norris@csiro.au; Michael.Kesteven@csiro.au

Abstract: The Parkes-Tidbinbilla took advantage of a real-time radio-link connecting the Parkes and Tidbinbilla antennas to form the world's longest real-time interferometer. Built on a minuscule budget, it was an extraordinarily successful instrument, generating some 24 journal papers including 3 *Nature* papers, as well as facilitating the early development of the Australia Telescope Compact Array. Here we describe its origins, construction, successes, and life cycle, and discuss the future use of single-baseline interferometers in the era of the Square Kilometre Array and its pathfinders.

Keywords: radio telescopes, interferometry, Parkes Radio Telescope, surveys, galaxies, radio continuum

1 INTRODUCTION

The Parkes-Tidbinbilla Interferometer (PTI) used the 64-m radio telescope at Parkes, New South Wales, together with the 70-m DSS43 antenna of the NASA Deep Space Network at the Canberra Deep Space Communication Complex (CDSCC) at Tidbinbilla. With a baseline of 275 km, it was the world's longest real-time interferometer, and operated at frequencies of 1.6, 2.3, 6.7, 8.4, and 12.2 GHz to give angular resolutions between 0.13 and 0.02 arcsec. Because of the large antennas, it also had a high sensitivity (rms ~0.2 mJy/beam in 5 minutes). The PTI was conceived as part of the development of the Australia Telescope Compact Array (ATCA) (Frater et al., 1992), both as a test-bed to tackle some of the technical challenges, and also to construct a reference frame of calibrators for the ATCA. It was successful in both these roles, but also proved to be a powerful astronomical instrument in its own right, offering a combination of high resolution, high sensitivity, and the practical advantage of real-time correlation and data processing.

At the time of its conception in 1983, the technique of Very Long Baseline Interferometry (VLBI) was being used to connect major radio telescopes around the world, including Parkes and Tidbinbilla (e.g. Preston et al. 1983), achieving milliarcsec resolution that could not be achieved with any other technique, yielding valuable insights into the astrophysics of galactic and extragalactic sources. However, the VLBI observations were technically challenging, recording data on to bandwidth-limiting video tapes that had to be synchronised to within a microsecond, and which did not yield any observational data until the tapes were correlated some weeks or months after the observations. As a result, while VLBI observations had great scientific value, they were generally limited to teams of 'black-belt' VLBI experts. The longest real-time radio interferometer in 1983 was the Manchester University's Multi-Element Radio-Linked Interferometer Network (MERLIN) with a maximum baseline of 127 km, and which, with a wider user base than VLBI, had made significant contributions to both Galactic and extragalactic science (e.g. see Booth et al., 1981; Browne et al., 1982).

The development of the PTI started in 1983 when a radio link was installed by NASA between Parkes and Tidbinbilla to facilitate the use of the two antennas to track the Voyager spacecraft on its flyby of Uranus. The Chief of the Division of Radiophysics, R.H. (Bob) Frater, asked for expressions of interest to use the link for astronomical purposes. On 19 February 1984 a "Preliminary Proposal" (Norris, 1984a) was submitted to construct a 'Parkes-Tidbinbilla Interferometer' at minimal cost. The proposal was evaluated, at the request of Bob Frater, by Alec Little, who supported it, resulting in a full proposal submitted in June 1984 (Norris, 1984b). John D. Murray agreed to build the one piece of necessary hardware, the coarse delay unit (at a total cost of ~AU$1k), and Mike Kesteven agreed to work with Norris on building the interferometer. This small team was later augmented by Kel Wellington and Mike Batty.

First fringes were obtained on the first day of observations in a limited mode (PTI Phase 1) in June 1985, and then the system was upgraded to use two 5 MHz bands (Phase 2) using the 1024-channel Parkes correlator. It was subsequently upgraded again (PTI Phase 3) in 1992 to use the new AT correlator.

2 DESIGN PRINCIPLES

A conventional interferometer typically brings together the signals from two antennas, translates them to a baseband frequency, and correlates them in a special-purpose correlator. In addition, a delay must be inserted into the signal path of one arm of the interferometer, to remove group delay and bring the wavefronts from the two antennas into synchronisation, and the phase of one arm must be rotated to remove

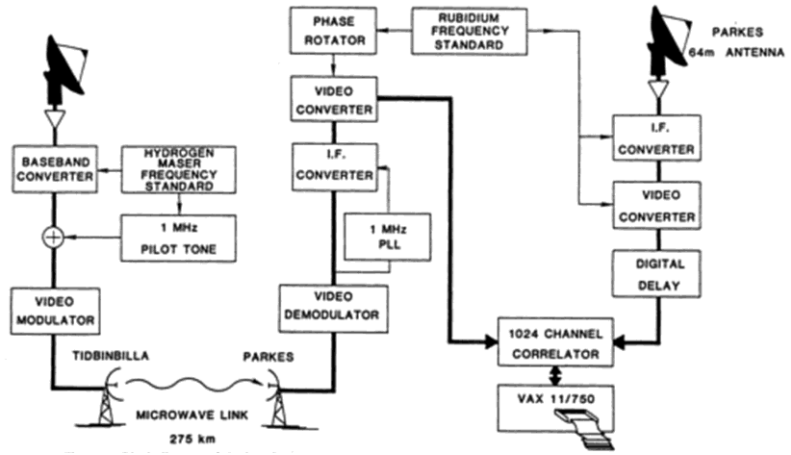

Figure 1: Block diagram of PTI Phase 1 (after Norris et al., 1985).

phase variations. Because of the rotation of the Earth, both phase and delay must be adjusted continuously, typically requiring special purpose hardware.

The goal of the PTI was to build an interferometer with as little specialised hardware as possible. It was called a 'software interferometer' because it used software for most of the functionality that would be provided by hardware in a traditional interferometer. It did so in three ways:

(1) The Correlator: The existing Parkes autocorrelation spectrometer (Ables et al., 1975) was used as a correlator. By measuring a full cross-correlation function[1] over many delay channels, and allowing the peak of the cross-correlation function to drift through the delay window of the spectrometer, most of the fine delay and phase corrections could be performed in software after correlation rather than in hardware before correlation. Only coarse phase and delay corrections, needed to prevent decorrelation during the integration time, needed to be applied before correlation.

(2) Delay Compensation: Because the cross-correlation function is allowed to drift through the delay window of the spectrometer, sufficient delay must be applied prior to correlation to keep the peak of the cross-correlation function within the delay window of the spectrometer. In PTI Phase 1 the delay could be changed very infrequently (e.g. once every 20 minutes) and so manual adjustment was sufficient. The increased bandwidth of later phases of the PTI required the delay to be changed once per integration (i.e. every few seconds), and so a computer-addressable delay was necessary. A delay unit to achieve this was the only special-purpose hardware that had to be constructed for the PTI.

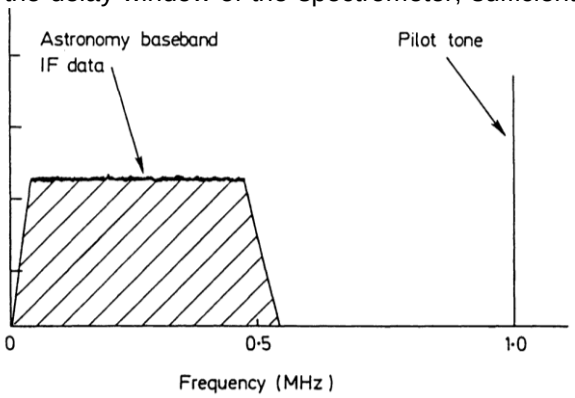

Figure 2: Spectrum of the signal sent from Tidbinbilla to Parkes in PTI Phase 1. The radio astronomy band occupies 0.5 MHz bandwidth, and a reference signal is inserted at 1 MHz to compensate for phase variations caused by instabilities in the radio link.

(3) Phase Rotation: Because the fine phase corrections were applied after correlation, the only phase rotation needed prior to correlation was the phase rate needed to prevent decorrelation during the integration. Over a period of one second, this phase rate is approximately constant, corresponding to a fixed frequency. The online software calculated the phase difference between the two signals from the two arms of the interferometer. Because this phase is changing at a typical rate of tens of Hz, the phase rotation was achieved by incorporating a programmable phase-continuous synthesiser into the local oscillator chain, and changing its frequency every second.

A further requirement is that the oscillators at the two antennas must be coherent. All local oscillators at Parkes were locked to a Rubidium frequency standard, while those at Tidbinbilla were locked to a Hydrogen Maser. The Parkes Rubidium oscillator limited the coherence time (i.e. the maximum interval between phase calibrators) to typically 10 minutes at 2.3 GHz.

In this and in several other respects, the techniques used by the PTI resembled those used in VLBI rather than those used in other real-time interferometers.

3 HISTORY

3.1 PTI Phase 1

PTI Phase 1 (Figure 1) was a proof-of-concept instrument built at very low cost. Although its bandwidth was only 0.5 MHz, the size of the antennas at each end (64m and 70m respectively) meant that its sensitivity was sufficient to do cutting-edge science. It had four novel features as follows:

(1) To remove arbitrary delay and phase variations that might occur in the radio link from Tidbinbilla to Parkes, a 1 MHz pilot signal was inserted into the astronomy signal at Tidbinbilla, and subsequently subtracted from the astronomical signal to cancel out phase variations

caused by the radio link (see Figure 2). Unknown to us, the radio link already had a phase compensation system, and so this part of the system turned out to be redundant, and was removed for PTI Phase 2.

To remove the phase changes caused by Earth rotation PTI used an off-the-shelf frequency synthesiser (a Rockland Model 5100, operating at about 1.25 MHz), whose frequency was updated every second. To prevent stochastic long-term drifts, the phase of this synthesiser was also set to zero at the end of each integration cycle time of 10s, causing phase steps which were then removed in software. Because frequency (and thus phase) changes could only be made at intervals of one second, the data also contained a residual phase error that varied slowly enough that it could be removed in software.

(2) To remove the changes in group delay caused by Earth rotation, together with the 1.3ms delay of the radio link from Tidbinbilla to Parkes, we performed a delay correction in three stages:

(a) A coarse delay unit with a minimum delay step size of 256 μs used a simple shift register to remove the bulk of this delay, and was typically adjusted by hand at the start of each scan (typically 20 minutes).

(b) The online software calculated the position of the peak of the cross-correlation function in the correlator, and transferred only 512 channels centred on that peak position, effectively shifting the cross-correlation function to remove the residual delay by an integral number of delay channels.

(c) The residual fine delay variations then appeared as a phase gradient across the frequency spectrum, which again could be removed in the online software by applying a phase gradient to the complex spectrum.

(3) Because telescope time on the two largest antennas in the Southern hemisphere was at a premium, we constructed a 'dummy telescope' to simulate every aspect of the PTI. A simulated noise spectrum could be injected into the spectrometer, and all the online and offline processing performed on these simulated data. The use of this simulator considerably speeded the debugging and commissioning of the interferometer.

After exhaustive testing and debugging using the dummy telescope, the PTI hardware and software were first connected to the real antennas on 27 June 1985, and fringes on the source 3C273 (shown in Figure 3) were obtained on that same day. Subsequent observations with PTI Phase 1 focussed on improving phase stability by understanding the phase variations introduced by the hardware, starting on the planned program of calibrator observations, and preparing for the higher bandwidth PTI Phase 2.

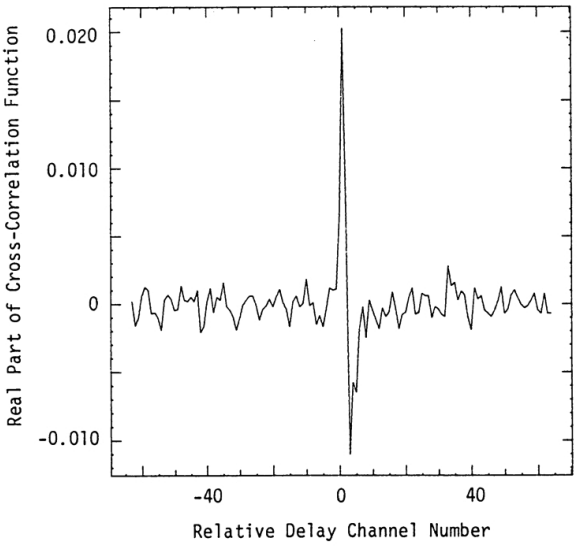

Figure 3: 'First fringes' recorded with the PTI on 27 June 1985, on the quasar 3C273. The plot shows the real part of the correlated power as a function of delay (after Norris et al., 1985).

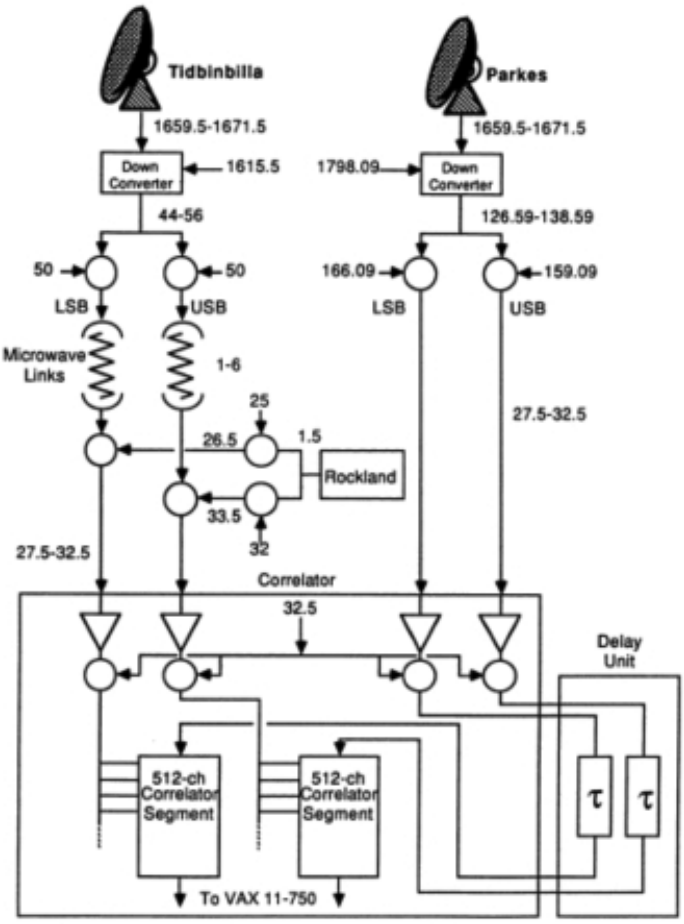

Figure 4: The block diagram of PTI Phase 2. The Parkes signal path uses the Standard Parkes frequency translators, although Marconi synthesisers rather than Systron Donners are necessary for phase stability.

Table 1: PTI Phase 2 Specifications

Baseline	275km
Available bandwidths	0.5, 1.0, 2.0, 5.0, 10.0 MHz
Frequency resolution	256 complex spectral channels
Operating frequency	1.7, 2.3, 8.4 GHz
Resolution (fringe spacing)	0.13, 0.09, 0.03 arcsec
Typical coherence time	15,10, 3 minutes
RMS sensitivity in a coherence time	1, 1.5, 3 mJy

3.2 PTI Phase 2

In 1986, PTI was upgraded to use two channels of 5 MHz each, providing a factor of 20 increase in bandwidth over PTI Phase 1 (see Figure 4). The resulting PTI Phase 2 (Norris, Kesteven, Wellington, and Batty, 1988) was in active operation from 1986 to 1993. The greater bandwidth required the correlator to use a faster sampling clock (10 MHz), which in turn meant that the delay space covered by the 500 channels of the correlator was only 50 μs. To keep the peak of the cross-correlation function within the correlator window, a new computer-addressable digital delay unit was built, enabling the delay to be adjusted every integration period (typically 5 seconds). However, the Rockland synthesiser continued to provide phase rotation.

At this time, arguably the most productive period of the PTI, the operational parameters were those shown in Table 1. At 1.7 GHz, the PTI achieved a sensitivity of 1 mJy in 15 minutes with a resolution of 0.13 arcsec. Longer effective integration times were achieved by switching against a phase-reference calibrator source, which could be as far as 5° away with no significant loss of phase (see Figure 5).

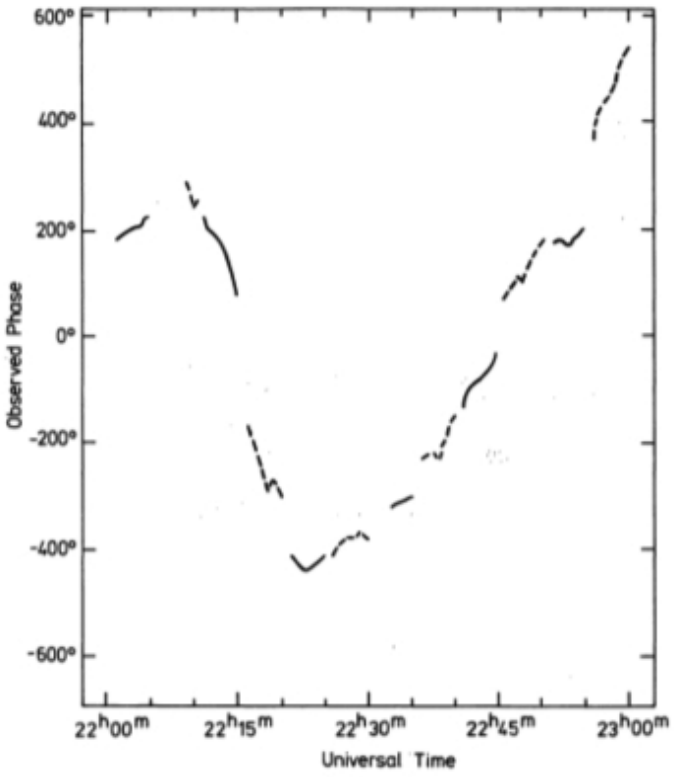

Figure 5: Plot of interferometer phase at 2.3 GHz as a function of time for unresolved calibrators (1414-189 and 0434-188) separated b y 5 degrees in the sky. The observed phase variations are caused by a combination of ionosphere and troposphere, and instability of the rubidium frequency standard used at Parkes.

PTI Phase 2 was used for a wide range of scientific work including pulsar proper motions, mapping of OH and methanol masers, searching for radio cores in quasars, active galaxies, and infrared galaxies.

3.3 PTI Phase 3

In 1992 a new correlator was installed at Parkes, making the PTI the only observing mode to require the old correlator. Upgrading the PTI to use the new correlator would mean that (a) the old correlator could then be scrapped, saving on maintenance, and (b) the PTI could benefit from the higher reliability and better performance (wider bandwidth, 2-bit sampling) of the new correlator. In June 1992 a proposal was submitted to upgrade the PTI (Norris, 1992) to use the new AT correlator. The upgrade was approved and in 1993/1994 the PTI was significantly revised (Norris, 1993) to use the new correlator, and at the same time a number of other changes were made to increase the sensitivity (by nearly a factor of 2), increase the versatility, and make it more user-friendly. The PTI continued to operate in this mode until about 1998, when the performance of VLBI recording systems overtook the capabilities of the PTI.

In PTI Phase 3, the IF signal from the Tidbinbilla antenna was converted to baseband at Tidbinbilla and limited to two bands of 0-8 MHz. At Parkes, the two baseband signals from Tidbinbilla were converted up to 8-16 MHz IF by a conversion chain that includes two programmable Stanford Research Systems frequency synthesisers operating at about 16 MHz. The frequency of these synthesisers was adjusted every second by the on-line software to provide the phase rotation. This process was restarted at the start of each scan, so that the absolute phase information was lost between scans, but was later reconstructed by the online software. The signal from Parkes was converted to two 8-16 MHz bands using a standard down-conversion scheme.

All four 8-16 MHz inputs from Parkes and Tidbinbilla were two-bit sampled, and then the Parkes signal was delayed by an amount equal to the geometric path difference between the

two signals. This delay was changed only once every integration, and the change in delay due to the Earth's motion during the 5-second integration time led to a small amount of decorrelation. The amount of this decorrelation was corrected offline (so that amplitude calibration was corrected), but obviously the lost signal-to-noise ratio could not be recovered.

4 SCIENCE

4.1 Overview

During its period of operation, some 24 journal papers, including 3 *Nature* papers (summarised in Table 2) were published based on PTI data, together with many conference papers. The PTI was also used as a real-time check for VLBI observations. In this section we discuss some of the science highlights.

4.2 SN1987A

SN 1987A, in the Large Magellanic Cloud, was discovered on 24 February 1987 (Kunkel et al., 1987) by Shelton and Duhalde at the Las Campanas Observatory in Chile, and by Jones in New Zealand. Easily visible to the naked eye, it was the closest observed supernova since SN 1604, and the nearest by far since the invention of radio astronomy. When news of it reached CSIRO on 25 February, Dick Manchester convened an urgent meeting of the Astrophysics Group to discuss what observations we should make. Since single-dish continuum observations would probably not have the sensitivity to detect it, there were three potential observing modes to make the historical first radio observations: (1) pulsars (championed by Manchester); (2) the Tidbinbilla short-baseline interferometer (championed by Jauncey), and (3) the recently-upgraded PTI (championed by Norris). It was decided that all three should observe it, with time on the antennas shared equally between them. We were also aware that the Sydney University group planned to observe it with the Molonglo Observatory Synthesis telescope (MOST).

Norris drove up to Parkes that evening while the Parkes staff ejected the scheduled observers and installed the 2.3 GHz receiver. Unfortunately, the receiver did not cool down until the next day, and so the first Parkes observations of SN1987A did not take place until 26 February. The PTI observations showed a detection within a few minutes of acquiring the source, giving us not only the flux density but also an upper limit on the size. The next day the flux density was measured with the PTI at 8.4 GHz, and the light-curve was followed over the next few days until it sank below the detection limit on 5 March. The results, together with the MOST observations, were then published in *Nature* (Turtle et al., 1987), showing both the time dependence and the spectral properties.

Scientifically, the results (Figure 6) were extremely important to our understanding of supernovae, since this was by far the most detailed and sensitive study of the radio properties of a supernova. It was also the first major paper to result from the PTI, establishing the role of the PTI as a cutting-edge instrument able to deliver significant scientific results.

4.3 Methanol Masers

Methanol masers were first discovered by Batrla et al. (1987) at 12.178 GHz. OH and H_2O masers had been used for many years to study star formation regions, but the discovery of the methanol masers, which were even stronger and just as widespread as the OH masers, seemed to herald an exciting new era of maser studies of star formation. Methanol masers had not been previously discovered because they lay well away from radio-astronomy bands, at a frequency which was swamped, in the US and Europe, by interference from TV broadcasting satellites.

Norris refereed the Batrla et al. paper, and wrote a short piece (Norris, 1987) emphasising the importance of their discovery. He also obtained the permission of Batrla et al. to propose observations of the masers with the Parkes Radio Telescope and the PTI prior to their paper appearing in *Nature*. Kel Wellington bought cheap consumer satellite TV receivers and mounted them on the Parkes and Tidbinbilla Radio Tele-

Table 2: PTI journal papers.*

Subject area	No. of papers	References
Instrumental	2	Norris et al., 1985; Norris, Kesteven, Wellington and Batty, 1988.
SN1987A	1 *Nature*	Turtle et al., 1987.
Masers	3 incl 1 *Nature*	McCutcheon et al., 1988; Norris, Caswell, Wellington, McCutcheon and Reynolds, 1988; Zijlstra et al., 2001.
Pulsar proper motions	3 incl. 1 *Nature*	Bailes et al., 1989; 1990a; 1990b.
Calibrators	1	Duncan et al., 1993.
Radio cores in AGN	14	Norris, Kesteven, Troup and Allen, 1988; Norris et al., 1990; Slee et al., 1990; Jones et al., 1994; Roy et al., 1994; Slee et al., 1994; Sadler et al., 1995; Morganti et al., 1997; Heisler et al., 1998; Roy et al., 1998; Kewley et al., 1999; Sadler, 1999; Kewley et al., 2000; Hill et al., 2001.

* This includes only peer-reviewed journal papers presenting PTI data, and excludes a number of conference papers

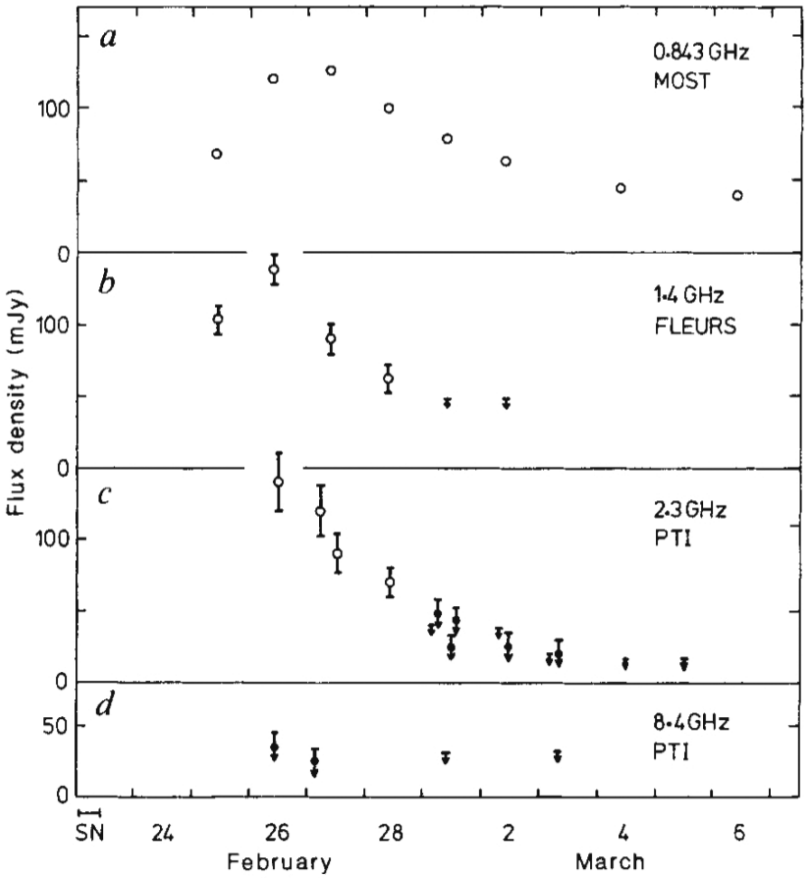

Figure 6: The radio flux of supernova SN1987A plotted as a function of time at four frequencies. The lower two plots show PTI data (after Turtle et al., 1987). This figure shows for the first time how the prompt radio emission from a supernova varied with time and frequency, placing stringent conditions on supernova models. It also confirmed that the emission was largely unresolved, and thus came from the core of the supernova rather than from a diffuse region which had been excited by the supernova.

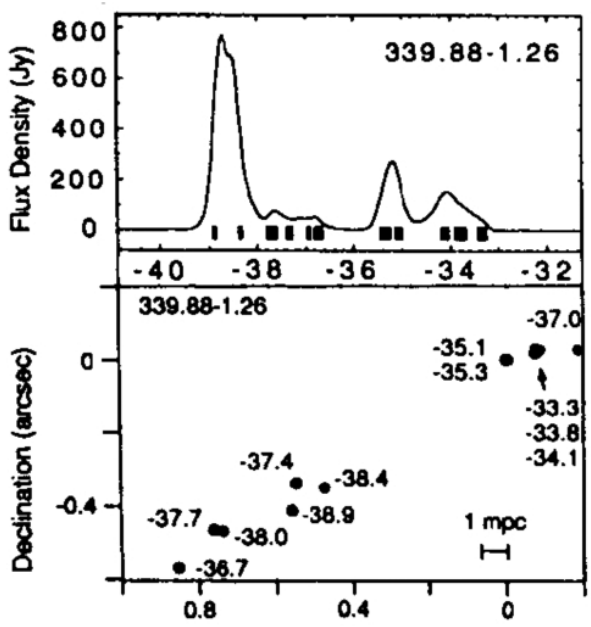

Figure 7: A PTI map of the 12.2 GHz methanol masers in the source G339.88-1.26 (after Norris, Kesteven, Troup and Allen, 1988). Top: the spectrum, with the horizontal axis showing the lsr velocity in km/s. Blocks mark the velocities of the masers mapped. Bottom: the map of the masers, shown as spots, with velocities in km/s marked against them. This map shows that the masers are arranged in a linear sequence, which subsequent observations have shown to be common in these masers, although the cause of this is still a matter of controversy.

scopes, and within four weeks of the *Nature* publication we had found that methanol masers were very common in star formation regions (Norris et al., 1987). A few months later the PTI observations showed that the masers were typically distributed over a few arcsec surrounding ultra-compact HII regions (Figure 7; McCutcheon et al., 1988; Norris, Kesteven, Troup and Allen, 1988). Those first PTI images were the source of significant anxiety because we were unsure of the sign of the phase, and an incorrect sign would cause the images to be inverted. Despite conducting many tests to check the phase polarity, we were still uncertain when the paper was submitted. Fortunately, the maps subsequently turned out to be correct.

We noted in our first paper that the methanol masers appeared to be in lines. Many authors have since confirmed this, although the cause of these lines is still a matter of dispute with both edge-on disks (Norris et al., 1998) and outflows (Walsh et al., 1998) being potential causes.

4.4 Pulsar Proper Motions

In 1988, the proper motions of 27 pulsars had been measured, showing the pulsars to have surprisingly high velocities, in some cases exceeding the escape velocity of our Galaxy. How-

ever, almost all these measurements had been made by one group (Lyne et al., 1982), using the same instrument and technique, and so it was important to make an independent check on these results. Furthermore, projecting the velocity vector backwards would enable the origin of the pulsar to be found, enabling us to check the assumption that their origin should lie at the centre of a supernova remnant (SNR).

Although the PTI could not measure absolute positions of sources, it could measure the position of a source relative to a nearby calibrator with great accuracy, and so could be used to make a direct measurement of pulsar proper motions. It could also measure parallax, enabling the distance to a pulsar to be measured independently of any model-dependent assumptions, testing the models used to estimate the distance to pulsars using the dispersion measure.

The first pulsar to be tackled with the PTI was the Vela Pulsar. It was one of only four pulsars known to be associated with a SNR, offering a rare chance to understand the relationship between pulsars and their progenitors. Bailes et al. (1989) used the PTI to measure its proper motion in a two-stage process. First, the PTI was used to observe potential phase reference calibrators near the Vela pulsar. The nearest suitable source was 40 arcmin away, so that the PTI had to be used in a switching mode with a 4-minute cycle, with 2 minutes on the pulsars followed by 2 minutes on the reference. Since NASA security precluded the Parkes observers from driving the Tidbinbilla antenna directly, this required that the Tidbinbilla operators manually switched the antenna every two minutes. Nevertheless, the technique was successful, and Bailes et al. measured the proper motion of the pulsar to an accuracy of 5 milliarcsec/year. Surprisingly, they showed that, although the pulsar was associated with the Vela SNR, it did not originate in the centre of the SNR, implying that the SNR had expanded asymmetrically since its birth.

The PTI was then used to measure the proper motions of six other pulsars. Again, a two-stage process was used, and in this case pulsars were chosen which had phase reference calibrators within the primary beam, removing the need for switching. The results (Figure 8) essentially confirmed the Lyne et al. result that pulsars are high-velocity objects migrating from the Galactic Plane (Bailes et al., 1990a). In one case, the proper motion showed that a pulsar did not originate from the centre of the SNR that had been assumed to be its progenitor, but may have come from a nearby young stellar cluster.

Finally, the PTI was used to measure the parallax of a pulsar to an accuracy of 0.3 milliarcsec (Bailes et al., 1990b), twice as accurate as any previous measurement, enabling an independent calibration of the pulsar distance scale that was based on dispersion measure.

4.5 Calibrators

A significant part of the initial justification for building the PTI was to construct a reference frame of calibrators for the ATCA. This program was the first to be started, by Norris and Kesteven, when the PTI commenced operations in 1985, and continued throughout the first few years of the PTI. As both Norris and Kesteven became heavily committed to the development of the ATCA, this project was taken over by Bob Duncan, who brought it to a successful conclusion eight years later (see Duncan et al., 1993).

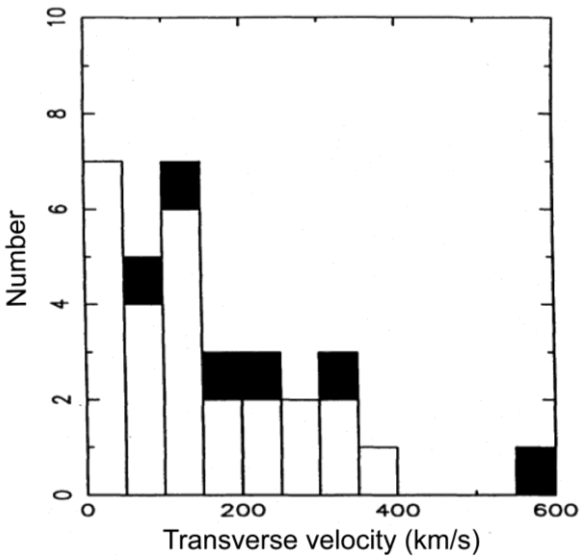

Figure 8: The distribution of transverse velocity of pulsars derived from PTI and other interferometric observations. (after Bailes et al., 1990a).

As well as identifying potential calibrators for the ATCA, this project had an unexpected astrophysical outcome. In 1985, several studies had indicated that flat-spectrum sources tended to be compact, but no definitive study of a large sample had been conducted at milliarcsec resolution. To construct a calibrator catalogue, the PTI was used to survey all sources from the the PKS survey (Bolton et al., 1979) with a spectrum flatter than –0.5, to identify those that were unresolved and therefore potentially good calibrators. The program was successful in identifying calibrators, but perhaps more importantly showed a clear correlation between spectral index and compactness, and with redshift (see Figure 9). This result was unexpected because the redshift range is sufficiently high that cosmic curvature causes the angular size of a standard ruler to be roughly independent of redshift. The PTI result therefore implied that there is a real evolutionary effect: in a flux-limited sample, radio-loud sources at high redshift are physically

smaller than low redshift sources. The reason for this is yet to be satisfactorily explained, but is presumably a result of cosmic evolution of radio-loud AGN.

4.6 Compact Cores in AGNs

Since AGNs have a much higher brightness temperature than star-forming (SF) galaxies (i.e. they can generate much strong radio emission from a small region of a given size), they are much more easily detectable with high-resolution instruments such as the PTI. Therefore, the PTI was a powerful tool for distinguishing whether radio sources were powered by AGN or SF activity. Although a non-detection would not necessarily rule out an AGN in any individual case, it should be possible to distinguish clearly between the powering mechanisms of samples of sources.

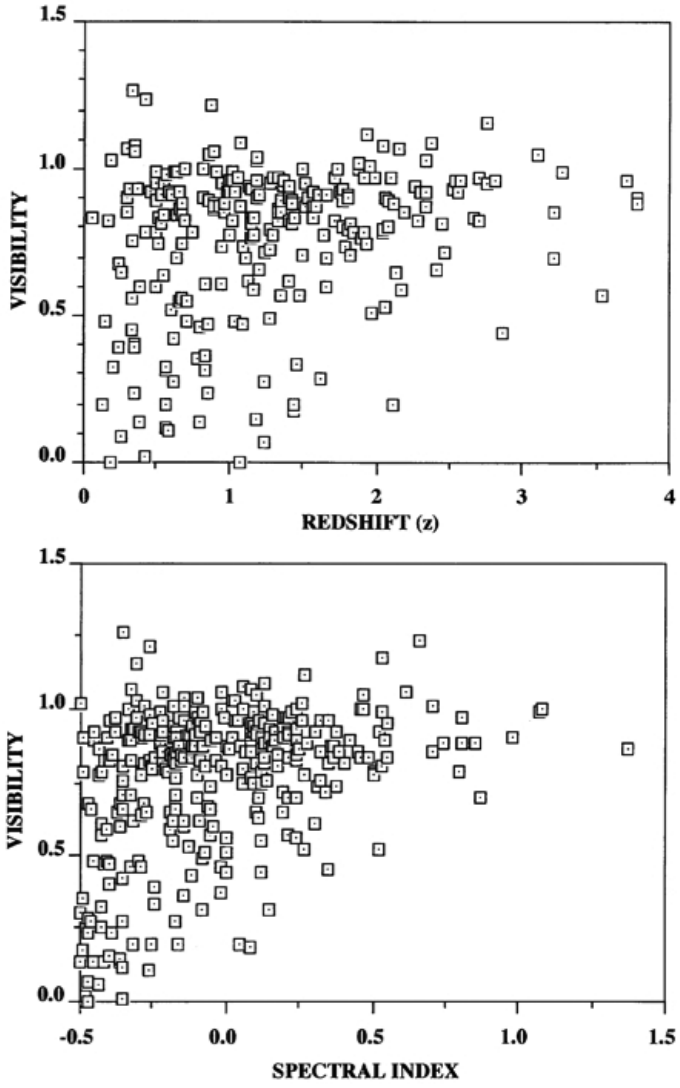

Figure 9 (Top): Visibility (defined as PTI flux/single-dish flux) of the putative calibrator sources as a function of redshift, showing that high-redshift objects tend to be more compact, from Duncan et al. (1993). Above z=1 the angular size of a standard ruler is approximately independent of distance, so this plot appears to show an evolutionary effect. Bottom: Visibility as a function of spectral index, showing that compactness increases with spectral index - the least compact sources tend to have steeper spectra.

As the PTI was first starting operation, several groups (Aaronson and Olszewski, 1984; Allen et al., 1985; Houck et al., 1985) had independently discovered that a number of bright IR sources, at that time named either ELF (Extremely Luminous FIR source) or ULIRG (Ultra-Luminous IR galaxy), had unexpectedly high luminosities, rivalling those of quasars. However, it was unclear whether they were powered by SF or AGN. These were therefore the first targets for the PTI compact-core work, and Norris, Kesteven, Troup and Allen (1988) and Norris et al. (1990) showed that while some contained obscured AGN, most did not, instead being powered primarily by SF activity.

Slee et al. (1990; 1994) used the same technique to examine a sample of optically-selected early-type galaxies with radio emission, and found radio cores similar to those seen in radio galaxies. While the PTI flux was strongly correlated with the Very Large Array core flux, it was only weakly correlated with any of the larger-scale indicators, at either radio or optical wavelengths. Surprisingly, sources with a weaker total power appeared to be more core-dominated. A similar result was obtained by Jones et al. (1994) who observed a sample of extended radio galaxies chosen from the Molonglo Reference Catalogue and found only a weak correlation between the PTI core power and the total power. These latter results supported the unified models (e.g. Padovani and Urry, 1990) in which the PTI core flux would be determined primarily by orientation, while large-scale emission would be independent of this. Sadler (1999) showed that the cores in bright elliptical galaxies are qualitatively similar to the central engines of radio galaxies but far less powerful, while those in spiral galaxies are qualitatively different, providing clues as to why radio galaxies are always ellipticals rather than spirals.

The unified model for Seyfert galaxies was tested by PTI observations of a large sample of Seyfert galaxies by Roy et al. (1994). Surprisingly, the PTI detection rate was significantly higher for Sy2 galaxies than for Sy1 galaxies, contrary to the prediction of the unified models, although the result was uncertain because of the small sample size. Sadler et al. (1995) extended this work by using the PTI at two frequencies to observe a heterogeneous sample of spiral galaxies, finding that those parsec-scale cores that were present tended to be steep-spectrum, in contrast to the flat-spectrum cores

seen in higher-power radio galaxies. Roy et al. (1998) subsequently observed a large sample of Seyferts with the PTI and found, surprisingly, that most followed the FIR-radio correlation (FRC), suggesting that while the radio cores were undoubtedly AGN, much of the radio emission from the Seyfert was generated by star-forming activity. For those galaxies which do not lie on the FRC, it was found that the difference between the total radio flux and the PTI core flux followed the FRC significantly better than the total radio flux, confirming that much of the radio emission was generated by SF. This result was confirmed in a different sample by Hill et al. (2001), who found that SF dominates the luminosity of composite galaxies, but that even a minor AGN contribution can be distinguished by optical spectroscopy.

Morganti et al. (1997) applied the PTI to a complete flux-density-limited sample of strong radio sources, and found that the PTI core flux is strongly correlated with the radio flux from the core region, but only weakly correlated with the total flux from the source. They also showed that the properties of the two Fanaroff-Riley types (Fanaroff and Riley, 1974) differed, suggesting that FRI cores are less strongly beamed than those in FRII galaxies. Their observations were broadly consistent with the unified model, but showed a number of complexities not reflected in the simplest models.

Heisler et al. (1998) used the PTI to observe a well-defined sample of IRAS galaxies with warm far-infrared colours and found that, contrary to expectations, none of those with SF optical spectrum contained a buried AGN, while those with AGN spectra appeared to represent nascent AGN growing in power on their way to becoming radio galaxies.

In all the work cited above it was assumed that the detection of a core signified an AGN. This was tested by Kewley et al. (1999; 2000) who combined PTI observations of an IR-selected sample of galaxies with spectroscopy and careful theoretical modelling. They showed that a clump of radio supernovae in a SF galaxy could generate a PTI detection, mimicking an AGN. However, the incidence of such radio supernovae is small, and the luminosities smaller than most AGN, so that in most cases a PTI detection can still be taken to imply an AGN.

5 THE PTI AND THE AUSTRALIA TELESCOPE COMPACT ARRAY

A primary motivation for building PTI was to help build a calibrator catalogue for the ATCA, and it clearly succeeded in that role. As noted above, its value in generating new science was probably even greater. However, its contribution to the construction and commissioning of the ATCA itself is, in hindsight, also significant.

First, it provided a hands-on focus for those who were given the job of designing the software for the ATCA. Without that, their role would have been to write memos for an interferometer whose commissioning date might be some years away. The PTI offered an opportunity to test the ideas and expertise in practice. Even now, software modules written for the PTI continue to be used as part of the ATCA software. For example, the RPFITS format, which is still used for ATCA data, was first developed for the PTI.

Second, it provided a valuable tool for commissioning and debugging the ATCA. For example, the first image produced by the ATCA (Norris et al., 1990) was generated in AIPS from uv data that had been manipulated, edited, and calibrated in the PTI data reduction program, PTILOOK.

6 CONCLUSION

It is surprising that the PTI was such a successful instrument, given its low budget and the fact that conventional VLBI techniques could, in principle, achieve many of the results obtained with the PTI.

We suggest the following factors were responsible for its success:

(1) A perception (not necessarily accurate) that VLBI could only be used by ‘black-belt VLBI gurus’, whilst the PTI could be used by anyone. This positive perception of the PTI was helped by a user manual that guided the user through all observing and data reduction steps, and a dummy telescope so that users could practice on dummy data prior to making their observations.

(2) Real-time results encouraged large surveys of many sources with short observations on each. In principle, VLBI could also be used in this mode, but in practice rarely was, perhaps because of a fear that a complicated schedule might cause errors that would not be detected until correlation took place, perhaps months later.

(3) Real-time results encouraged rapid publication. The data were usually reduced while the astronomers were still observing, and the first drafts of some of the observational PTI papers cited here were generated during the observations, while the observers were still engaged and motivated. While this can happen in other branches of astronomy, it is not, of course, possible with VLBI.

The PTI was a specialised instrument, unable to produce images, but capable of doing

one job very well: measuring complex visibilities on a long baseline with high sensitivity. While of limited value for studying individual sources, such instruments are of enormous value for studying large samples of sources.

The Square Kilometre Array and its path-finders such as ASKAP (Johnston et al., 2008) will produce catalogs of millions of sources, for which VLBI imaging will be impossible given realistic telescope time allocations. A next-generation single-baseline instrument could be built using ASKAP and the Parkes antenna equipped with a phased-array feed. With a GHz bandwidth, this interferometer would be able to survey tens of millions of sources in a few months, to μJy sensitivities. Such an instrument would be a powerful resource for identifying which populations of galaxies contained AGN. We predict that the era of single baseline interferometers is far from over.

7 NOTES

1. The fundamentals of radio interferometers are described by Thompson et al. (2001). A wavefront from the celestial source reaches the correlator by two paths of different lengths, one through each of the two antennas. Because of the difference in path length, one signal must be delayed relative to the other to align the wavefronts. In the PTI, the correlator is used to progressively delay one signal relative to the other in a number of small steps, and the two signals are multiplied at each of these delay steps. The resulting product, the cross-correlation function, is thus measured as a function of delay, as shown in Figure 3. Hardware limitations restrict the number of possible delay steps, resulting in a finite delay range (the 'window') over which the cross-correlation function can be measured.

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8 REFERENCES

Aaronson, M., and Olszewski, E.W., 1984. Optical counterparts of unidentified IRAS point sources Infrared luminous galaxies. *Nature*, 309, 414-417.

Ables, J.G., Cooper, B.F.C., Hunt, A.J., Moorey, G.G., and Brooks, J.W., 1975. A 1024-channel digital correlator. *Review of Scientific Instruments*, 46, 284-295.

Allen, D.A., Roche, P F., and Norris, R.P., 1985. Faint IRAS galaxies - a new species in the extragalactic zoo. *Monthly Notices of the Royal Astronomical Society*, 213, 67P-74P.

Bailes, M., Manchester, R.N., Kesteven, M.J., Norris, R.P., and Reynolds, J., 1989. The proper motion of the VELA pulsar. *Astrophysical Journal*, 343, L53-L55.

Bailes, M., Manchester, R.N., Kesteven, M.J., Norris, R.P., and Reynolds, J.E., 1990a. The proper-motion of six southern radio pulsars. *Monthly Notices of the Royal Astronomical Society*, 247, 322-326.

Bailes, M., Manchester, R.N., Kesteven, M.J., Norris, R.P., and Reynolds, J.E., 1990b. The parallax and proper motion of PSR1451-68. *Nature*, 343, 240-241.

Batrla, W., Matthews, H.E., Menten, K.M., and Walmsley, C.M., 1987. Detection of strong methanol masers towards galactic H II regions. *Nature*, 326, 49-51.

Bolton, J.G., Savage, A., and Wright, A.E. 1979. The Parkes 2700-MHZ Survey - part fourteen - catalogue and new optical identifications. *Australian Journal of Physics Astrophysical Supplement*, 46.

Booth, R.S., Norris, R.P., Porter, N.D., & Kus, A.J., 1981. Observations of a circumstellar shell around the OH/IR star OH127.8-0.0. *Nature*, 290, 382-384.

Browne, I.W.A., Clark, R.R., Moore, P.K., et al. 1982. MERLIN observations of superluminal radio sources. *Nature*, 299, 788-793.

Duncan, R.A., White, G.L., Wark, R., et al., 1993. A survey of 526 southern flat spectrum radio sources with the Parkes/Tidbinbilla Interferometer. *Publications of the Astronomical Society of Australia*, 10, 310-319.

Fanaroff, B.L., and Riley, J.M., 1974. The morphology of extragalactic radio sources of high and low luminosity. *Monthly Notices of the Royal Astronomical Society*, 167, 31P-36P.

Frater, R.H., Brooks, J.W., and Whiteoak, J.B., 1992. The Australia Telescope – overview. *Journal of Electrical and Electronics Engineering Australia*, 12, 103-112.

Heisler, C.A., Norris, R.P., Jauncey, D.L., Reynolds, J.E., and King, E.A., 1998. Compact radio emission in 60-μm peaker galaxies. *Monthly Notices of the Royal Astronomical Society*, 300, 1111-1118.

Hill, T.L., Heisler, C.A., Norris, R.P., Reynolds, J.E., and Hunstead, R.W., 2001. Starburst or Seyfert? Adding a radio and far-infrared perspective to the investigation of activity in composite galaxies. *Astronomical Journal*, 121, 128-139.

Houck, J.R., Schneider, D.P., Danielson, G.E., et al., 1985. Unidentified IRAS sources – ultra-high-luminosity galaxies. *Astrophysical Journal*, 290, L5-L8.

Johnston, S., et al., 2008. Science with ASKAP The Australian square-kilometre-array pathfinder. *Experimental Astronomy*, 22, 151-273.

Jones, P.A., McAdam, W.B., and Reynolds, J.E., 1994. Compact radio cores in radio galaxies. *Monthly Notices of the Royal Astronomical Society*, 268, 602-608.

Kewley, L.J., Heisler, C.A., Dopita, M.A., and Norris, R.P., 1999. The AGN/starburst connection in luminous infrared galaxies. *Astrophysics & Space Science*, 266, 131-136.

Kewley, L.J., Heisler, C.A., Dopita, M.A., et al., 2000. Compact radio emission from warm infrared galaxies. *Astrophysical Journal*, 530, 704-718.

Kunkel, W., Madore, B., Shelton, I., et al., 1987. Supernova 1987A in the Large Magellanic Cloud. IAU Circular, 4316, 1.

Lyne, A.G., Anderson, B., and Salter, M.J., 1982. The proper motions of 26 pulsars. *Monthly Notices of the Royal Astronomical Society*, 201, 503-520.

McCutcheon, W.H., Wellington, K.J., Norris, R.P., et al., 1988. Milliarcsecond observations of 12 GHz methanol masers. *Astrophysical Journal*, 333, L79-L82.

Morganti, R., Oosterloo, T.A., Reynolds, J.E., Tadhunter, C.N., and Migenes, V., 1997. A study of cores in a complete sample of radio sources. *Monthly Notices of the Royal Astronomical Society*, 284, 541-551.

Norris, R.P., 1984a. A Preliminary Proposal for a Parkes-Tidbinbilla Interferometer. AT Technical memo.

Norris, R.P., 1984b. A Proposal for a Parkes-Tidbinbilla Interferometer. AT Technical memo AT/20.1.1/002.

Norris, R.P., 1987. A new signpost in the sky. *Nature*, 326, 12.

Norris, R.P., 1992. “Proposed Upgrade to the Parkes-Tidbinbilla Interferometer.” 13 June 1992.

Norris, R.P., 1993. AT Technical memo AT/42.1.2/003.

Norris, R.P., Batty, M.J., Kesteven, M.J., and Wellington, K.J., 1985. The Parkes-Tibdinbilla interferometer. *Publications of the Astronomical Society of Australia*, 6, 137-140.

Norris, R.P., Caswell, J.L., Gardner, F.F., and Wellington, K.J., 1987. Widespread strong methanol masers near H II regions. *Astrophysical Journal*, 321, L159-L162.

Norris, R.P., Kesteven, M.J., Troup, E., and Allen, D.A., 1988. Compact radio cores in infrared galaxies. *Monthly Notices of the Royal Astronomical Society*, 234, 51P-55P.

Norris, R.P., Kesteven, M.J., Wellington, K.J., and Batty, M.J., 1988. The Parkes-Tidbinbilla interferometer. *Astrophysical Journal Supplement*, 67, 85-91.

Norris, R.P., Caswell, J.L., Wellington, K.J., McCutcheon, W.H., and Reynolds, J.E., 1988. Milliarcsecond maps of 12 GHz methanol masers. *Nature*, 335, 149-151.

Norris, R.P., Kesteven, M.J., Troup, E.R., Allen, D.A., and Sramek, R.A., 1990. Compact radio cores in extremely luminous far-infrared galaxies. *Astrophysical Journal*, 359, 291-295.

Norris, R.P., Kesteven, M.J., Sramek, R.A., et al., 1990. 2152-69 - the first image from the Australia Telescope. *Publications of the Astronomical Society of Australia*, 8, 252-253.

Norris, R.P., Byleveld, S.E., Diamond, P.J., et al., 1998. Methanol masers as tracers of circumstellar disks. *Astrophysical Journal*, 508, 275-285.

Padovani, P., and Urry, C.M., 1990. Fanaroff-Riley I galaxies as the parent population of BL Lacertae objects. I - X-ray constraints, *Astrophysical Journal*, 356, 75-82.

Preston, R.A., Wehrle, A.E., Morabito, D.D., et al., 1983. VLBI observations of the nucleus of Centaurus A. *Astrophysical Journal*, 266, L93-L96.

Roy, A.L., Norris, R.P., Kesteven, M.J., Troup, E.R., and Reynolds, J.E., 1994. Compact radio cores in Seyfert galaxies. *Astrophysical Journal*, 432, 496-507.

Roy, A.L., Norris, R.P., Kesteven, M.J., Troup, E.R., and Reynolds, J.E., 1998. Seyfert galaxies and the radio-far-infrared correlation. *Monthly Notices of the Royal Astronomical Society*, 301, 1019-1030.

Sadler, E.M., Slee, O.B., Reynolds, J.E., and Roy, A.L., 1995. Parsec-scale radio cores in spiral galaxies. *Monthly Notices of the Royal Astronomical Society*, 276, 1373-1381.

Sadler, E.M., 1999. Activity in elliptical galaxies, *Advances in Space Research*, 23, 823-832.

Slee, O.B., White, G.L., Reynolds, J.E., and Caganoff, S., 1990. Long-baseline interferometry of a complete southern sample of early-type galaxies. *Astrophysical Letters and Communications*, 27, 361-372.

Slee, O.B., Sadler, E.M., Reynolds, J.E., and Ekers, R.D., 1994. Parsecscale radio cores in early type galaxies. *Monthly Notices of the Royal Astronomical Society*, 269, 928-946.

Thompson, A.R., Moran, J.M., and Swenson, G.W., 2001. *Interferometry and Synthesis in Radio Astronomy*. New York, Wiley.

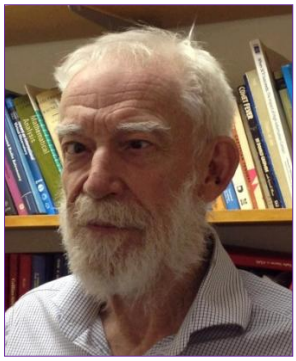
Turtle, A.J., Campbell-Wilson, D., Bunton, J.D., et al., 1987. A prompt radio burst from supernova 1987A in the Large Magellanic Cloud. *Nature*, 327, 38-40.

Walsh, A.J., Burton, M.G., Hyland, A.R., and Robinson, G., 1998. Studies of ultracompact HII regions - II. High-resolution radio continuum and methanol maser survey. *Monthly Notices of the Royal Astronomical Society,* 301, 640-698.

Zijlstra, A.A., Chapman, J.M., te Lintel Hekkert,

P., et al., 2001. Bipolar outflows in OH/IR stars. *Monthly Notices of the Royal Astronomical Society*, 322, 280-308.

Professor Ray Norris is a Chief Research Scientist at CSIRO Astronomy & Space Science in Sydney, Australia. His main research field is the use of large radio surveys to understand the evolution of galaxies over cosmic time. He leads the Evolutionary Map of the Universe (EMU) project, which is one of the two key science projects driving the design and construction of the new $165m Australian Square Kilometre Array Pathfinder telescope in Western Australia. He also studies the astronomy of Indigenous Australians, and is an Adjunct Professor at Warawara (the Department of Indigenous Studies) at Macquarie University in Sydney. As well as his research papers, he has authored a book on Aboriginal astronomy (*Emu Dreaming*) and a novel (*Graven Images*).



Dr Michael Kesteven is a Senior Principal Research Scientist at CSIRO Astronomy & Space Science in Sydney, Australia. His main research fields are antenna metrology, telescope systems, radio frequency interference mitigation, and the study of supernova remnants. He is also the Antenna Project Scientist for the new $165m Australian Square Kilometre Array Pathfinder telescope in Western Australia.

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ALBRECHT UNSÖLD: HIS ROLE IN THE INTERPRETATION OF THE ORIGIN OF COSMIC RADIO EMISSION AND IN THE BEGINNING OF RADIO ASTRONOMY IN GERMANY

Richard Wielebinski
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69,
53121 Bonn, Germany.
Email: rwielebinski@mpifr.de

Abstract: Albrecht Unsöld's career spanned over 50 years at the beginning of the 20th century. In this period atomic physics made great advances and Unsöld applied this to astrophysical questions. He came in contact with the early radio astronomy observations and devoted part of his career to the interpretation of the origin of cosmic radio waves. Although hampered by the post-war situation, Unsöld's contributions to the interpretation of cosmic radio waves were important.

Keywords: Albrecht Unsöld, radio astronomy, emission processes, Germany

1 INTRODUCTION

Albrecht Unsöld (Figure 1) was born on 20 April 1905 in Bohlheim (Württenberg), and died on 23 September 1995 in Kiel. Already as a 14-year-old, Unsöld began correspondence with Arnold Sommerfeld (1868–1951; Figure 2), the Professor of Physics in Munich, after reading his book *Atombau und Spektrallinien.* Unsöld studied first in Tübingen and later went on to complete his doctoral degree under Sommerfeld in Munich. This was an exciting time in physics with Schrödinger's wave mechanics, the Bohr-Sommerfeld atomic model and Heisenberg's quantum mechanics making great advances in the development of physics. Unsöld was awarded his doctorate in 1927 (at the age of 21) for a dissertation titled *Beiträge zur Quantenmechan-ik der Atome*.

The earliest papers by Unsöld deal with the interpretation of spectral lines observed in the Sun. Following his doctoral thesis Unsöld received a Rockefeller Foundation Fellowship and carried out spectral work at Mount Wilson Observatory using the 100-in telescope. Unsöld returned to Munich to complete his 'Habilitation' thesis, that was needed for an appointment in a German university. He spent a brief period from 1930 to 1932 at Hamburg Observatory (Figure 3) where he came in contact with Walter Baade (1893–1960).

In 1932 Unsöld was appointed to the Chair of Theoretical Physics at the University of Kiel, at the age of only 26. With this appointment he initiated a very successful study of stellar atmospheres in Kiel, which continued under his lifelong direction. His seminal book *Physik der Sternatmosphären (mit besonderer Berücksichtigung der Sonne)* (Unsöld, 1938) dealt with stellar atmospheres and became a classic in this research area. Unsöld developed good contacts with colleagues in the USA, that led to a Visiting Professorship in Chicago in 1939. While at the Yerkes Observatory and working with Otto

Figure 1: Albrecht Unsöld (techniklexikon.net).

Figure 2: Arnold Sommerfeld (en.wikipedia.org).

Figure 3: Hamburg Observatory (eso.org).

Struve (1897–1963), Unsöld took spectra of the BO star τ Scorpii at the McDonald Observatory.

During his visit to the Yerkes Observatory Unsöld became aware of the radio observations of Karl Jansky (1905–1950). He also received information about the early radio observations of Grote Reber (1911–2002), and immediately realised the close connection between the observed radio waves and his research on stellar atmospheres.

The origin of the radio emission observed by Jansky and Reber at first eluded interpretation. The few theoretical discussions at this time centred on a possible thermal (free-free) interpretation. This was also the interpretation that Unsöld first took. Unsöld concentrated his attention on the questions of intensity calibration of the observed cosmic radio waves, which led to the realisation that very high thermal temperatures would be necessary for the thermal interpretation. Soon the idea was born that an 'Ultrastrahlung' (ultra radiation) was needed to explain the observational radio results.

This 'Ultrastrahlung' was proposed by Unsöld to be emitted by energetic particles in magnetic fields. Unsöld did not become involved in details of emission theories, instead accepting the classical work of George Adolphus Schott (1868–1937) as a basis for the interpretation of emission from relativistic particles in magnetic fields (Schott, 1912). Unsöld worried instead for a long time about the origin of energetic particles. He knew that magnetic fields were present in sunspots as a result of the Zeeman Effect that was detected in 1908 by George Ellery Hale (1868–1938). Unsöld proposed that the origin of the cosmic radio emission was by the 'magnetic bremsstrahlung' process, and was similar to the emission seen in 'betatrons'. This later became the standard interpretation, under the name of 'synchrotron emission'.

Figure 4: The 100-in Hooker Telescope at Mt Wilson Observatory (www.mtwilson.edu).

Some historical details of Unsöld's work have been discussed by Jesse Greenstein in Sullivan (1984). Also Sullivan (2009) investigates the impact of Unsöld's work in detail. In a monograph recently edited by Gudrun Wolfschmidt two related contributions are found: one about the life and letters of Albrecht Unsöld, by Weidemann (2011), and a second one about his research on stellar atmospheres, by Baschek (2011). In the present paper my investigation will cover Unsöld's published papers that deal with the origin of cosmic radio waves. But first, a short description of Unsöld's early work on stellar atmospheres, which led to his interest in radio astronomy, will be presented. The work of other 'players', astrophysicists and physicists, who were involved in the hunt for an interpretation of cosmic radio waves only will be included if they affected the development of Unsöld's research. Unsöld's venture into observational radio astronomy at Kiel University also will be described since this had a significant impact on the establishment of observational radio astronomy in Germany.

2 THE EARLY WORK

Unsöld's earliest work concentrated on the application of the new atomic theory to the interpretation of spectral emission lines in stars. Early papers (e.g. Unsöld, 1926; 1927) concentrate on the derivation of the spectrum of hydrogen, based on atomic theory. During a Rockefeller Foundation Fellowship, following completion of his doctoral thesis, Unsöld used the Mount Wilson 100-in telescope (Figure 4) for spectral line observations. He then returned to Munich to complete his Habilitation thesis, a 'must' for a future university appointment in Germany. The thesis, *Über die Balmer-Serie des Wasserstoffs im Sonnenspektrum*, was a masterpiece that combined atomic theory and observational details. In the following years Unsöld expanded this work by taking into consideration radiation transfer and quantum mechanical line width broadening due to collisional damping and electric fields (the Stark Effect). In this era Unsöld laid the basis for the quantitative analysis of stellar spectra, in particular the determin-

ation of the abundance of elements in stellar atmospheres.

Starting his investigations with the hydrogen line spectrum, Unsöld developed similar procedures for other elements, e.g. calcium (Unsöld et al., 1930) and helium (Unsöld, 1931). At this time Unsöld's (1936) interests shifted to the theory of solar emission, and to the abundance of elements in stars. Unsöld was also involved in writing his seminal book *Physik der Sternatmosphären (mit besonderer Berücksichtigung der Sonne)* (Unsöld, 1938). This book saw several editions (e.g. 1955, 1968) and became a standard work, with over 1000 citations. In 1939 Unsöld was invited by Otto Struve (Figure 5) to accept a Visiting Professorship at the University of Chicago. He spent most of the time taking spectra of the B0 star τ Scorpii at the recently-completed McDonald Observatory. Upon his return to Germany WWII broke out and Unsöld was required to work in a weather office, but he continued to analyse his observations, which led to several important publications (Unsöld, 1942a; 1942b; 1942c; 1944). As a result of his visit to Yerkes Observatory, and with his background in stellar atmospheres research, Unsöld became involved in the quest to interpret the origin of the recently-discovered cosmic radio waves.

3 CONNECTIONS TO EARLY RADIO ASTRONOMY

The serendipitous discovery of cosmic radio waves by Karl Jansky (1932; 1933; Figure 6) was made at a low radio frequency, around 20 MHz. In the USA Fred Lawrence Whipple (1906–2004) and Jesse Leonard Greenstein (1909–2002) became interested in this monumental discovery. A paper by Whipple and Greenstein (1937) discussed 'interstellar radio disturbances' from the physicist's point of view, and gave arguments about what the cosmic radiation could *not* be. Stellar origin was excluded as well as secondary radiation in the Earth's atmosphere. Later in this paper an attempt was made to interpret the observed radio waves as thermal emission from interstellar dust. Their major conclusion was that *"...* the black-body radiation theory failed to account for Jansky's observations by a factor of 10^4 in the most favourable case." (Whipple and Greenstein, 1937: 181).

Following Jansky, a publication by Grote Reber (1940; Figure 7) reported observations at the much higher frequency of 162 MHz. Reber also made test observations at 3300 MHz but failed to detect any emission.

The next discussion about the possible origin of cosmic radio waves was by Louis G. Henyey (1910–1970) and Philip C. Keenan (1908–2000), who gave an account of the intensities expected from free-free emission of hydrogen. Although

Figure 5: Otto Struve (astron.kharkov.ua).

they suggested that this may be the process responsible for the observed radio waves, Henyey and Keenan (1940) thought that the intensity values published by Jansky were too high. At that time interest in cosmic radio waves was not very great within the astronomical community, so Henyey and Keenan's 1940 paper was only cited 19 times (see ADS) while a 1941 paper by Henyey and Greenstein, about diffuse optical emission in our Galaxy, received 743 citations.

Unsöld started his investigations based on the data available to him in 1940, and at first tried to use the free-free emission process to explain the radio observations. In 1944 he submitted a paper to the German journal *Die Naturwissenschaften*, but this only was published after the war. In this paper Unsöld (1946) recalculated in detail the free-free emission mechanism that was dealt with by Henyey and Keenan, proved their physical arguments to be correct and agreed that this may explain cosmic radio emission.

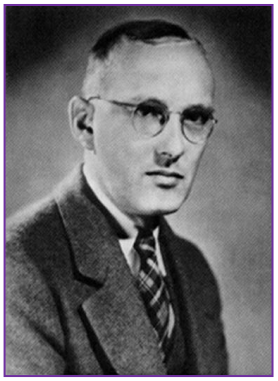

Figure 6 (left): Karl Jansky (members.westnet.com.au).
Figure 7 (right): Grote Reber (nrao.edu).

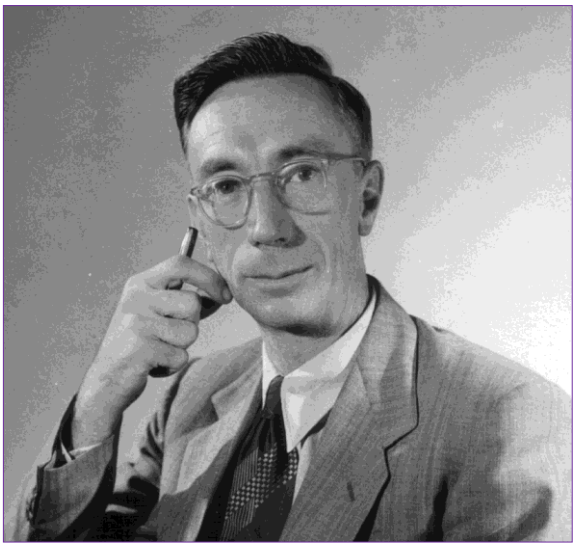

Figure 8: Joseph Pawsey (courtesy: CSIRO Astronomy and Space Sciences).

One of the problems that Unsöld discovered in Reber's 1940 paper was that the beam (hence the intensity calibration) was based on "... a cone of acceptance of 3°." (Unsöld, 1946: 37; my English translation). This obviously was wrong for a 31.4-ft dish operating at 160 MHz. Unsöld had contacts with Kurt Fränz (1912–2002), an engineer with the Telefunken Company, who actually repeated some of the Jansky observations at 30 MHz in Germany (Fränz, 1942). Unsöld and Fränz discussed the intensity definitions for radio emission used by Reber and Jansky, and Unsöld became worried about the differing intensity units used by the various authors: microvolt/meter by the engineers and ergs/sec/cm^2/kc by the physicists. Unsöld suggested that using the Rayleigh-Jeans approximation would lead to 'Rauschtemperatur *T*' (the effective temperature), as used in radio astronomy today. This was an important step forward, allowing clear spectral derivations. Fränz also suggested that Reber's beamwidth should have been ~12°, which was in agreement with antenna theory. Hence the intensity calibration may have been in error. The beamwidth was actually corrected by Reber in his important 1944 survey paper to 6° × 8°, still an over-estimate, but this information did not reach Unsöld at the time.

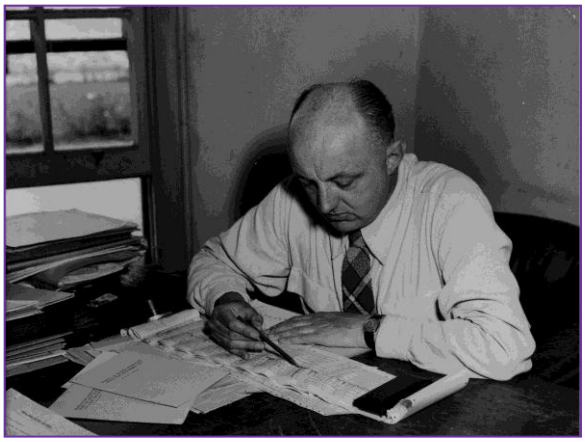

Figure 9: David Martyn (courtesy: CSIRO Astronomy and Space Sciences).

In his 1946 paper Unsöld also suggested that Reber's claim to have detected the Andromeda Nebula was plausible, given its basic similarity to our own Galaxy. However Unsöld was unaware that solar radio emission had already been recorded (see Sullivan, 2009: 79-99), and he pointed out that it should exist, although the editor of the journal added a note stating that solar radio emission had by then been detected. The final paragraph in Unsöld's paper is devoted to suggesting that this may "... for some people be the fulfilment of a dream of interstellar communication while for the physicists it is a love game of electrons and protons." (Unsöld, 1946: 40; my English translation).

During the war the Kiel University astronomical observatory and Unsöld's home was destroyed by bombs, so Unsöld found accommodation with Werner Kroebel (1904–2001), who later became the Professor of Experimental Physics at Kiel and Unsöld's close associate in developing radio astronomical observations (see Weidemann, 2011). After the war Unsöld was appointed by the British military administration as the Dean of the Faculty of Arts and Humanities at Kiel University and entrusted with the reconstruction of the 'Institute for Theoretical Physics and Astronomical Observation'. In spite of his administrative work Unsöld continued active research, but at first he did not have access to recent journals—an unfortunate result of the post-war destruction. Also, the papers written by Unsöld at this time did not reach the wider astrophysical community since they were available only in the German language.

A claim that German radar units in northern Denmark and elsewhere in Europe detected solar radio emission at 125 and 175 MHz and at other frequencies between 1939 and 1945 (inclusive) was made by E. Schott (1947) after the war, but no detailed proof of this was provided. However, given the sensitivity of the various German radar systems this claim seems plausible.

The detection of solar radio emission between 1942 and 1945 (inclusive) was definitely made by Allied radar operators, and the names of George Clark Southworth (1890–1972; Sullivan, 2009: 91-99), James Stanley Hey (1909–2000; Sullivan, 2009: 80-83), Elizabeth Alexander (1908–1958; Orchiston, 2005; Sullivan, 2009: 84-85) and Bruce Slee (b. 1924; Orchiston and Slee, 2002; Orchiston et al., 2006) are associated with these different independent discoveries. Hey's (1946) 1942 observations in England were made at frequencies between 55 and 85 MHz, while in 1945 Alexander (1946) in New Zealand and Slee in Australia observed

at 200 MHz. Meanwhile, in 1942 Southworth (1945) in the USA observed at the much higher frequency of 9370 MHz. In addition to these radar-based discoveries, Reber (1946) was successful in detecting solar radio emission at 160 MHz in 1943 (Sullivan, 2009: 65-66).

In October 1945, following Alexander's successful research in New Zealand, an Australian group at the CSIR's Division of Radiophysics began an intensive programme of solar radio research at 200 MHz using ex-WWII radar equipment located in and near Sydney (e.g. see Pawsey, Payne-Scott and McCready, 1946; cf. Orchiston, 2005; Orchiston et al., 2006). Leading this dynamic group was Joseph Lade Pawsey (1908–1962; Figure 8), and in a paper published in *Nature* in 1946 he claimed a temperature of one million Kelvin for the solar corona. This certainly aroused Unsöld's attention.

At this time another, much smaller, group based at Mt Stromlo Observatory near the Australian capital, Canberra, was also observing solar emission at 200 MHz (Orchiston et al., 2006). A member of this team was David Forbes Martyn (1906–1970; Figure 9), who played an important role in the observation and interpretation of solar radio waves. On theoretical grounds he postulated a temperature of one million Kelvin for the corona in a paper that was published end-to-end with Pawsey's (1946) paper in *Nature* (see Martyn, 1946b). Martyn (1946a) also was the first to determine that solar bursts were polarised, and he predicted that limb-brightening would occur at longer radio wavelengths (Martyn, 1946b), a topic that Unsöld later would study in detail.

When news of these British and Australian research programs finally reached Unsöld he began anew to search for an interpretation of solar and galactic radio emission.

The interpretation of galactic radio emission posed greater problems. All astrophysicists working in this field attempted to explain the radio observations in terms of thermal (free-free) emission theory. Charles H. Townes (b. 1915) critically discussed the existing free-free emission theory and the observations in 1946, concluding that only temperatures of 100,000K to 200,000K could explain the radio intensities.

The results of the radio observations of the Galaxy, the Sun and the Moon were reviewed in a major paper by Unsöld in 1947. By then Unsöld had access to recent publications. The detection of the Moon by Robert H. Dicke (1916–1997) and E. Robert Beringer (1946; 1917–2000) at a frequency of 24,000 MHz and all the other new observations published in 1946 impressed Unsöld (1947: 194; my English translation) as "The enormous possibilities for astronomy as a result of opening the spectral range from λ1cm to λ15m … allow the author … to return once more to this subject and discuss it." Unsöld continued to use the 'effective temperature' (T_e) definition obtained from the Rayleigh-Jeans approximation that he had proposed in 1946 (Unsöld, 1946). He examined the results of solar observations and concluded that the chromosphere must have an effective temperature ~6000K while the solar corona can have T_e >500,000K. Still much higher intensities of the solar bursts (the Sun was particularly active in 1946) led him to the conclusion that an 'Ultrastrahlung' (ultra-radiation) must be present, in addition to thermal free-free emission (from the quiet Sun).

Unsöld (1947) also computed the expected disc-limb variation for solar radio emission at lower frequencies. These early computations pointed out that the solar limb emission would be higher than the disc, contradicting the optical situation where limb-darking was well established. Considering the observed radio emission, Unsöld pointed out that a thermal interpretation would require the temperature of the interstellar gas to be ~100,000K or more.

Unsöld then discussed the publication by L.A. Moxon (1946) that showed that galactic radio emission had a non-thermal spectrum. As a result of this, the measurement of the spectrum of the radio emission became an important observational result in Unsöld's thinking. Concerning the nature of the 'Ultrastrahlung', Unsöld (1947: 201; my English translation) suggested that this could be due to energetic particles emitting in "... time variable magnetic fields ..." and that this emission would be similar to the situation found in 'betatrons'. In the final sentence of this 1947 paper Unsöld pointed out that this may be the first time that a viable interpretation of the cosmic radio waves has been given. It must be noted that at this time most astrophysicists interested in galactic radio astronomy still favoured the thermal emission interpretation. For example, the paper by G. Burkhardt, G. Elwert and Unsöld (1948) begins with a clear statement that cosmic radio emission can be interpreted only as 'bremsstrahlung' of free electrons.

Other European theoreticians (Hannes Alfvén, 1908–1995; Karl-Otto Kiepenheuer, 1910–1975), as well as Soviet researchers (e.g. Josif Shklovskii, 1916–1985; Vitaly Ginzburg, 1916–2009; and others), became active in this field. The Soviet results were not widely disseminated internationally since they were published in rarely-available journals and written in Russian. Also, the Soviet researchers were subject to a rigid censorship that prevented them from openly publishing their results, and in addition there

Figure 10: Karl-Otto Kiepenheuer (kis.uni-freiburg.de).

were long delays before approval was granted for publication. As a result, the papers by the Soviet researchers did not reach Unsöld (or other Western colleagues) for a long time, which he pointed out in one of his papers. Even today, most of the early Soviet papers (in Russian) are not available via the Astrophysics Data System. On the other hand, papers by Unsöld were cited by the Soviet astrophysicists.

The German solar astrophysicist Karl-Otto Kiepenheuer (Figure 10) fortunately lived in Freiburg, which at the end of the war ended up in the French Zone of Germany. Although some of his astronomical equipment was taken away by the French navy, Kiepenheuer received support from some of his French colleagues and hence had immediate access to recently-published papers. Details of Kiepenheuer's life have been discussed by Seiler (2005). In 1946 Kiepenheuer suggested that intense solar emission may be related to sunspots, where strong magnetic fields were known to be present. This was indeed an important step in the quest for the interpretation of the emission mechanisms of cosmic radio waves. Also Martyn (1946a) and McCready, Pawsey and Payne-Scott (1947) observed enhanced solar radio emission when large sunspots were visible. Ginzburg (1946; Figure 11) made his first contribution to radio astronomy by discussing the possible reasons for the million degree temperature of the solar corona. Then, the following year, Shklovskii (1947; Figure 12) managed to publish a paper in English in *Nature*, where he discussed various alternative emission mechanisms for solar radio emission (e.g. plasma oscillations), and tried to associate high-intensity solar burst emission with magnetic storms. In this paper Shklovskii follows the general assumption that thermal emission at high temperatures could be responsible for the radio waves (see also Ginzburg, in Sullivan, 1984).

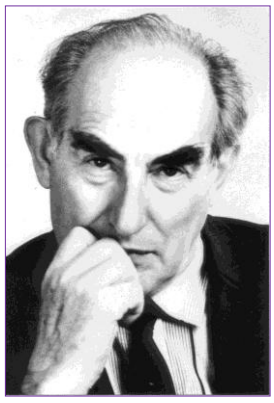

Figure 11 (left): Vitaly Ginzburg (en.wikipedia.org).
Figure 12 (right): Josif Shklovskii (courtesy: H. Friedman).

4 THE PARALLEL WORK OF THE PHYSICISTS

It also is necessary to go back and look at the work of theoretical physicists in this period. The basic work on the emission from relativistic electrons in magnetic fields was already given by Schott (1912). The development of energetic particle accelerators led to several configurations: the betatron, synchrotron, microtron, linear wave guide accelerator, and others (e.g. see Schiff, 1946). Dmitri Iwanenko (1904–1994) and Isaak Pomeranchuk (1944; 1913–1966) described the performance of a betatron. In a publication describing the General Electric synchrotron F.R. Elder et al. (1948) stated that blue light was seen when the synchrotron beam was observed in the accelerator tube (hence in the Earth's magnetic field). Furthermore, the blue light was found to be polarised. Julian Schwinger (1949; 1918–1994) described the classical radiation of accelerated electrons emitting in magnetic fields, as observed in synchrotrons. There was no theoretical investigation of the polarisation properties of the synchrotron emission at this time. In the Soviet Union numerous theoretical physicists also worked on similar problems, but at first they did not see the connection to astrophysical emission processes.

The question of the origin of cosmic rays was discussed right from the time of their detection by Victor Francis Hess (1883–1964). One of the early discussions was by Alfvén (1937; Figure 13). He investigated cosmic ray energies and suggested that the higher-energy particles could be produced by acceleration in magnetic fields. Observations of massive increases in the intensity of cosmic rays correlated with solar storms

were reported by Scott E. Forbush (1946; 1904–1984). Another important contribution came from Enrico Fermi (1901–1954; Figure 14), who realised that cosmic rays may possess the energy to generate radio emission in magnetic fields. Fermi (1949) discussed the existence of an inverse power spectral law for the spectral distribution of the cosmic rays. In a way, the physicists provided all that was needed for the interpretation of cosmic radio waves. An early paper by German G. Getmantsev (1926–1980) published in 1952, presumably discussed earlier in a seminar, examines the possibility that cosmic electrons produce galactic radio waves.

The presence of magnetic fields in sunspots and in Ap stars was observed by George Ellery Hale and by Horace W. Babcock (1912–2003) respectively. The existence of a magnetic field in our Galaxy was first established by the optical polarisation observations of William Albert Hiltner (1949; 1914–1991), followed by their interpretation by Leverett Davis (1914–2003) and Greenstein (1951) in terms of alignment of dust particles in magnetic fields. Additional support for the existence of galactic magnetic fields came from Subrahmanyan Chandrasekhar (1910–1995), Fermi (1953) and Biermann and Schlüter (1951). Hence a discussion of the emission mechanisms in which energetic cosmic rays emit in galactic magnetic fields could take place.

5 THE RAPID DEVELOPMENT OF RADIO ASTRONOMY 1946-1949

In addition to the solar observations several new directions of research were initiated (see Sullivan, 2009). After Reber's (1944) pioneering work surveying the radio sky at 160 MHz, a whole bonanza of new results was published. J. Stanley Hey (1909–2000), James W. Phillips, and S. John Parsons surveyed the northern sky at 60 MHz (see Hey, Phillips and Parsons, 1946). In these observations the scintillation of strong radio emission from a position in Cygnus led Hey, Parsons and Phillips (1946) to suggest the existence of compact radio sources. The results of these radio astronomical observations were reviewed by Reber and Greenstein in 1947.

At the same time, interferometry was adopted in Australia by John G. Bolton (1922–1993), Gordon J. Stanley (1921–2001) and O. Bruce Slee (b. 1924) in a bid to dramatically increase the angular resolution of the equipment used (see Bolton and Stanley, 1948; Bolton, Stanley and Slee, 1949). Observing at 100 MHz, they quickly confirmed the existence of the discrete source in Cygnus, and by the end of January 1948 had discovered five more discrete sources (see Orchiston, 1993; 1994). Meanwhile, Martin Ryle (1918–1984) and F. Graham Smith (b. 1923) discovered a strong new radio source in the constellation of Cassiopeia, also using an interferometer (Ryle and Smith, 1948). A short discussion between Marcel G.J. Minnaert (1948; 1893–1970) and Ryle and Smith (1948) led to the suggestion that the observed radio sources were 'radio stars', and this idea was followed for quite some time even though Bolton et al. (1949) showed that stars were not responsible for the emission when they demonstrated two of the radio sources (Virgo A and Centaurus A) were associated with active galaxies and a third (Taurus A) with the Crab Nebula (the remnant of a supernova whose eruption in AD 1054 was recorded by Chinese, Japanese and Korean astronomers—see Stephenson and Green, 2002). Observations by Moxon (1946) of galactic radio emission at four frequencies—already discussed by Unsöld—indicated a (non-thermal) inverse power law spectrum that pointed to a magnetic bremsstrahlung process.

Figure 13: Hannes Alfén (en.wikipedia.org).

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Figure 14: Enrico Fermi (solmagazine.wordpress.com).

6 INTERPRETATION ATTEMPTS BY UNSÖLD IN VIEW OF THE NEW OBSERVATIONAL DATA

In a major paper entitled "Über den Ursprung der Radiofrequenzstrahlung und der Ultrastrahlung in der Milchstraße" ("The origin of the radio frequency emission and the ultra-emission in the Milky Way") Unsöld (1949a) dealt first with solar radio emission. He agreed with the free-free mechanism for the 'quiet Sun', with temperatures of ~6000 K in the chromospheres and ~500,000K in the corona He stated categorically that the free-free emission interpretation could not hold for solar bursts, and he suggested once more that the 'ultra-radiation' was generated by energetic particles in magnetic fields, "… a sort of plasma oscillations." (Unsöld, 1949a: 197; my English translation). Since then, the origin of solar radio emission has filled books, and is still the subject of detailed research.

When it came to galactic radio emission Unsöld (1949a: 183; my English translation) decisively stated: "The radio emission from our Galaxy cannot be considered to be due to free-free emissions of the interstellar gas." Unsöld did, however, consider the possibility that the galactic radio emission came from numerous 'radio stars'. He suggested that this non-thermal 'radio star' emission, similar to solar bursts, could be responsible for the radio emission from our Galaxy. The main worry that is seen in all of Unsöld's papers is connected to the origin of energetic particles—he simply could not imagine that such particles could come from stellar processes. On the other hand, Ryle (1949) claimed that there was observational evidence for the stellar origin of cosmic rays. After all, just a short time before this publication, Babcock showed that magnetic fields exist in Ap stars. In a shorter paper, his first written in English, Unsöld (1949b) admitted that he had for a long time adhered to the thermal interpretation, yet this could not be upheld in view of the recent discovery of discrete sources ('radio stars'). He pointed out that while solar magnetic fields could produce 10^9 to 10^{10} eV, the radio stars had to produce energies of up to 10^{15} eV, possibly in "… much larger spots." (Unsöld, 1949b: 491).

6.1 Interpretation of the Origin of Cosmic Radio Emission

Although solar research was a driving force in the development of early radio astronomy, the interpretation of radio waves from our Galaxy and from extragalactic discrete radio sources was important for the further development of the subject. The interpretation of cosmic radio emission is usually dated to 1950 when H. Alfvén and N. Herlofson (1950) suggested that radio emission from 'radio stars' was a result of energetic electrons emitting in magnetic fields. In this paper the problem of energetic particles was discussed, and a reference to the paper by Fermi (1949) is made—suggesting that cosmic rays may have sufficient energy to produce cosmic radio emission. A reference also is made to a paper by F.R. Elder et al. (1948) where it is suggested that emission like in the synchrotron machine may be the source of cosmic radio waves. Kiepenheuer (1950a; 1950b) took up this idea and argued that this emission mechanism also can be responsible for the radio waves from our Galaxy.

The acceptance of the idea that cosmic rays may possess enough energy to be responsible for radio and optical emissions in magnetic fields was the break-through point in this discussion. This step was initiated by a brilliant suggestion from Shklovskii (1953), who proposed that the optical and radio emission from the Crab Nebula could be a result of relativistic electrons emitting in a magnetic field. From then on, his proposed interpretation influenced the theoretical discussions. The importance of the Crab Nebula in the interpretation of astrophysical emission processes was realised by Soviet astronomers. The energy of a supernova explosion was obviously sufficient for the generation of relativistic particles. Soviet optical astronomers V.A. Dombrovskii and Mikhail A. Vashakidze studied the Crab Nebula, and in 1954 both published papers that reported the detection of polarised optical emission. In particular, Dombrowskii (1954) pointed out that this emission could be the same sort of radiation as suggested by Shklovskii. This statement was made although Shklovskii did not point out that the radio emission would be polarised. The connection between the polarisation of the radio continuum and bremsstrahlung emission was realised later by Isaak M. Gordon, in 1954. Ginzburg (1984: 296) says that he "... supported the proposed polarisation observations in 1953/54 while Shklovskii felt in 1954 that such measurements would have insufficient sensitivity." Possibly, as early as 1952, there was discussion in seminars about this polarisation aspect, but it took time for a relevant publication to appear. The observation of linear polarisation of radio waves became a major method to study cosmic magnetic fields, but details of the polarisation properties of synchrotron emission were not dealt with until much later.

In his later publications, Unsöld slowly comes to terms with the theoretical advances. In 1951 he still favoured the 'radio star' model, but his argument hinged on the possibility of cosmic rays due to "... activity qualitatively similar to that of the Sun but several billion times stronger." (Unsöld, 1951: 859). Another publication (Unsöld, 1955) reiterated the radio star model and dis-

cussed the need for strong galactic magnetic fields to allow energies of up to 10^{17} eV. In his 1955 paper Unsöld was fascinated by cosmology, and he asked if "... the origin of the ultra-radiation could come from the creation of the universe". (Unsöld, 1955: 71; my English translation). He even suggested that the 'Ultra-strahlung' could be a result of the 'Urknall' (Big Bang)! By 1957, Unsöld reluctantly agreed with the interpretation that supernova remnants could be the source of the energetic particles, but he still suggested the alternative view, that cool dwarf stars may be a source of these particles. Note that in none of these papers did Unsöld refer to the work of the Soviet researchers. In a way, Unsöld was on the right track in his interpretation of cosmic radio waves, but he did not coin the term 'synchrotron emission', using instead 'Ultrastrahlung' or 'betatron emission'. He still hoped for a stellar process as the basis of the cosmic radio emissiond.

It is interesting to note that the term 'synchrotron emission' was not used for a long time in astronomical papers. In the work of the Soviet researchers (e.g. Shklovskii and Ginzburg) the term was 'emission from energetic particles in magnetic fields' or 'magnetic bremsstrahlung'. Ginzburg and Syrovatskii title their important 1965 review paper "Cosmic magnetobremsstrahlung (synchrotron radiation)". The first thorough discussion of the emission process using the term 'synchrotron radiation' was published by Jan Oort (1900–1992) and Theodore Walraven (1916–2008) in 1956, possibly as a result of Oort's visit to Russia to attend the reinauguration of the Pulkovo Observatory in 1955.

7 OBSERVATIONAL RADIO ASTRONOMY IN KIEL

Professor Unsöld developed close ties with Werner Kroebel, who became Professor of Applied Physics at Kiel University (see Figure 15). Unsöld recognised the need for observational radio astronomy in Germany and he proposed to Kroebel that they develop a suitable antenna. At that time radio (and particularly radar) research was forbidden by the West German Allied authorities, but a way around this was to build a steerable dipole array rather than a parabolic reflector. A thesis by H.J. Loose, submitted in 1951, describes an antenna intended for radio astronomical observations. Unsöld decided to observe at 198 MHz (a wavelength of 1.5 metre), so that he could derive the spectral index of galactic continuum emission. The resulting instrument, a 5m x 5m array with three rows of seven full-wave dipoles, was described by Franz Dröge (b. 1925) in 1955. Subsequent observations led to the publication of a radio map by Dröge and Wolfgang Priester (1924–2005) in 1956. The authors also used the southern sky-data from Clabon W. Allen (1904–1987) and Colin Gum (1924–1960), originally published in 1950, to make the first all-sky radio continuum map at this frequency. In this map the North Polar Spur at l = 30°, and other spurs, were clearly delineated for the first time (see Figure 16).

The full-wave dipole array posed some calibration problems, and these were investigated by Bernd-Harald Grahl (b. 1930) in 1958. The array antenna then was dismounted and a corner reflector was placed on the stand to determine the absolute temperature of the radio emission. The spectrum of the galactic radio emission could be determined by comparing the German observations with those made by John E. Baldwin (1931–2010) at 81.5 MHz and published in 1955. A definite non-thermal spectrum was found.

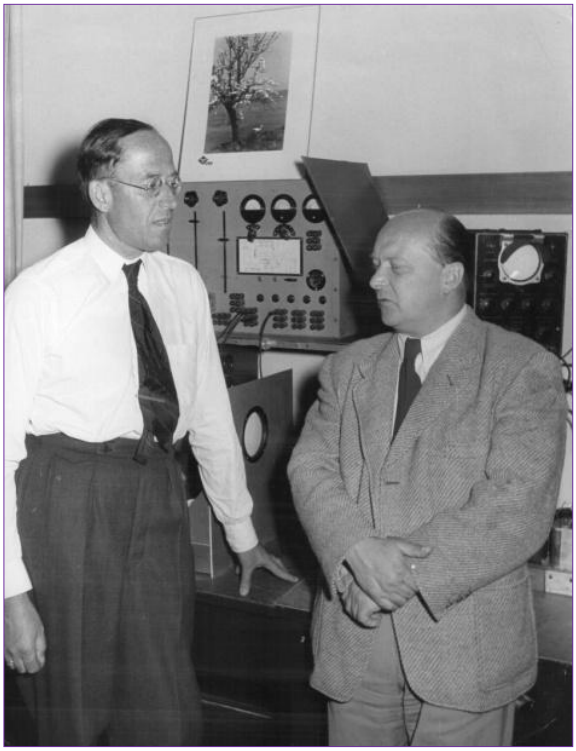


Figure 15: Professor Albrecht Unsöld (left) and Professor Werner Kroebel (right) photographed in a laboratory at the Institute for Applied Physics by Hans Hinkelmann.

Around the time when the survey was finished the prohibition on radar research in Germany was lifted and a 25m dish was under construction at Stockert Mountain for the Astronomy Department of Bonn University. Subsequently, the major investigators (Priester and Grahl) left Kiel University for the larger radio telescope. Unsöld continued to support observational radio astronomy, securing funds for a 7.5m dish that was dedicated to solar research. This antenna was used for many years, first for regular solar patrol observations (e.g. see Dröge et al., 1961) and later for high-resolution solar burst observations (e.g. see Dröge, 1977; Zimmermann, 1971). The

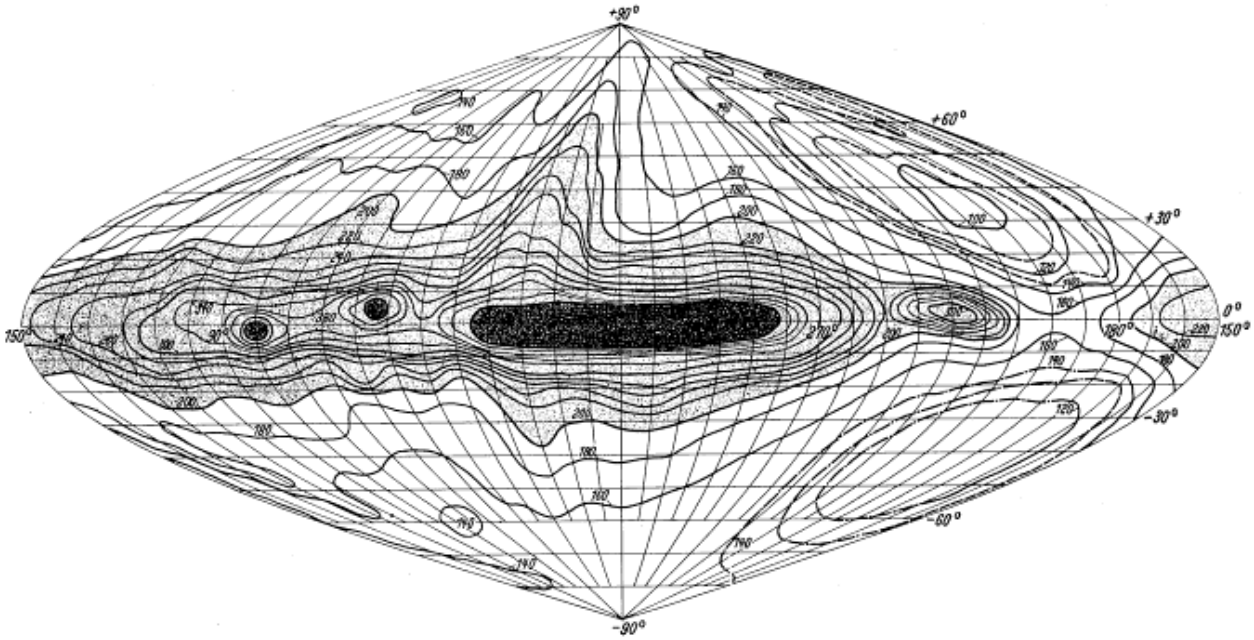


Figure 16: Isophotes of 198 MHz all-sky emission (after Dröge and Priester, 1956: 245).

development of observational radio astronomy in Kiel University is discussed in more detail by Wielebinski and Grahl (2013).

8 THE LATER YEARS

Even during the time when Unsöld was involved in the interpretation of cosmic radio waves he published many additional papers on various theoretical topics in astrophysics, but the main direction of his research—the physics of stellar atmospheres—never changed. He studied the Fraunhofer lines of the Sun, and derived a solution for the centre-limb variation (Unsöld, 1948a). He also ventured into cosmology (see Unsöld, 1948b). The second edition of *Physik der Sternatmosphären (mit besonderer Berücksichtigung der Sonne)* was published in 1955. Then Unsöld was asked by the Royal Astronomical Society to give the George Darwin Lecture, and this was published in 1958. A series of papers, published between 1960 and 1963, dealt in detail with the solar chromosphere. In 1967 Unsöld's next major book, *Der neue Kosmos*, appeared; this book was primarily intended to accompany his lectures at Kiel University, and through several different editions it became a standard work for a whole generation of students.

The theory of solar flares (Unsöld, 1968) was in a way Unsöld's farewell to radio astronomy, and his retirement in 1973 led ultimately to the closure of the radio astronomy observatory at Kiel University on 31 December 1976. This brought to an end two decades of pioneering research in German radio astronomy.

9 ACKNOWLEDGEMENTS

The biographical data on Albrecht Unsöld presented in the first two sections of this paper came from the home page of the Christian-Albrechts-Universität zu Kiel: http://www.uni-kiel.de/ps/cgi-bin/fo-bio.php?nid=unsoeld. I wish to thank Drs Bernd-Harald Grahl and Norbert Junkes for various comments on the radio astronomy observatory at Kiel. Dr Grahl kindly supplied the photograph shown in Figure 15. I profited from discussions with Leonid Gurvits, who helped in the literature search for original publications of the early Soviet theoreticians. I also thank the referees, for pointing out some forgotten historical details, and Professor Wayne Orchiston for helping revise the original version of this paper.

10 REFERENCES

Alexander, F.E.S., 1946. The Sun's radio energy. *Radio & Electronics*, 1(1), 16-17, 20.

Alfvén, H., 1937. Versuch zu einer Theorie über die Entstehung der kosmischen Strahlung. *Zeitschrift für Physik*, 105, 319-333 (in German).

Alfvén, H., and Herlofson, N., 1950. Cosmic radiation and radio stars. *Physical Review*, 78, 616.

Allen, C.W., and Gum, C.S., 1950. Survey of galactic radio-noise at 200 MHz. *Australian Journal of Scientific Research*, 3, 224-233.

Baldwin, J.E., 1955. A survey of the integrated emission at a wavelength of 3.7m. *Monthly Notices of the Royal Astronomical Society*, 115, 684-689.

Baschek, B., 2011. Physics of stellar atmospheres – new aspects and old problems. In Wolfschmidt, G (ed.). *Entwicklung der theoretischen Astrophysik Nuncius Hamburgensis.* Hamburg, Tredition. Pp. 383-397.

Biermann, L., and Schlüter, A., 1951. Cosmic radiation and cosmic magnetic fields. II. Origin

of cosmic magnetic fields. *Physical Review*, 82, 863-868.

Bolton, J.G., and Stanley, G.J., 1948. Variable source of radio frequency radiation in the constellation of Cygnus. *Nature*, 161, 312-313.

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.

Burkhardt, G., Elwert, G., and Unsöld, A., 1948. Über das langwellige Ende des kontinuierlichen Röntgenspektrums und die Theorie der Radiofrequenzstrahlung der Milchstraße und der Sonne. *Zeitschrift für Astrophysik*, 25, 310-314 (in German).

Chandrasekhar, S., and Fermi, E., 1953. Magnetic fields in spiral arms. *Astrophysical Journal*, 118, 113-115.

Davis, L., and Greenstein, J.L., 1951. The polarisation of stardust by aligned dust grains. *Astrophysical Journal*, 114, 206-240.

Dicke, R.H., and Beringer, R., 1946. Microwave radiation from the Sun and Moon. *Astrophysical Journal*, 103, 375-376.

Dombrowsky, V.A., 1954. On the nature of the radiation from the Crab Nebula. *Doklady Akad. Nauk SSSR*, 94, 1021-1024 (in Russian).

Dröge, F., 1955. Die Radiosternwarte Kiel. *Zeitschrift für Astrophysik,* 37, 125-131 (in German).

Dröge, F., 1977. Millisecond fine-structures of solar radio bursts in the range 0.2-1.4 GHz. *Astronomy and Astrophysics*, 57, 285-290.

Dröge, F., and Priester, W., 1956. Durchmusterung der allgemeinen Radiofrequenz-Strahlung bei 200 MHz. *Zeitschrift für Astrophysik*, 40, 236-248 (in German).

Dröge, F., Howeger, F., and Unsöld, A., 1961. Information Bulletin of Solar Radio-Observatories, 6. *Contributions of the Radiosternwarte Kiel.*

Elder, F.R., Langmuir, R.V., and Pollock, H.C., 1948. Radiation from electrons accelerated in a synchrotron. *Physical Review*, 74, 52-58.

Fermi, E., 1949. On the origin of cosmic radiation. *Physical Review*, 75, 1169-1174.

Forbush, S.E., 1946. Three unusual cosmic ray increases possibly due to charged particles from the Sun. *Physical Review*, 70, 9-10.

Fränz, K., 1942. Messung der Empfängerempfindlichkeit bei kurzen elektrischen Wellen. *Hochfrequenztechnik und Elektroakustik*, 59, 143-144 (in German).

Getmantsev, G.G., 1952, Cosmic electrons produce galactic radio waves. *Doklady Akad. Nauk SSSR*, 83, 557-560 (in Russian).

Ginzburg, V.L., 1946. On solar radiation in the radio spectrum. *Doklady Akad. Nauk SSSR.*, 52, 491 (in Russian).

Ginzburg, V.L., 1984. Remarks on my work on radio astronomy. In Sullivan, W.T. III (ed.). *The Early History of Radio Astronomy.* Cambridge, Cambridge University Press. Pp. 289-302.

Ginzburg, V.L., and Syrovatskii, S.I., 1965. Cosmic magnetobremsstrahlung (synchrotron radiation). *Annual Reviews of Astronomy and Astrophysics*, 3, 297-349.

Gordon, I.M., 1954. New theory of chromospheric eruptions. *Doklady Akad. Nauk Ukrain-SRS*, 1, 13-16 (in Russian).

Grahl, B.-H., 1958. Absolutmessung radioastronomischer Flächenhelligkeiten bei 198 MHz mit einer 90°-Winkelantenne. *Zeitschrift für Astrophysik*, 45, 49-67 (in German).

Greenstein, J.L., 1984. Optical and radio astronomers in the early years. In Sullivan, W.T. III (ed.). *The Early Years of Radio Astronomy: Reflections Fifty Years After Jansky's Discovery.* Cambridge, Cambridge University Press. Pp. 67-81.

Henyey, L.G., and Greenstein, J.L., 1941. Diffuse radiation in the galaxy. *Astrophysical Journal*, 93, 70-83.

Henyey, L.G., and Keenan, P.C., 1940. Interstellar radiation from free electrons and hydrogen atoms. *Astrophysical Journal*, 91, 625-630.

Hey, J.S., 1946. Solar radiation in the 4-6 metre radio wavelength band. *Nature*, 157, 4.

Hey, J.S., Phillips, J.W., and Parsons, S.J., 1946. Cosmic radiation at 5 metres wavelength. *Nature*, 157, 296-297.

Hey, J.S., Parsons, S.J., and Phillips, J.W., 1946. Fluctuations in cosmic radiation at radio frequencies. *Nature*, 158, 234.

Hiltner, W.A., 1949. On the presence of polarisation in the continuous radiation of stars. *Astrophysical Journal*, 109, 471-481.

Iwanenko, D., and Pomeranchuk, I., 1944. On the maximal energy attainable in a betatron. *Physical Review*, 65, 343.

Jansky, K.G., 1932. Radio waves from outside the Solar System. *Nature*, 132, 66.

Jansky, K.G., 1933. Electrical disturbances apparently of extraterrestrial origin. *Proceedings of the Institute of Radio Engineers*, 21, 1387-1389.

Kiepenheuer, K.O., 1946. Origin of solar radiation in the 1-4 metre radio wavelength band. *Nature*, 158, 340.

Kiepenheuer, K.O., 1950a. Cosmic rays as the source of general galactic radio emission. *Physical Review*, 79, 738-773.

Kiepenheuer, K.O., 1950b. Cosmic rays and radio astronomy. *Astronomical Journal*, 55, 172-173.

Loose, H.J., 1951. Entwurf einer scharf bündelnden Antenne für Schmalbandbetrieb bei 200 MHz *Diplomarbeit*, *Institut für angewandte Physik der Universität Kiel* (in German)

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, *A.* 190, 357-775.
Martyn, D.F., 1946a. Polarisation of solar radio-frequency emission. *Nature*, 158, 308-309.
Martyn, D.F., 1946b. Temperature radiation from the quiet Sun in the radio spectrum. *Nature*, 158, 632-633.
Minnaert, M., 1948. Origin of fluctuating galactic noise. *Nature*, 162, 858.
Moxon, L.A., 1946. Variation of cosmic radiation with frequency. *Nature*, 158, 758-759.
Oort, J.H., and Walraven, Th., 1956. Polarization and composition of the Crab Nebula. *Bulletin of the astronomical institutes of the Netherlands*, *12, 285-308.*
Orchiston, W., 1993. New Zealand's role in the identification of the first "radio stars". *Southern Stars*, 35, 46-52.
Orchiston, W., 1994. John Bolton, discrete sources and the New Zealand field trip of 1948. *Australian Journal of Physics*, 47, 541-547.
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*. New York, Springer. Pp. 71-92.
Orchiston, W., and Slee, B., 2002. The Australasian discovery of solar radio emission. *AAO Newsletter*, 101, 25-27.
Orchiston, W., Slee, B., and Burman, R., 2006. The genesis of solar radio astronomy in Australia. *Journal of Astronomical History and Heritage*, 9, 35-56.
Pawsey, J.L., 1946. Observation of million degree thermal radiation from the Sun at a wavelength of 1.5 metres. *Nature*, 158, 633-634.
Pawsey, J.L., Payne-Scott, R., and McCready, L.L., 1946. Radio-frequency energy from the Sun. *Nature*, 157, 158-159.
Reber, G., 1940. Cosmic static. *Astrophysical Journal*, 91, 621-623.
Reber, G., 1944, Cosmic static. *Astrophysical Journal*, 100, 279-287.
Reber, G., 1946, Solar radiation at 480 MHz, *Nature*, 158, 945.
Reber, G., and Greenstein, J.L., 1947. Radio-frequency investigations of astronomical interest. *The Observatory*, 67, 15-26.
Ryle, M., 1949. Evidence for the stellar origin of cosmic rays. *Proceedings of the Physical Society*, *A* 62, 491-499.
Ryle, M., and Smith, F.G., 1948. A new intense source of radio frequency radiation in the constellation of Cassiopeia. *Nature*, 162, 462-463.
Schiff, L.I., 1946. Production of particle energies beyond 200 MeV. *Reviews of Scientific Instruments*, 17, 6-10.
Schott, E., 1947. 175 MHz Strahlung der Sonne. *Physikalische Blätter*, 2,159-160 (in German).
Schott, G.A., 1912, *Electromagnetic Radiation: and the Mechanical Reactions Arising From It*. Cambridge, Cambridge University Press.
Schwinger, J., 1949. On the classical radiation of accelerated electrons. *Physical Review*, 73, 1912-1925.
Seiler, M.P., 2005. Solar research in the Third Reich. In Wittmann, A.D., Wolfschmidt, G., and Duerbeck, H. (eds.). *Development of Solar Research.* Frankfurt am Main Harri Deutsch. Pp. 199-228.
Shklovskii, I.S., 1947. Emission of radio waves by the Galaxy and the Sun. *Nature*, 159, 752-753.
Shklovskii, I.S., 1953. On the nature of Crab Nebula's optical emission. *Doklady Akad. Nauk SSSR.*, 90, 983-986 (in Russian).
Southworth, J., 1945. Microwave radiation from the Sun. *Journal Franklin Institute*, 239, 285-297.
Stephenson, F.R., and Green, D.A., 2002. *Historical Supernovae and their Remnants*. Oxford, Oxford University Press.
Sullivan, W.T. III., 1984. *The Early Years of Radio Astronomy*. Cambridge, Cambridge University Press.
Sullivan, W.T. III., 2009. *Cosmic Noise: A History of Early Radio Astronomy.* Cambridge, Cambridge University Press.
Townes, C.H., 1946. Interpretation of radio radiation from the Milky Way. *Astrophysical Journal*, 105, 235-240.
Unsöld, A., 1926. Über das Spektrum des Wasserstoffs. *Zeitschrift für Physik*, 38, 237-241 (in German).
Unsöld, A., 1927. Quantentheorie des Wasserstoffmoleküls und der Born-Landéschen Kräfte. *Zeitschrift für Physik*, 43, 563-574 (in German).
Unsöld, A., 1931. Die Kontur der Heliumlinie λ 5976 (D_3) im Spektrum der Sonnenchromosphäre. *Zeitschrift für Astrophysik*, 3, 77-80 (in German).
Unsöld, A., 1936. Stoßdämpfung in der Sonnenatmosphäre. *Zeitschrift für Astrophysik*, 12, 56-64 (in German).
Unsöld, A., 1938. *Physik der Sternatmosphären*, *mit besonderer Berücksichtigung der Sonne.* Berlin, Julius Springer Verlag (Later editions: 1955; 1968) (in German).
Unsöld, A., 1942a. Quantitative Spektralanalyse des BO-Sternes τ Scorpii I. Messung der Linienintensitäten. *Zeitschrift für Astrophysik*, 21, 1-21 (in German).
Unsöld, A., 1942b. Quantitative Analyse des BO-Sternes τ Scorpii II. Deutung des Linienspektrums. Kosmische Häufigkeit der Leichten Elemente. *Zeitschrift für Astrophysik*, 21, 21-71 (in German).
Unsöld, A., 1942c. Quantitative Analyse des BO-Sternes τ Scorpii III. Theorie des kontinuierlichen Spektrums. *Zeitschrift für Astrophysik*, 21, 229-248 (in German).
Unsöld, A., 1944. Quantitative Analyse des BO-

Sternes τ Scorpii IV. Druckverbreiterung der He und He^+ Linien. Eine neue Methode zur Bestimmung des Häufigkeitsverhältnisses von Wasserstoff und Helium. *Zeitschrift für Astrophysik*, 23, 75-97 (in German).

Unsöld, A., 1946. Die kosmische Kurzwellenstrahlung. *Die Naturwissenschaften*, 33, 37-40 (in German).

Unsöld, A., 1947. Die Kurzwellenstrahlung der Milchstraße, der Sonne und des Mondes. *Die Naturwissenschaften*, 34, 194-201 (in German).

Unsöld, A., 1948a. Über die Fraunhoferschen Linien und ihre Mitte-Rand-Variation auf der Sonnenscheibe. *Annalen der Physik*, 438, 124-138 (in German).

Unsöld, A., 1948b. Kernphysik und Kosmologie. *Zeitschrift für* Astrophysik, 24, 278-305 (in German).

Unsöld, A., 1949a. Über den Ursprung der Radiofrequenzstrahlung und der Ultrastrahlung in der Milchstraße. *Zeitschrift für Astrophysik*, 26, 176-199 (in German).

Unsöld, A., 1949b. Origin of the radio frequency emission and the cosmic radiation in the Milky Way. *Nature*, 489-49.

Unsöld, A., 1951. Cosmic radiation and cosmic magnetic fields I. Origin and propagation of cosmic rays in our Galaxy. *Physical Review*, 82, 857-863.

Unsöld, A., 1955. Astrophysikalische Bemerkungen zur Entstehung der kosmischen Ultrastrahlung. *Zeitschrift für Physik*, 141, 70-82 (in German).

Unsöld, A., 1957. Radio astronomy and the origin of cosmic rays. In Van der Hulst, H.C. (ed.). *Radio Astronomy* (Proceedings of the 4th IAU Symposium). Cambridge, Cambridge University Press. Pp. 238-240.

Unsöld, A., 1958. On the quantitative analysis of stellar spectra (George Darwin Lecture). *Monthly Notices of the Royal Astronomical Society*, 118, 3-13.

Unsöld, A., 1967. *Der Neue Kosmos*. Berlin, Springer-Verlag (in German).

Unsöld, A., 1968. On the theory of flares and some related solar phenomena. *Quarterly Journal of the Royal Astronomical Society*, 9, 294-301.

Unsöld, A., Struve, O., and Elvey, C.T., 1930. Zur Deutung der interstellaren Calciumlinien. *Zeitschrift für Astrophysik*, 1, 314-325 (in German).

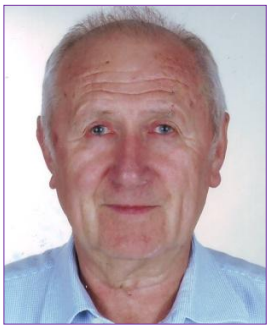
Vashakidze, M.A.. 1954. On the degree of polarisation of the light near extragalactic nebulae. *Astronomicki Cirkular*, 147, 11-13 (in Russian).

Weidemann, V., 2011. Albrecht Unsöld – Biographie und Briefwechsel. In Wolfschmidt, G. (ed.). *Entwicklung der theoretischen Astrophysik Nuncius Hamburgensis.* Hamburg, Tredition. Pp. 357-378 (in German).

Whipple, F.L., and Greenstein, J.L., 1937. On the origin of interstellar radio disturbances. *Publications of the National Academy of Sciences*, 23, 177-191.

Wielebinski, R., and Grahl, B-H., 2013. Radio astronomy at Kiel University. In Wolfschmidt, G. (ed.). *Nuncius Hambugensis* (in press).

Zimmermann, G., 1971. Statistical investigation of the time-dependent fine structure of solar bursts. *Astronomy and Astrophysics*, 15, 433-443.



Richard Wielebinski was born in Pleszew, Poland on 12 February 1936. The family was evicted from their home in 1939 and after a ten year odyssey settled in Hobart, Tasmania. Richard studied Electrical Engineering at the University of Tasmania, completing B.E (Hons.) and M.Eng. Sc. degrees. In his student days Richard met Grote Reber, and was involved in the construction of a long-wavelength antenna at Kempton, Tasmania. For two years he worked for the Postmaster General's Department in Hobart, as the engineer in charge of the construction of the television transmitter ABT2 on Mt. Wellington. After being awarded a Shell Scholarship Richard studied at the Cavendish Laboratory, Cambridge, in Martin Ryle's radio astronomy group. His 1963 Ph.D. thesis discussed the detection and nature of polarised galactic radio emission. From 1963 to 1969 Richard worked with Professor W.N. (Chris) Christiansen in the Department of Electrical Engineering at the University of Sydney, and he made absolute calibrations of galactic emission with the Fleurs Synthesis Telescope, mapped the southern sky at 150 MHz with the Parkes Radio Telescope, and became involved in the early Australian pulsar detections. At the Molonglo Radio Observatory the detection of some 20 pulsars established the galactic distribution of these objects. In 1970 Richard was invited to accept the Directorship of the Max-Planck-Institute für Radioastronomie in Bonn, where he was responsible for the instrumentation of the 100m radio telescope at Effelsberg. In addition, he built up a research group that became involved in mapping the sky in the radio continuum, studying the magnetic fields of galaxies, and pulsar research. Further developments were the French-German-Spanish institute for mm-wave astronomy, IRAM, and co-operation with the Steward Observatory, University of Arizona, in the Heinrich-Hertz Telescope Project. Richard has been active in many international co-operations, in Australia, Poland, Russia (Soviet Union), India and China. He

holds Honorary Professorships in Bonn and Beijing, and until recently in Townsville (Australia). He is a member of several academies, and has been awarded honorary doctorates by three universities. After retirement in 2004 Richard became involved in history of radio astronomy research. He is currently the Vice-Chairman of the IAU Working Group on Historic Radio Astronomy.

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KEEPERS OF THE DOUBLE STARS

Joseph S. Tenn
Sonoma State University, Rohnert Park, CA 94928, USA.
E-mail: joe.tenn@sonoma.edu

Abstract: Astronomers have long tracked double stars in efforts to find those that are gravitationally-bound binaries and then to determine their orbits. Early catalogues by the Herschels, Struves, and others began with their own discoveries. In 1906 court reporter and amateur astronomer Sherburne Wesley Burnham published a massive double star catalogue containing data from many observers on more than 13,000 systems. Lick Observatory astronomer Robert Grant Aitken produced a much larger catalogue in 1932 and coordinated with Robert Innes of Johannesburg, who catalogued the southern systems. Aitken maintained and expanded Burnham's records of observations on handwritten file cards, and eventually turned them over to the Lick Observatory, where astrometrist Hamilton Jeffers further expanded the collection and put all the observations on punched cards. With the aid of Frances M. "Rete" Greeby he made two catalogues: an Index Catalogue with basic data about each star, and a complete catalogue of observations, with one observation per punched card. He enlisted Willem van den Bos of Johannesburg to add southern stars, and together they published the *Index Catalogue of Visual Double Stars, 1961.0*. As Jeffers approached retirement he became greatly concerned about the disposition of the catalogues. He wanted to be replaced by another "double star man," but Lick Director Albert E. Whitford had the new 120-inch reflector, the world's second largest telescope, and he wanted to pursue modern astrophysics instead. Jeffers was vociferously opposed to turning over the card files to another institution, and especially against their coming under the control of Kaj Strand of the United States Naval Observatory. In the end the USNO got the files and has maintained the records ever since, first under Charles Worley, and, since 1997, under Brian Mason. Now called the Washington Double Star Catalog (WDS), it is completely online and currently contains more than 1,200,000 measures of more than 125,000 star systems.

Keywords: double stars, binary stars, William Herschel, John Herschel, James South, Wilhelm Struve, Otto W. Struve, Sherburne W. Burnham, Robert Aitken, Robert Innes, Hamilton Jeffers, Willem van den Bos, Frances Greeby, Albert Whitford, Kaj Strand, Charles Worley, Brian Mason, William Hartkopf, Pulkova, Lick Observatory, United States Naval Observatory.

1 INTRODUCTION

Double stars—pairs of stars that appear close together in the sky—have been known since ancient times. Ptolemy described the pair now known as ν^1 and ν^2 Sgr as a double star nearly two thousand years ago. Mizar (Figure 1) was observed as double through a telescope in 1617 by Galileo's student Benedetto Castelli (1578–1643) (Ondra, 1999; Fedele, 1949).

In 1767 the English clergyman John Michell (Figure 2), who would later predict black holes, applied his statistical skill to the by-then substantial number of double stars known:

> We may from hence, therefore with the highest probability conclude (the odds against the contrary opinion being many million millions to one) that the stars are really collected together in clusters in some places, where they form a kind of systems, whilst in others there are either few or none of them, to whatever cause this may be owing, whether to their mutual gravitation, or to some other law or appointment of the Creater [sic]. And the natural conclusion from hence is that it is highly probable in particular, and next to a certainty in general, that such double stars, &c. as appear to consist of two or more stars placed very near together, do really consist of stars placed near together, and under the influence of some general law, whenever the probability is very great, that there would not have been any such stars so near together, if all those, that are not less bright than themselves, had been scattered at random through the whole heavens. (Michell, 1767: 249–250).

Figure 1: Mizar, the first double star seen through a telescope (courtesy: George Kristiansen).

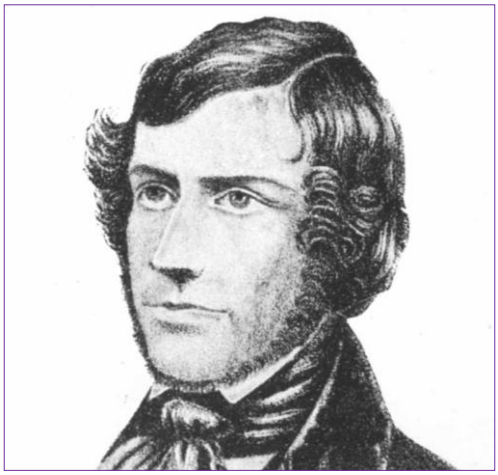


Figure 2: John Michell (1724–1793) (http://wdict.net/word/john+michell/).

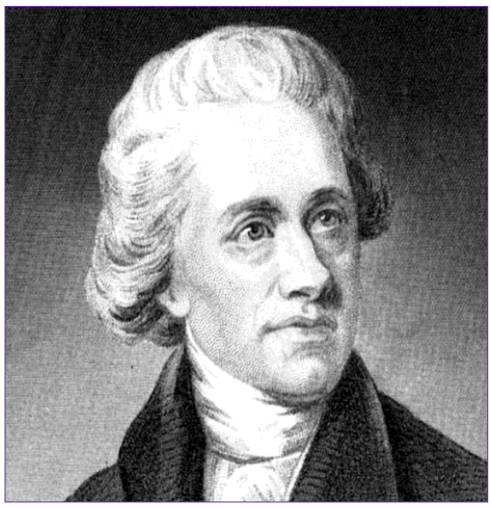


Figure 3: William Herschel (1738–1822), the founder of double star astronomy (after Holden, 1881: Frontispiece).

DE
NOVIS IN COELO SIDEREO
PHAENOMENIS
IN
MIRIS STELLARUM FIXARUM COMITIBUS
MANNHEMII
IN SPECULA NOVA ELECTORALI
RECENS DETECTIS
AUCTORE
ABBATE *CHRISTIANO MAYER*
SERENISSIMI AC POTENTISSIMI
ELECTORIS PALATINI
ASTRONOMO AULAE & CONSILIAR. ECCLESIAST.
UNIVERSITATIS HEIDELBERGENSIS PROFESS.
ASTRONOMIAE P. O.
ACADEMIAE ELECTORAL. SCIENT. MANNHEIM. ET MONACENSIS
UTI ET SOCIETATIS TEUTONICAE, SOCIETAT. REG. LONDIN.
ET PHILADELPH., INSTITUTI BONONIENS. ET INSTIT.
HISTOR. GOETTINGAE ET SOCIETATIS IMPER.
NATURAE CURIOS. SOCIO.
MANNHEMII,
Ex Typographia Elector. Aulica & Academica, 1779.

Figure 4: Title page of first double star catalogue (after Mayer, 1779).

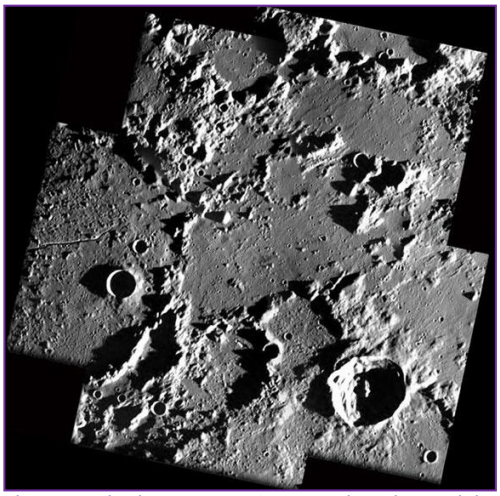


Figure 5: The lunar crater C. Mayer is at lower right (ESA/Space-X Space Exploration Institute).

In 1803 William Herschel (Figure 3) proved that Michell was right in suspecting "… their mutual gravitation." After 25 years of recording the positions of α Geminorum, γ Leonis, ε Bootis, ζ Herculis, δ Serpentis and γ Virginis (Herschel, 1803), he had become convinced that all were orbiting systems, or *binary stars*, a term he had coined the previous year (Herschel, 1802: 480-481). He had started these observations confident that the pairs were chance optical alignments, and he had measured them hoping to be able to detect stellar parallax by measuring shifts in the positions of the brighter, presumably nearer, stars with respect to the dimmer, more distant ones.

By this time astronomers were adept at applying Newtonian physics to such systems. If distances could be determined, as they could starting in the late 1830s with the first parallax measurements by Friedrich Wilhelm Bessel (1784–1846), Friedrich Georg Wilhelm Struve (1793–1864), and Thomas James Henderson (1798–1844), then angular separations in arcseconds could be converted to separation distances in astronomical units. Then the separation distance (in au) cubed divided by the period (in years) squared gave the sum of the masses of the two stars (in solar masses). Individual stellar masses could even be computed if the relative distances from the stars to the center of mass of the system could be found.[1] To this day this is the only direct means to determine stellar masses. Binary stars are important!

2 EARLY CATALOGUES

But which pairs of double stars are binary? How common are double stars? How can an astronomer who discovers a close pair learn whether there are earlier observations which could be combined with his own to determine whether the system is binary? The solution to all of these problems is to construct catalogues.

The first catalogue of double stars was published by Christian Mayer (1719–1783) in 1779. This multitalented and multilingual Jesuit priest, born in what is now the Czech Republic, listed 72 double star systems in a small book (Figure 4; Mayer, 1779; Schlimmer, 2007). Most of these were discovered by him, although some had been observed by others, such as William Herschel. He presented separation angles, but neither in this book nor in a slightly longer list published later in the *Astronomische Jahrbuch* for 1784 (Mayer, 1781) did he give position angles. He merely stated that the dimmer star was southwest or south, etc. of the brighter one. There do not appear to be any portraits of Mayer, who taught physics and mathematics at Heidelberg and served as court astronomer in Mannheim until the Jesuit order was dissolved by the Pope in 1773,

but he can be represented by the fine lunar crater that carries his name (Figure 5).

A number of others published catalogues of double stars over the next hundred years. Many consisted of simple lists of doubles discovered or rediscovered by the author, but some included observations by others. The most important catalogues were by two fathers and their sons. William Herschel published a list of 269 doubles, 227 of which he claimed to be the first to see, in 1782 (Herschel, 1782), the year he took up his few duties as astronomer to England's King George III. Three years later he followed up with a list of 434 more, all of his own discovery. As he put it,

> The happy opportunity of giving all my time to the pursuit of astronomy, which it has pleased the Royal Patron of this Society to furnish me with, has put it in my power to make the present collection much more perfect than the former; almost every double star in it having the distance and position of its two stars measured by proper micrometers; and the observations have been much oftener repeated. (Herschel, 1785: 40).

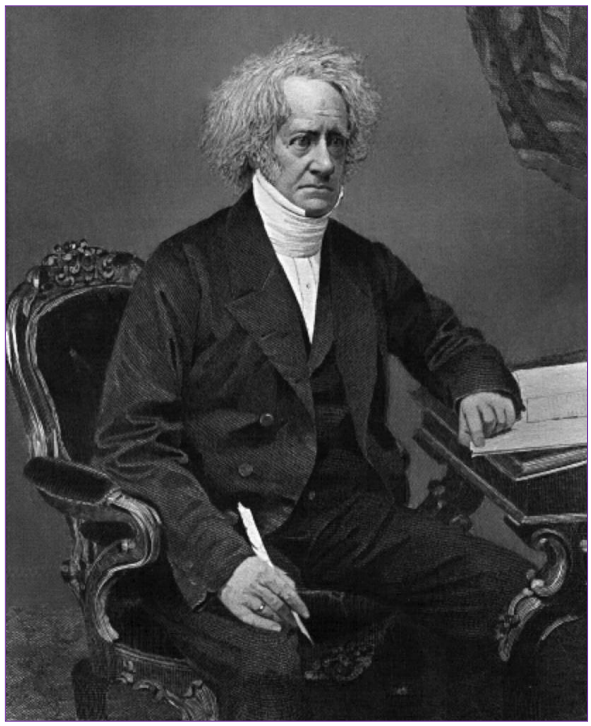


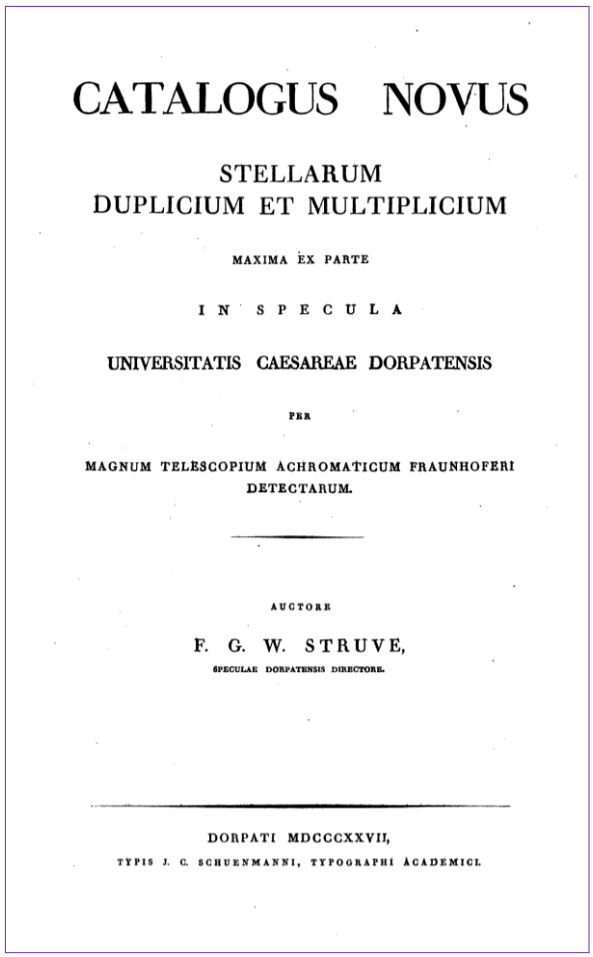
Figure 6: John Herschel (1792–1871) (after Duyckinick, 1873).

His last, less detailed, catalogue was presented when he was in his eighties and serving as first President of what would become the Royal Astronomical Society (Herschel, 1821). Shortly afterward his son, John (Figure 6), published, with surgeon and wealthy amateur James South (Figure 7), his first catalogue, with 380 stars arranged in order of right ascension and including accounts of other measurements besides their own (Herschel and South, 1824).

Figure 7: James South (1785–1867) (NPG P120(20) by Maull & Polyblank (detail), 1855 © National Portrait Gallery, London, used by permission).

Meanwhile in Dorpat, Russia (now Tartu, Estonia), Wilhelm Struve (Figure 8) was publishing a catalogue of 795 stars in 1822 (Struve, 1822) and a much bigger one, with 3112 stars, five years later (Struve, 1827). This catalogue (Figure 9), based on Struve's examination with the Dorpat Observatory's new 9.6-in Fraunhofer refractor of all stars (~120,000) brighter than 9th magnitude and north of –15°, included more than 2500 newly-discovered doubles. It became the world's most important catalogue for some time. It was renowned for the "… extraordinary accuracy for the epoch …" (Jackson, 1922: 4) of the author's measurements despite the fact that he sometimes ex-

Figure 8: Wilhelm Struve (1793–1864) (after a lithograph made from a painting by C.A. Jensen, 1843).



CATALOGUS NOVUS

STELLARUM
DUPLICIUM ET MULTIPLICIUM

MAXIMA EX PARTE

IN SPECULA

UNIVERSITATIS CAESAREAE DORPATENSIS

PER

MAGNUM TELESCOPIUM ACHROMATICUM FRAUNHOFERI
DETECTARUM.

AUCTORE

F. G. W. STRUVE,

SPECULAE DORPATENSIS DIRECTORE.

DORPATI MDCCCXXVII,

TYPIS J. C. SCHUENMANNI, TYPOGRAPHI ACADEMICI.

Figure 9: The title page of F.G.W. Struve, 1827 (Google Books).

amined as many as 400 stars per hour, finding one out of every thirty-five to have a companion within 32 arcseconds (Batten, 1988: 51). Struve published additional catalogues (Struve, 1837; 1852) in later years after becoming founding Director of the Pulkovo Observatory outside St. Petersburg, where he secured a 15-in refractor.

Figure 10: Otto W. Struve (1819–1905) (photograph by W. Clasen).

Struve's son, Otto W. (Figure 10), who worked with his father at Pulkovo from 1839 and would succeed him as Director in 1862, added another major catalogue in 1843 (Struve, O.W., 1843) and supplemented it with several much smaller lists until 1878, giving him a total of 547 systems catalogued.

By the late nineteenth century, many astronomers thought that most binaries that could be discovered had been found. For example, according to Robert Aitken in 1935:

> The feeling that the Herschels, South, and the Struves had practically exhausted the field of double star discovery, at least for astronomers in the northern hemisphere, continued for thirty years after the appearance of the Pulkowa Catalogue in 1843. (Aitken, 1964: 20).

There was, of course, ample reason to reobserve the known doubles. John Herschel, who published a number of lists of newly-discovered double stars in the 1820s and 1830s, was working on a very large catalogue of all known pairs when he died in 1871. It was completed by others and published posthumously (Herschel, 1874) and contained about 10,300 double star systems. However, Herschel had only compiled the measurements of separations and orientations for two-fifths of the systems when he died. His editors published just the list of the stars with their coordinates and precessions. It was in this catalogue that John Herschel introduced a set of symbols that was to last a long time: stars in Wilhelm Struve's final catalogue are denoted by the Greek letter Σ, while those in Otto Struve's catalogues are labeled OΣ and OΣΣ. William Herschel's discoveries are labeled H, and John Herschel's, h. In each case the letters are followed by catalogue numbers. There were other letters as well, and later observers would expand this system with, for example, β for Burnham. In a modified form, with STF replacing Σ for Wilhelm Struve and STT replacing OΣ for Otto Struve, it is retained today as a cross reference in the Washington Double Star Catalog (WDS, n.d.).

3 BURNHAM AND THE BDS

The American Sherburne Wesley Burnham (Figure 11) raised double star cataloguing to new heights. He had little formal education but taught himself shorthand and became a stenographer, a profession of high standing and pay in his time. After recording courts martial for the Union Army in the American Civil War, he became a court reporter in Chicago and bought a six-inch (15-cm) Clark refractor, which he used in his spare time to discover hundreds of double stars that had been

missed by professional astronomers with larger instruments. Soon he was elected a Fellow of the Royal Astronomical Society and allowed to use the 18.5-inch (47-cm) refractor (Figure 12) of the Dearborn Observatory[2] to look for more doubles. He gave up his amateur standing to serve on the initial staff of the Lick Observatory from 1888 to 1892, but resigned to go back to Chicago and court reporting. The needs of his large family for schooling, which was not available on Mount Hamilton, the opportunity to double his salary, and his (widely shared) dislike of Lick Director Edward Singleton Holden (1846–1914) were ample reasons for the move (Osterbrock, et al., 1988). For the rest of his career Burnham worked in the federal courts of Chicago, but his renown among astronomers enabled him to make avocational use of the long refractors of Yerkes Observatory, the Washburn Observatory, and the United States Naval Observatory (USNO), as well as the Dearborn. By the end of the century he had

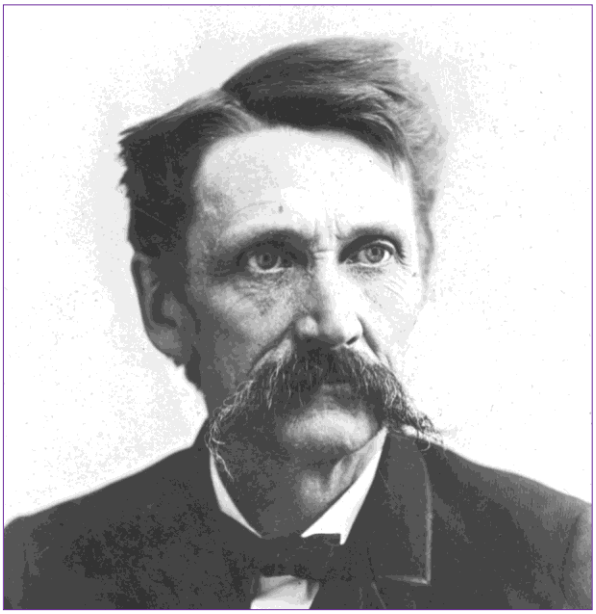


Figure 11: Sherburne Wesley Burnham (1838–1921) (University of Chicago Photographic Archive, apf6-02814, Special Collections Research Center, University of Chicago Library).

discovered and published some 1290 pairs of his own (Burnham, 1900), and he had been collecting observations of others for many years.

In 1906 Burnham published his magnum opus, *A General Catalogue of Double Stars within 121° of the North Pole* (Burnham, 1906), containing observations of 13,665 star systems from around the world. Known as the BDS (Burnham Double Stars), it would serve astronomers for decades. Immediately after completing this work, he started preparing for a second edition by making a handwritten card catalogue of all subsequent observations with one card for each observation. When, he found himself unable to continue, in about 1912, he turned the cards over to Eric Doolittle (Figure 13), the Director of the Flower (later Flower and Cook) Observatory of the University of Pennsylvania.

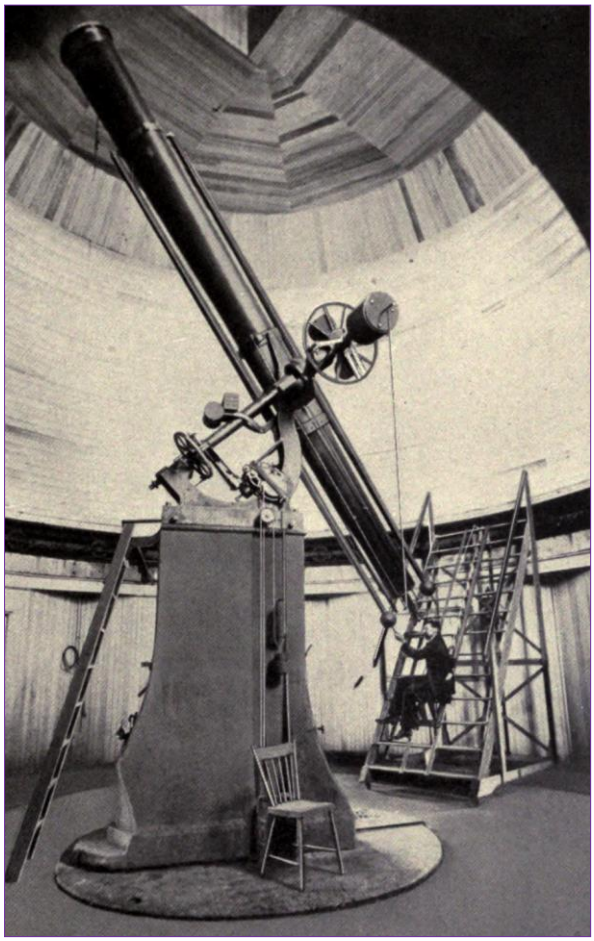


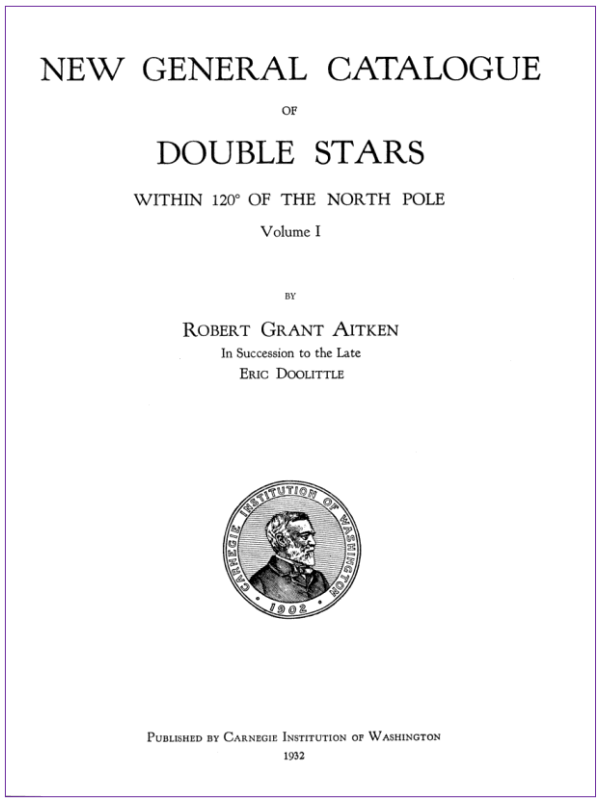
Figure 12: The 18½-in Clark Refractor of the Dearborn Observatory (after Burnham, 1900: opposite page xii).

Figure 13: Eric Doolittle (1870–1920) as a student at Lehigh University in 1891 (courtesy: Special Collections, Lehigh University Libraries, Bethlehem, Pennsylvania).

Figure 14: Robert Grant Aitken (1864–1951) (courtesy of his grandson, Robert Aitken).

4 AITKEN AND INNES, THE ADS AND THE SDS

Doolittle had maintained the card catalogue for only a few years when his health began to fail, so he prevailed on Lick Observatory astronomer Robert Aitken (Figure 14) to take over the responsibility. Aitken began maintaining the card catalogue shortly after Doolittle's death in 1920.



NEW GENERAL CATALOGUE

OF

DOUBLE STARS

WITHIN 120° OF THE NORTH POLE

Volume I

BY

ROBERT GRANT AITKEN

In Succession to the Late

ERIC DOOLITTLE

PUBLISHED BY CARNEGIE INSTITUTION OF WASHINGTON

1932

Figure 15: The title page of the ADS (Aitken, 1932).

Born in a mining town in California shortly after the California gold rush, Robert Aitken crossed the continent to study for the ministry at Williams College in Massachusetts. There he came under the influence of astronomy professor Truman H. Safford (1836–1901) and earned his B.A. in mathematics instead. Shortly after graduation he taught both subjects at the University of the Pacific, then in San Jose at the foot of Mount Hamilton, where the Lick Observatory had gone into operation just six years earlier. In 1894 Aitken wrote Holden, asking to visit Lick during the summer in order to learn to use the transit and micrometer in his teaching. He was successful, and soon he was asking to study astronomy full-time if a way could be found to support his family. He was eager to leave teaching and become a research astronomer (Tenn, 1993; 2013a).

In 1895, Aitken, his wife, and three young sons took the horse-drawn stage up Mount Hamilton, initially so that he could be a summer student. Offered a one-year appointment after just two weeks at Lick, he stayed for forty years, ultimately becoming the Observatory Director.

From the beginning Aitken concentrated on visually measuring double stars with the 36-in and 12-in refractors. At first he measured stars on lists sent to him by Burnham, but soon he was discovering his own. In 1898 he and colleague William Joseph Hussey (1862–1926) divided the sky and set out to examine all stars down to the ninth magnitude and catalogue the doubles. Burnham had to add a supplement to the BDS to include nearly a thousand new systems discovered by Hussey and Aitken in just a few years. Most of the time Hussey used the big Lick Refractor and Aitken the 12-in. After Hussey left in 1905 to head up the new astronomy program at the University of Michigan, Aitken carried on alone. Now he had a great deal of time on the 36-in. Ultimately, Aitken discovered 3087 new double stars and made 26,650 double star observations (Couteau, 1988). After maintaining and expanding Burnham's card catalogue through the beginning of 1927, he set about producing his two-volume, *New General Catalogue of Double Stars within 120° of the North Pole* (Aitken, 1932, Figure 15). Both the title and the lengthy historical introduction make it clear that the book was to be considered a successor to BDS. And it was.

The ADS (Aitken Double Stars), as it became known, contained about 17,000 stars. Like Burnham before him, Aitken had had to find a patron to pay for the costly printing. Burnham had relied on philanthropist Catherine Wolfe Bruce[3] for his 1900 catalogue, while the Carnegie Institution of Washington published both his BDS and Aitken's ADS.

The ADS succeeded the BDS as the double star astronomers' chief reference work, except for stars far to the south. However, this time there was something new. Aitken had coordinated with Robert T.A. Innes (Figure 16), who was simultaneously preparing a double star catalogue of the southern sky. Born in Scotland, where he started publishing papers in celestial mechanics as a highly-skilled amateur despite leaving school at age twelve, Innes had emigrated to Australia, where he ran a liquor and wine business. There he became a serious amateur observer, publishing a short list of his own discoveries of double stars as early as 1894 and attempting unsuccessfully to publish a more general catalogue the following year (Orchiston, 2001; Astronomical Society of Southern Africa, n.d.). He moved to South Africa in 1896 for the opportunity to work in a professional observatory. By 1903 he was founding Director of what would later be called the Union Observatory, and near the end of his career he brought out what was intended to be a preliminary catalogue of mimeographed loose sheets (Innes, et al., 1927). Called the SDS (Southern Double Stars), it was in the same format as the ADS, and between them they covered the sky with some overlap.

Aitken eventually reported some 26,650 observations of double stars. He also spent a great deal of time on writing, speaking, and education and public outreach, much of it done through the Astronomical Society of the Pacific. He edited the *Publications of the ASP* from 1898 to 1942 and twice served as ASP President. He served as Associate Director of Lick from 1923 to 1930, under the thumb of Director William Wallace Campbell (1862–1938), who was in Berkeley, serving as President of the University of California, and finally as Director from 1930 to 1935. Aitken then retired and moved to Berkeley. He gave up maintaining the card catalogue and presented it, along with his personal library (some of it inherited from Burnham via Doolittle), to the Lick Observatory in 1944, when he was eighty. It was promptly turned over to Hamilton Jeffers.

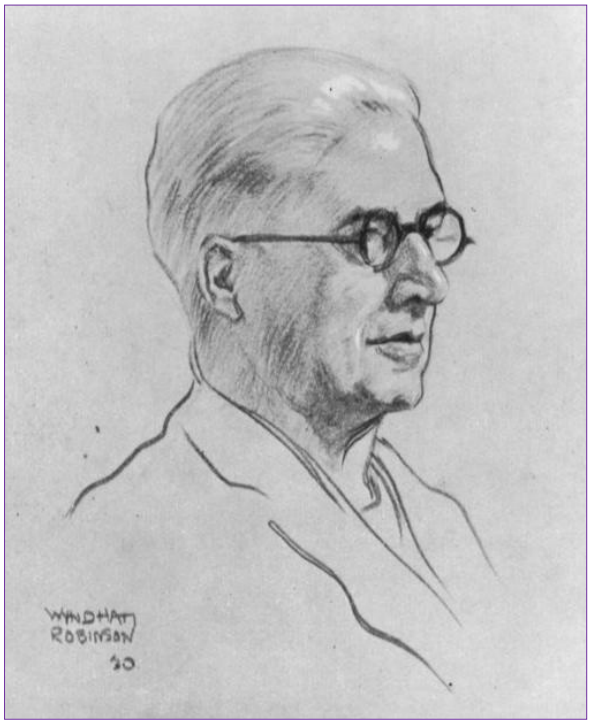


Figure 16: Robert Thorburn Ayton Innes (1861–1933) (after *Journal of the Astronomical Society of South Africa*, 3: 1).

5 JEFFERS, VAN DEN BOS, AND THE IDS

Hamilton Jeffers (Figure 17) was born in Pennsylvania, the son of a Professor of Biblical History, and he remained deeply conservative, both personally and politically, throughout his life. His older brother, Robinson (1887–1962), became a rather prominent poet and settled fairly near the Lick Observatory at Carmel on the central California coast. Jeffers first worked at Lick while a graduate student at the University of California from 1917 to 1921. He returned when Aitken hired him to work at Lick in 1924. He would remain there the rest of his career. In his early years he became an expert with the meridian circle, measuring positions of reference stars, and also with timekeeping and short wave radio. A man of many hobbies, he delighted in flying his own plane across the country to attend astronomical meetings. He was the principal user of the venerable 36-in Lick refractor both before and after service in WWII, and it was natural that he would succeed Aitken in maintaining the catalogue of double stars (Tenn, 2013b).

Using the eyepiece interferometer invented by South African astronomer W.S. Finsen (1905–1979), Jeffers added greatly to Aitken's collection of file cards, which included data on about 17,000 double stars when he acquired it. By the early 1950s it was clear to Jeffers that the time had come to replace the handwritten cards of Burnham, Doolittle, and Aitken with new technology:

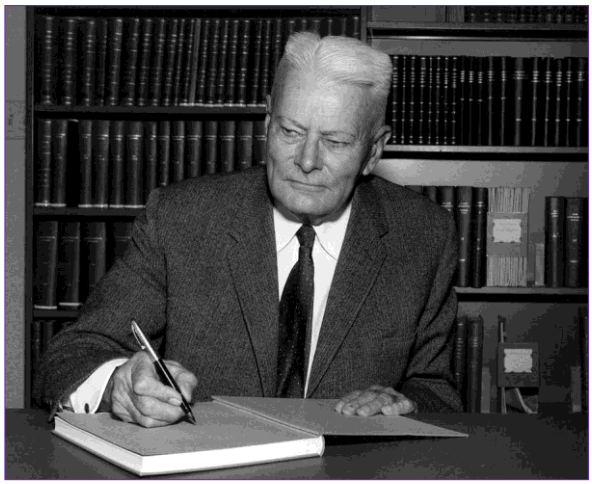


Figure 17: Hamilton Jeffers (1893–1976) (courtesy: Special Collections & Archives, University of California Santa Cruz).

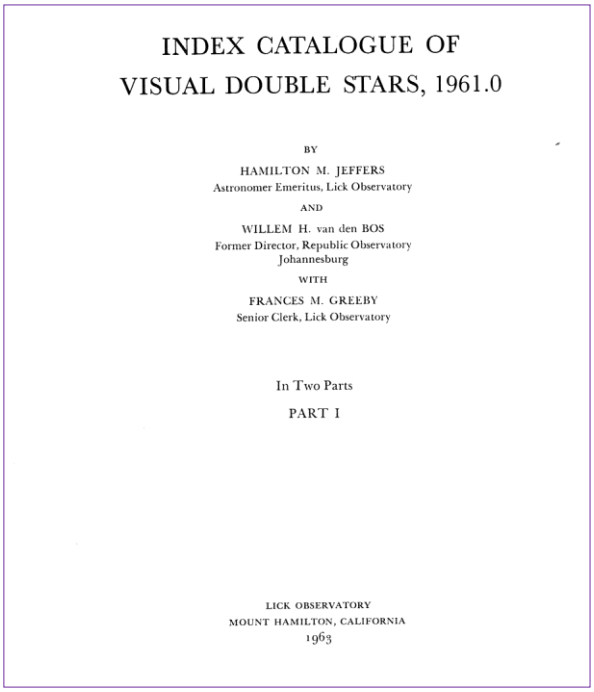
Figure 18: Frances M. 'Rete' Greeby (1921–2002) (courtesy: California Academy of Sciences).

machine readable punched cards. He secured a grant from the National Scientific Foundation and hired Frances M. 'Rete' Greeby to do the key-punching. Greeby had recently moved to Mt. Hamilton when her husband took a job at Lick; she had previously worked for the California Academy of Sciences in San Francisco, where she made the star plates for the Morrison Planetarium, as shown in Figure 18.

As he extended the punched card catalogue back to 1927.0, the date of the ADS, Jeffers realized that it would now be possible to combine all observations of double stars, north and south, into one catalogue. He joined forces with Willem van den Bos, the Dutch-born Johannesburg astronomer who as a young man had been a coauthor of the SDS and was now Director of the Union Observatory. So after punching 95,000 cards representing observations of double stars north of –20°, Greeby punched another 50,000 using data on southern stars sent by van den Bos, who became a close friend of Jeffers and visited Lick from 1961 to 1963 (Figure 19).

Figure 19: Willem van den Bos and Hamilton Jeffers at Lick Observatory, 1963 (courtesy: James B. Breckinridge).

But how could they publish so much data? It was decided to split it into two catalogues. The *Index Catalogue* (Figure 20, to be known as IDS) was prepared from one 80-column card per star system. It contained positions in 1900 and 2000, discoverer's symbol, discoverer's number, if any, multiplicity, first and last measures with their dates,



INDEX CATALOGUE OF
VISUAL DOUBLE STARS, 1961.0

BY
HAMILTON M. JEFFERS
Astronomer Emeritus, Lick Observatory
AND
WILLEM H. van den BOS
Former Director, Republic Observatory
Johannesburg
WITH
FRANCES M. GREEBY
Senior Clerk, Lick Observatory

In Two Parts
PART I

LICK OBSERVATORY
MOUNT HAMILTON, CALIFORNIA
1963

Figure 20: Title page of the IDS (Jeffers, et al., 1963).

number of measures, position angles, separation distances, magnitudes, spectral classes, proper motions, catalogue numbers in previous catalogues, and indication if an orbit had been computed. It was published on paper, as a volume of the *Publications of the Lick Observatory* (Jeffers, et al., 1963). It contained 64,247 pairs and claimed to be "a list of essentially all visual double stars for which measures have been published up to the end of the year 1960" (ibid.: vii). All of the other observations would remain on punched cards. Jeffers thought that three sets of cards would be sufficient for the world's astronomers, one each at Lick and Union Observatories, and the third somewhere in Europe. As they described the project,

> … it seems reasonable to suppose that, broadly speaking, double star discovery has now been accomplished. Our principal requirements at present are not further additions to the large number of known double stars, but more and more reliable data on the latter—on their motions as well as their general physical characteristics (van den Bos and Jeffers, 1957: 323).

There was a problem, however. Jeffers turned seventy the year the *Index Catalogue* was published. He had formally retired two years earlier, but had been hired back part-time to see the catalogue through publication. He desperately wanted the Lick Observatory to hire another 'double star man' to replace him and maintain the tradition of Burnham, Aitken, and himself. He wrote letters for several years campaigning for such a hire, but he got nowhere with the new Lick Director, Albert Edward Whitford (Figure 21). Lick had acquired a 120-in (3-meter) reflector, the second largest telescope in the world, in 1958, and Whitford, a pioneer of photoelectric photometry (Tenn, 2013c), was not going to hire an astrometrist to do research with the nineteenth-century Lick refractor. Astrophysics was in vogue and would remain so. Jeffers tried to get a lower level hire: his assistant, James B. Gibson, could maintain the double star program and card catalogue under minimal supervision. Whitford was not interested, and Gibson left to work for Kaj A. Strand (Figure 22) of the United States Naval Observatory (USNO) at its new station near Flagstaff, Arizona.

By 1964 Jeffers was desperate. He suggested that Mrs. Greeby could maintain the card catalogue in one afternoon per week. He wrote emotional letters trying for any solution other than the one he feared: that the catalogues would come under the control of Strand. He wrote Whitford, "Strand is energetic and ambitious, but he is hardly popular as an administrator or as a co-worker." (Jeffers, 1964a). He suggested that if the catalogues could not remain at Lick, then they should go to Paris or Greenwich, where they could be maintained by Paul Muller (1910–2000) or Richard van der Riet Woolley (1906–1986). When Whitford accused him of basing his position on "… poorly concealed reasons of personal dislike …" (Whitford 1964), Jeffers claimed to personally like Strand but,

> On the official or professsional side, though, I have not appreciated his ten years of politicking and influence wielding with the object of getting control of the double star catalogues. However, I cannot help but admire the manner in which his campaign was brought to an apparently successful conclusion. (Jeffers, 1964b).

From most accounts Strand was a difficult person to work with—one person called him "imperious"—but he was certainly an able scientist who got things done. A Dane, he had been an assistant to Ejnar Hertzsprung at Leiden before emigrating to the United States in 1938. His oral history interviews (Strand, 1983) reveal that he did not lack ego. In any case, Jeffers' efforts to keep the catalogues away from the USNO were all in vain. The International Astronomical Union (IAU) Commission 26 Double and Multiple Stars had appointed a subcommittee on 'Disposition and Management of the Double Star Catalogues'. This group met just before the 1964 IAU meeting in Hamburg and recommended that the catalogues be transferred to the USNO under the following conditions:

Figure 21: Albert Edward Whitford (1905–2002) in 1968 (courtesy: William Whitford).

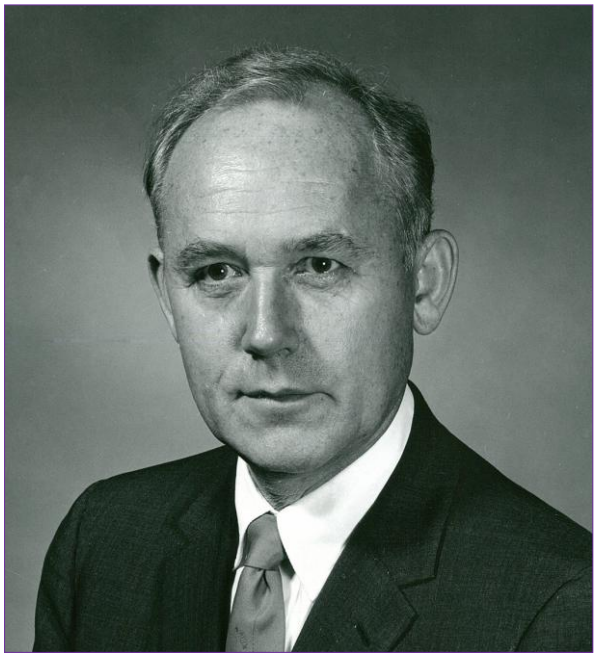


Figure 22: Kaj Aage Strand (1907–2000) (courtesy: U.S. Nav--al Observatory).

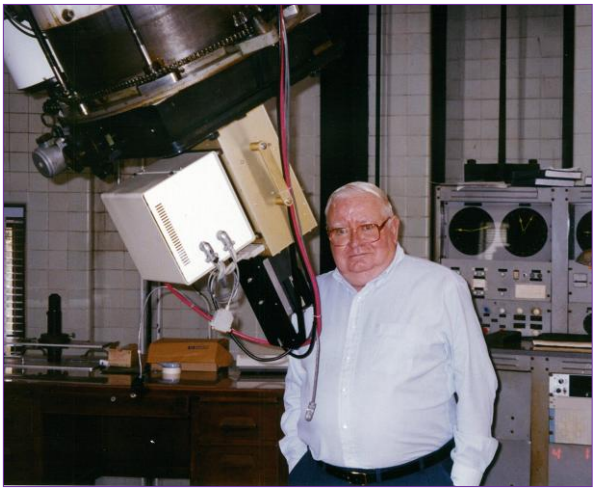


Figure 23: Charles Edmund Worley (1935–1997) (courtesy: U.S. Naval Observatory).

> The Double Star Centre at the United States Naval Observatory has the following obligations:
> (1) The sole responsibility to maintain the catalogues to date.
> (2) To furnish the other centres and the Lick Observatory with supplements when new data become available.
> (3) To furnish individuals with data from the two catalogues at cost.

Strand was a member of the subcommittee, but he did not attend the meeting. Whitford, who apparently had asked the Commission what to do with the records, did attend. Jeffers, now fully retired, did not go to Hamburg. The proposal was adopted by the Commission, and Strand became its President (van de Kamp, 1966).

6 THE USNO AND THE WDS

Jeffers, who afterward referred to "Whitford's sell-out of the card catalogues," (Jeffers, 1965) may not have been aware that Strand had been promoted in 1963 from Head of the Astrometry and Astrophysics Division to Scientific Director at the USNO. He would never be in direct charge of the double star catalogues. Instead they came under the management of Charles Worley (Figure 23), who had worked at Lick from 1959 to 1961 and who was respected and liked by his colleagues (Mason, et al., 2007). Worley flew to California in 1965 and took the catalogues back to Washington. They had been converted from cards to magnetic tape, as the cards were too bulky to transport. At the USNO they were transferred back to punched cards. When asked why, Worley replied:

> The reason is simple: one needs to do interleaving. That is, to add new observations and even old observations to the data file. And you can't do that easily on tape. The technology of the time, in the 1960s, cards were the best way to do that. We could prepare new cards and insert them in proper spots in the data file. (Worley, 1988).

Worley maintained the catalogues until his death in 1997, just two days before he was scheduled to retire. During his thirty-two years he added 290,400 observational records to the 179,000 he received, and the number of multiple star systems increased from 64,000 to more than 81,000 (Mason, et al., 2007: 30). Alone or with others he produced three *Catalogs of Orbits of Visual Binary Stars* (Worley, 1963; Finsen and Worley, 1970; Worley and Heintz, 1985).

Worley also played a key role in bringing binary star observations—considered by some to be old-fashioned astronomy—into the modern age by obtaining a speckle interferometer for the USNO in 1990 (Douglass, et al., 1997). Mounted on the historic 26-in refractor, which was built in 1873 and moved to its present location in 1893, it is still used regularly for precise measurements of visual binary stars, even though it is in the midst of the brightly-lit capital city (Hartkopf and Mason, 2005). Worley started the USNO practice of hiring astronomers who had worked with Harold McAlister (b. 1949), a leader in developing the speckle technique, at Georgia State University (GSU). Among these are Brian Mason, who earned his Ph.D. at GSU and has directed the Washington Double Star Catalog since Worley's death, and William Hartkopf, who formerly served as Assistant Director of GSU's Center for High Angular Resolution Astronomy. Now Mason and Hartkopf (Figure 24) are the 'keepers of the double stars'.

Figure 24: William I. Hartkopf (b. 1951) and Brian D. Mason (b. 1961) in 2012 (photograph by the author).

Today the Washington Double Star Catalog (WDS) is entirely online, and it is updated nightly. A direct descendant of Burnham's BDS, Aitken's ADS, Innes's SDS, and Jeffers and van den Bos's IDS, it is, as its website (WDS, n.d.) states, "… the world's principal database of astrometric double and multiple star information." As of 26 February 2013, it contained 1,201,492 mean measurements of 125,273 star systems.

7 NOTES

1. This is oversimplified, as the inclination of the orbital plane to the plane perpendicular to the line of sight, which can also be determined

from the visual observations, has to be taken into account in order to compute the actual masses. The determination of masses became much more feasible with the discovery of spectroscopic binaries with their much shorter periods, especially those systems that display eclipses, for which the orbital inclination can also be determined. This paper deals only with visual binaries, systems in which the two stars can be seen or imaged distinctly. Radial velocities of visual binaries can often be used to determine the absolute size of the orbit for those systems that lack a trigonometrical parallax.

2. The Dearborn Observatory began operation in 1865 under the Old University of Chicago (not to be confused with the present one) and after that institution's bankruptcy in 1881 passed to the Chicago Astronomical Society and later to Northwestern University. From 1862 to 1869 the 18.5-in telescope was the largest refractor in the world.
3. Miss Bruce is remembered today for endowing the eponymous medal that has been awarded by the Astronomical Society of the Pacific to the world's leading astronomers since 1898 (Tenn, 1986).

8 ACKNOWLEDGEMENTS

A preliminary and much shorter version of this paper was presented to the Historical Astronomy Division of the American Astronomical Society in January 2013. The reader interested in learning more about the early history of double star astronomy may wish to consult the series of papers by T. Lewis (1908). The author is grateful to Alan H. Batten, William I. Hartkopf, Brian D. Mason, and Elizabeth Roemer for advice and comments, and to those who provided images and materials, including James B. Breckinridge, Rebecca Morin, Kelly Jensen, Alan H. Batten, William I. Hartkopf, Eric Shelton, and Ilhan Citak. Excerpts from letters in the Mary Lea Shane Archives of Lick Observatory are published courtesy of Special Collections & Archives, University of California Santa Cruz. This research has made extensive use of the SAO/NASA Astrophysics Data System.

9 REFERENCES

Aitken, R.G., 1964. *The Binary Stars.* (Republication of the 2nd edition of 1935.) New York, Dover.

Aitken, R.G., 1932. *New General Catalogue of Double Stars within 120° of the North Pole.* Washington, Carnegie Institution of Washington.

Astronomical Society of Southern Africa, n.d. ASSA Historical Section: Innes, Robert Thorburn Ayton. http://assa.saao.ac.za/html/his-astr-innes_rta.html.

Batten, A.H., 1988. *Resolute and Undertaking Characters: The Lives of Wilhelm and Otto Struve.* Dordrecht, Reidel.

Burnham, S.W., 1900. A general catalogue of 1290 double stars discovered from 1871 to 1899 by S.W. Burnham. Arranged in order of right ascension with all the micrometrical measures of each pair. *Publications of the Yerkes Observatory of the University of Chicago,* 1, i-xxx, 1-296.

Burnham, S.W., 1906. *A General Catalogue of Double Stars within 121° of the North Pole.* Washington, Carnegie institution of Washington.

Couteau, P. *Ces Astronomes Fous du Ciel, ou l'Histoire de l'Observation des Etoiles Doubles.* Aix-en-Provence, Édisud.

Douglass, G.G., Hindsley, R.B., and Worley, C.E., 1997. Speckle interferometry at the US Naval Observatory. I. *Astrophysical Journal Supplement*, 111, 289-334.

Duyckinick, E.A., 1873. *Portrait Gallery of Eminent Men and Women in Europe and America*. New York, Johnson, Wilson & Company.

Fedele, U., 1949. Le prime osservazioni di stelle doppie. *Coelum*, 17, 65-69 (http://www.leosondra.cz/en/mizar/fedele/).

Finsen, W.S., and Worley, C.E., 1970. Third catalogue of orbits of visual binary stars. *Republic Observatory, Johannesburg Circular* 7, 203-254.

Hartkopf, B., and Mason, B., 2005. So what is speckle interferometry good for, anyway? 2005 Michelson Summer Workshop: Discovering New Worlds Through Astrometry http://nexsci.caltech.edu/workshop/2005/presentations/Hartkopf.pdf.

Herschel, J.F.W., and South, J., 1824. Observations of the apparent distances and positions of 380 double and triple stars, made in the years 1821, 1822, and 1823, and compared with those of other astronomers; together with an account of such changes as appear to have taken place in them since their first discovery. Also a description of a five-feet equatorial instrument employed in the observations. *Philosophical Transactions of the Royal Society of London,* 114, 1-412.

Herschel, J.F.W., 1874. A catalogue of 10,300 multiple and double stars, arranged in the order of right ascension by the late Sir J.F.W. Herschel, Bart. edited by Rev. R. Main, M.A., F.R.S. and Rev. C. Pritchard, M.A., F.R.S. *Memoirs of the Royal Astronomical Society,* 40.

Herschel, W., 1782. Catalogue of double stars. *Philosophical Transactions of the Royal Society of London,* 72, 112-162.

Herschel, W., 1785. Catalogue of double stars. *Philosophical Transactions of the Royal Society of London,* 75, 40-126.

Herschel, W., 1802. Catalogue of 500 new nebulae, nebulous stars, planetary nebulae, and clusters of stars; with remarks on the construc-

tion of the heavens. *Philosophical Transactions of the Royal Society of London,* 92, 477-528.

Herschel, W., 1803. Account of the changes that have happened, during the last twenty-five years, in the relative situation of double-stars; with an investigation of the cause to which they are owing. *Philosophical Transactions of the Royal Society of London,* 93, 339-382.

Herschel, W., 1821. On the places of 145 new double stars. *Memoirs of the Astronomical Society,* 1, 166-181 [reprinted in Dreyer, 1912: vol. 2, 614-627. http://www.archive.org/stream/scientificpapers02hersuoft#page/n637/].

Holden, E.S., 1881. *Sir William Herschel, his Life and Works*. New York, Scribner's.

Innes, R.T.A., Dawson, B.H., and van den Bos, W.H., 1927. *Southern Double Star Catalogue – 19 deg. to –90 deg.* Johannesburg, Union Observatory.

Jackson, J. 1922. The W. Struve (Σ) double stars. *Monthly Notices of the Royal Astronomical Society,* 83, 4-32.

Jeffers, H.M., 1964a. Letter to A.E. Whitford, dated 12 September. Mary Lea Shane Archives of Lick Observatory, Special Collections & Archives, University of California Santa Cruz.

Jeffers, H.M., 1964b. Letter to A.E. Whitford, dated 12 October. Mary Lea Shane Archives of Lick Observatory, Special Collections & Archives, University of California Santa Cruz.

Jeffers, H.M., 1965. Letter to W.H. van den Bos, dated 28 February. Mary Lea Shane Archives of Lick Observatory, Special Collections & Archives, University of California Santa Cruz.

Jeffers, H.M., and van den Bos, W.H. with Greeby, F.M. 1963. Index Catalogue of Visual Double Stars, 1961.0. *Publications of the Lick Observatory,* 21.

Lewis, T., 1908. Double-star astronomy. *The Observatory,* 31, 88-93, 125-129, 162-168, 205-208, 242-247, 279-282, 307-13, 339-346, 379-384.

Mason, B.D., Hartkopf, W.I., Corbin, T.E., and Douglass, G.G., 2006. Charles Edmund Worley (1935–1997). In Hartkopf, W.I., Guinan, E.F. and Harmanec, P. (eds.). *Binary Stars as Critical Tools & Tests in Contemporary Astrophysics (Proceedings of IAU Symposium No. 240).* Cambridge, Cambridge University Press. Pp. 28-32.

Mayer, C., 1779. *De novis in Coelo sidereo Phaenomenis in miris Stellarum fixarum comitibus.* Mannheim (http://digiwunschbuch.sub.uni-goettingen.de/ddms/dimg/?PPN=PPN514949503).

Mayer, C., 1781. Verzeichnis aller bisher entdeckten Doppeltsterne. In Bode, J.E., (ed). *Berliner Astronomisches Jahrbuch für 1784.* Pp. 183-186 (http://www.epsilon-lyrae.de/Beobachtungstipp/BAJ1784.html).

Michell, J., 1767. An inquiry into the probable parallax, and magnitude of the fixed stars, from the quantity of light which they afford us, and the particular circumstances of their situation. *Philosophical Transactions,* 57, 234-264.

Ondra, L., 1999. A New View Of Mizar. http://www.leosondra.cz/en/mizar/.

Orchiston, W., 2001. From amateur astronomer to observatory director: the curious case of R. T. A. Innes. *Publications of the Astronomical Society of Australia,* 18, 317-328.

Osterbrock, D.E., Gustafson, J.R., and Unruh, W.J.S., 1988. *Eye on the Sky: Lick Observatory's First Century.* Berkeley, University of California Press.

Schlimmer, J.S., 2007. Christian Mayer's double star catalog of 1779. *Journal of Double Star Observations*, 3, 151-158.

Strand, K.A., 1983. Interviews conducted by David DeVorkin and Steven Dick on 8 December, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD USA (http://www.aip.org/history/ohilist/23026_1.html).

Struve, F.G.W., 1822. Catalogus 795 stellarum duplicium: ex diversorum astronomorum observationibus congestus in specula Dorpatensi. *Observationes astronomicae in specula universitatis Dorpatensis,* III.

Struve, F.G.W., 1827. *Catalogus novus stellarum duplicium et multiplicium : maxima ex parte in specula Universitatis Caesarea Dorpatensis per magnum telescopium achromaticum Fraunhoferi detectarum.* Dorpat, Schuenmann.

Struve, F.G.W., 1837. *Stellarum duplicium et multiplicium mensurae micrometricae per magnum Fraunhoferi tubum annis a 1824 ad 1837 in specula Dorpatensi Institutae: adjecta est synopsis observationum de stellis compositis Dorpati annis 1814 ad 1824 par minora instrumenta perfectarum.* Tartu, Astronoomia Observatoorium.

Struve, F.G.W., 1852. *Stellarum fixarum imprimis duplicium et multiplicium positiones mediae: pro epocha 1830,0, deductae ex observationibus meridianis annis 1822 ad 1843 in Specula Dorpatensi Institutis.* Petrograd, Ex typographia Academica.

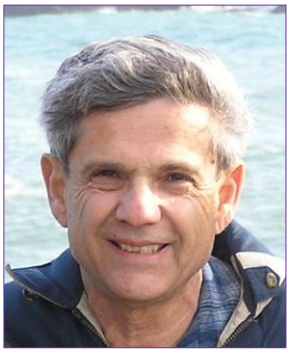
Struve, O.W., 1843. *Catalogue de 514 Étoiles Doubles et Multiples découvertes sur l'hémisphère celeste boréal par la grande lunette de l'Observatoire Central de Poulkova, et Catalogue de 256 Étoiles Doubles Principales où la distance des composantes est de 32 secondes à 2 minutes et qui se trouvent sur l'hémisphere boreal.* St. Petersburg, Academy of Sciences.

Tenn, J.S., 1986. A Brief History of the Bruce Medal of the A.S.P. *Mercury,* 15, 103-111. http://phys-astro.sonoma.edu/BruceMedalists/BruceMedalHistory.pdf.

Tenn, J.S., 1993. Robert G. Aitken: The twenty-first Bruce medalist. *Mercury,* 22, 20-21.

Tenn, J.S., 2013a. Robert G. Aitken (http://phys-

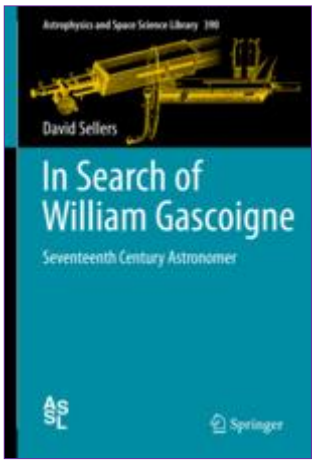
astro.sonoma.edu/BruceMedalists/Aitken/).
Tenn, J.S., 2013b. Hamilton Jeffers. In Hockey, T. (ed.). *Biographical Encyclopedia of Astronomers. Second Edition.* New York, Springer (in press).
Tenn, J.S., 2013c. Albert E. Whitford (http://phys-astro.sonoma.edu/BruceMedalists/Whitford/).
van de Kamp, P., 1966. Report of Meeting, 26 August 1964. Etoiles Doubles (Double Stars). *Transactions of the International Astronomical Union,* 12B, 267-268.
van den Bos, W.H., and Jeffers, H.M., 1957. An index catalogue of visual double and multiple stars. *Publications of the Astronomical Society of the Pacific,* 69, 322-325.
WDS, n.d. The Washington Double Star Catalog. http://ad.usno.navy.mil/wds/.
Whitford, A.E., 1964. Letter to H.M. Jeffers, dated 29 September. Mary Lea Shane Archives of Lick Observatory, Special Collections & Archives, University of California Santa Cruz.
Worley, C.E., 1963. A Catalogue of Visual Binary Orbits. *Publications of the United States Naval Observatory*, 18(3).
Worley, C.E., 1988. Interview conducted by David DeVorkin 31 March at the USNO. Smithsonian Institution Archives, Record Unit 9534, Classical Observation Techniques Interviews.
Worley, C.E., and Heintz, W.D., 1983. Fourth catalog of orbits of visual binary stars. *Publications of the United States Naval Observatory*, 24(7).



Joseph S. Tenn taught physics and astronomy at Sonoma State University in the California wine country from 1970 to 2009. He now serves as Secretary-Treasurer of the Historical Astronomy Division of the American Astronomical Society and as an Associate Editor of the *JAHH*. He maintains the Bruce Medalists website at http://phys-astro.sonoma.edu/brucemedalists/.

BOOK REVIEWS

***In Search of William Gascoigne: Seventeenth Century Astronomer,* by David Sellers (New York, Springer, 2012), ix + 222 pp., ISBN 978-1-4614-4096-3, ISBN 978-1-4614-4097-0 (ebook), 160 × 240 mm. US$129.**



This book is well-titled: all I knew about William Gascoigne before I read it was that he lived in the seventeenth century and had something to do with the early development of the filar micrometer. Apparently I was not the only one whose knowledge was so limited, and David Sellers has indeed gone "… in search of William Gascoigne …" and has been to some extent frustrated by the fact that papers and correspondence known to have survived Gascoigne's death have since been lost. Perhaps those papers will one day be found in some dusty attic but, meanwhile, biographers must make do with the limited source material available. Considering the importance of the filar micrometer in positional astronomy and the study of visual double stars, Gascoigne certainly deserves a full-length biography.

Credit for the invention of the filar micrometer is often given to the French astronomer Adrien Auzout (a somewhat younger contemporary of Gascoigne but longer lived), and much of Sellers' account is given to establishing clearly Gascoigne's priority. Auzout himself, it seems, was perfectly willing to give Gascoigne the credit, but some of his compatriots were less generous—shades of the later conflict between the supporters of Adams and Le Verrier, although on that occasion the French had greater justification for their claims.

Also contemporary with Gascoigne were William Crabtree and Jeremiah Horrox (Sellers' preferred spelling), famed for being the first to observe a transit of Venus. All three lived in northern England and had short lives. Crabtree and Gascoigne met at least once and corresponded frequently. Unfortunately, Horrox died before Crabtree could arrange a meeting between the other two. One can only speculate what these three young men might have achieved had they been granted normal life spans. As it is, Flamsteed admired Gascoigne's work, and we owe a part of our knowledge of the latter to the former's efforts to preserve some of his writings.

Gascoigne's life and work were cut short by the civil wars of seventeenth-century England and Scotland. He joined the Royalist cause and probably was killed at the battle of Marston Moor in 1644, although even this is not certain. If he did die there, he would have been at most 33 years old. Horrox died even younger, three years earlier, and Crabtree died at the age of 34, in the same year as his friend Gascoigne.

Sellers' book gives a good account of what is known of Gascoigne's work, and also sets the man in his times. Some of this 'setting' occasionally may read like padding, but this can be forgiven in view of the paucity of information on which to base a full biography of Gascoigne. At times, a little more editing by the publisher would have been beneficial. For example, the "… bisection of the eccentricity …" is introduced on page 54 but not defined until page 93. I also found the lack of consistency in the capitalization of adjectives derived from proper names to be somewhat irritating: "Galilean" almost always gets upper-case, while "Keplerian" hardly ever does. On the other hand, an appendix of over 60 pages reprints much of Gascoigne's surviving correspondence (mainly with Crabtree). The general reader may skip this—I read it somewhat cursorily myself—but other historians of astronomy will find it extremely useful.

This book has clearly been a labour of love, and it fills an important gap in the history of English astronomy. Unless that hypothetical dusty attic does one day give up its secrets, Sellers has probably told us all that we can hope to learn about William Gascoigne. He does, however, leave us wondering how three young men, largely self-taught in astronomy, and remote from the centres of learning in the England of their time, came to achieve so much. Perhaps that will be the subject of another book.

Dr Alan Batten
Victoria, B.C., Canada
Email: ahbatten@telus.net

***Nicolas-Louis de la Caille Astronomer and Geodesist*, by I.S. Glass (Oxford, Oxford University Press, 2013), [vi] + 194 pp., ISBN 978-0-19-966840-3 (hardback), 160 × 240 mm. £35.**

Nicolas-Louis de la Caille, also known as La Caille and Lacaille (his usual signature), is described by Ian Glass as "... one of the greatest astronomers of the eighteenth century …" (page 1), and in this book Glass sets out to explain why.

La Caille—as we shall call him—was born in a small town near the border of France and Belgium in 1713. After completing his schooling, he

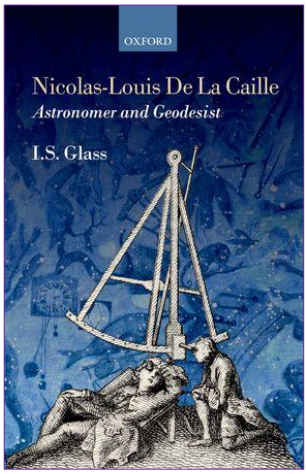
studied rhetoric, philosophy, theology, geometry and eventually astronomy at colleges that formed part of the University of Paris, and soon after graduating he found employment at Paris Observatory, where he impressed the Director, Jean-Dominique Cassini I. However, three and a half years later he moved to a Chair in Mathematics at the Collège Mazarin in Paris, and remained there for the rest of his working life. In 1742 and 1748 he arranged for two observatories to be erected on the spacious roof of the building, and with research at Paris Observatory in decline, the well-equipped Collège Mazarin Observatory soon became the most important observatory in all Paris.

Although he conducted research on the shape of the Earth and on the motions of the planets, La Caille is best remembered for his one and a half year visit to the Cape of Good Hope in 1751-1752, and this occupies Chapters 2-4 in Glass' book. After some introductory comments there is information about La Caille's observatory and instruments before Glass describes La Caille's pioneering survey of the southern sky which "… was the first really systematic one ever to have been made in either hemisphere. Every part of the sky south of the Tropic of Capricorn was examined …" (page 50). This survey started on 6 August 1751 and ended on 18 July 1752 and resulted in the charting of 9766 'stars' (actually some of the 'nebulous stars' would later turn out to be clusters or gaseous nebulae). La Caille also prepared a large (1.95-m diameter) planisphere; identified and defined fourteen new constellations; and either re-organized or completely abolished three constellations that previously had been established by other astronomers. But La Caille did more than this, for while at the Cape he observed the Moon, Venus, Mars, and Jovian satellite phenomena; determined the latitude and longitude of his observatory; and used triangulation to measure the height of nearby Table Mountain.

In Chapter 3 Glass has La Caille returning to the first major project he embarked on when he joined Paris Observatory: researching the shape of the Earth. Geodesy was then deemed a branch of astronomy, and with five months 'to kill' before he could return to Paris La Caille determined to measure an arc of the meridian while in South Africa. This involved an initial reconnaissance near Cape Town, followed by a more ambitious full-scale expedition, which showed that the Earth was an oblate spheroid but was more heavily flattened in the southern hemisphere than in the northern hemisphere.

While at the Cape and during his geodetic surveys La Caille kept a diary in which he recorded a wealth of non-astronomical local information. This fascinating document is reviewed by Glass in Chapter 4, and after the preceding scientific chapters is a welcome diversion that also reveals something of La Caille, the man.

After leaving Cape Town La Caille returned to Paris via Mauritius and Réunion Island, and then published his astronomical observations, other books on astronomical topics and a map of the Cape region. He also had teaching duties at the Collége, and among his students were some who would go on to achieve international reputations. Glass discusses these in Chapter 5 (titled "Later Years"), along with La Caille's on-going astronomical research programs and observations. His last astronomical observations were made on 28 February 1762 and he died three weeks later, on 21 March.



The final chapter ("Paradox Resolved") in this interesting book looks mainly at later scientists who critically investigated La Caille's geodetic conclusions. Some of them even tried to retrace La Caille's steps and identify his trig survey stations. Thomas Maclear, HM Astronomer at the Cape from 1833 to 1870, also managed to pin down the precise location of La Caille's observatory in Cape Town.

Rounding out this well-written, nicely-researched, copiously-illustrated and very modestly-priced book are six Appendices and an Index, but I was rather surprised to find Knobel's 1917 paper on Frederick de Houtman absent from Glass' 6-page Bibliography. To me, this was the one thing missing from the book: a brief discussion of Houtman and Keyser's earlier survey of the southern sky, published in 1603, and the extent to which La Caille's work built on this (which it certainly did).

But this is a minor quibble, as this is an excellent book that is well worth buying and reading.

References

Knobel, E.B., 1917. On Frederick de Houtman's catalogue of southern stars, and the origin of the southern constellations. *Monthly Notices of the Royal Astronomical Society*, 77, 414-432.

Professor Wayne Orchiston
National Astronomical Research Institute of Thailand, Chiang Mai, Thailand
Email: wayne.orchiston@narit.or.th