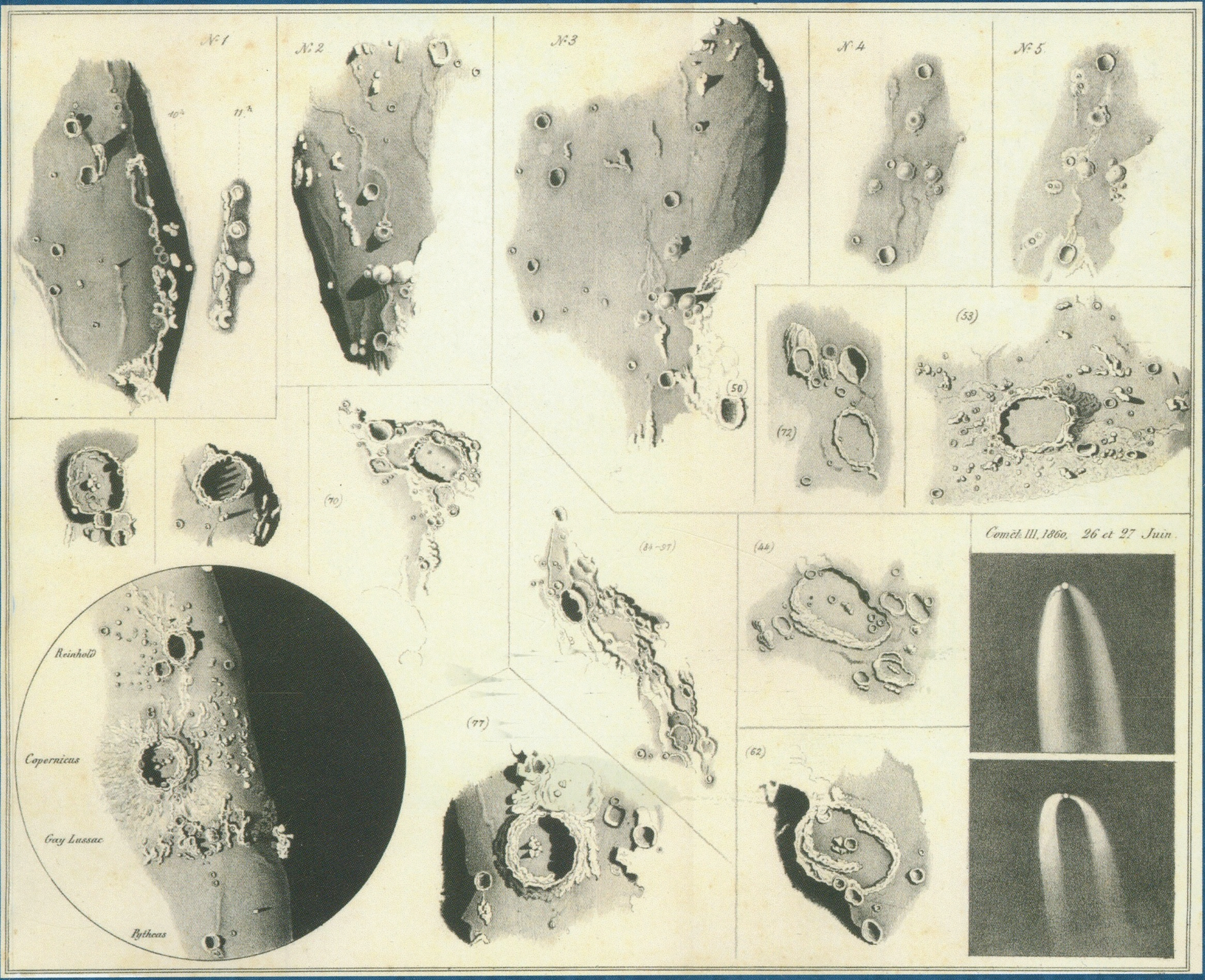
JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE



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COVER PHOTOGRAPH

Wilhelm Tempel (1821–1889) is well known for the comet and minor planet discoveries he made while based in Venice, Marseille and later Milan, but few would realise that he was a trained lithographer. The image on the cover of this issue of JAH^2 is from the Archives of the INAF-Arcetri Astrophysical Observatory, and reveals something of Tempel's artistic talent. He prepared this previously-unpublished lithograph in 1860 while based in Marseille, and it portrays a series of drawings of lunar features and craters made during the previous year when he was in Venice. The two inset drawings at bottom right depict Comet C/1860 M1. For details of Tempel's remarkable astronomical career, his modest 10.8-cm Steinheil refractor, and further examples of his drawings see the paper by Bianchi et al. on pages 43 to 58 in this issue of the Journal.

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CONTENTS

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THE RADIOPHYSICS FIELD STATION AT PENRITH, NEW SOUTH WALES, AND THE WORLD'S FIRST SOLAR RADIOSPECTROGRAPH

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Abstract: The Solar Radio Astronomy Group within the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics built the world's first radiospectrograph at Penrith (Australia) in 1948. The instrument was used to study radio emission from the active Sun over the continuous frequency range of 70 to 130 MHz. This led to the first spectral classification of solar radio bursts which advanced the scientific study of space research by the real time monitoring of the active corona.

Keywords: radio astronomy, solar radio emission, radiospectrograph, Division of Radiophysics, CSIRO.

1 INTRODUCTION

Although the foundations of radio astronomy date from Karl Jansky's pioneering research in 1931-1932 (Sullivan, 1984), radio emission from the Sun was first detected during World War II when Hey (1946) in England, Reber (1944) and Southworth (1945) in the USA, Alexander in New Zealand (see Orchiston, 2005), Slee in Australia (see Orchiston and Slee, 2002) and German radar operators in Denmark (Schott, 1947) made and reported a succession of independent discoveries at a variety of frequencies.

Figure 1: The 200 MHz radar installation at Dover Heights, circa 1945 (courtesy: ATNF Historic Photographic Archive).

Because of the pivotal role that radar played in the War effort most of these discoveries had to remain 'top secret' until hostilities ended, but in mid-1945 a copy of Reber's paper and reports about Hey's and Alexander's projects were received by staff in the CSIR's Division of Radiophysics in Sydney (Payne-Scott, 1945),[1] and these spawned a local solar radio astronomy program. This became a mainstay of the Division's efforts when it was necessary to redirect attention from wartime radar developments to peacetime research, and Australia quickly established an international reputation in the fledgling discipline of radio astronomy—as it became known (e.g. see Pawsey, 1961; Sullivan 2009).[2] In this paper we review the early solar radio astronomy program that inspired the construction of the world's first solar radiospectrograph in 1948, and the pioneering work on spectra that was then carried out at the Penrith field station.[3]

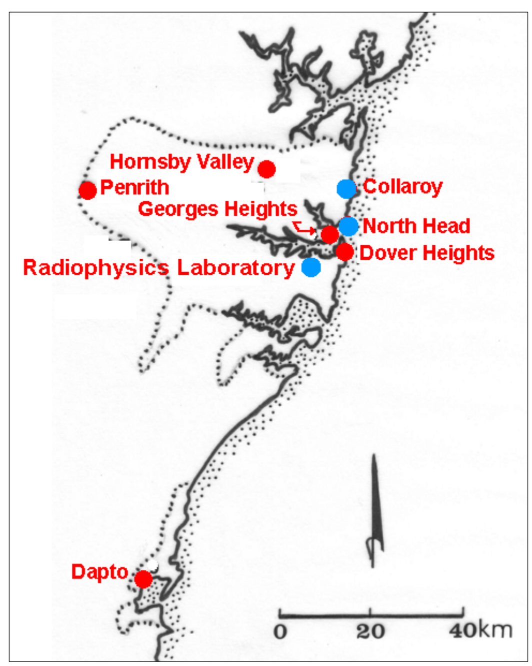

Figure 2: Localities mentioned in the text. The upper dotted outline marks the approximate current boundary of suburban Sydney and the lower dotted outline of suburban Wollongong. Different Radiophysics field stations are indicated by red circles, and other sites by blue circles.

Figures 3a (left) and 3b (right): J.L. Pawsey, 1908-1962, and Ruby Payne-Scott, 1912-1981 (courtesy: ATNF Historic Photographic Archive and Miller Goss, respectively).

2 THE EARLY 200 MHz OBSERVATIONS

Orchiston, Slee and Burman (2006) have recounted how the first observations of the Sun by Radiophysics scientists were conducted during October 1945 using a 200 MHz wartime coastal radar unit at Collaroy and led to the detection of solar emission. This prompted further observations through to March 1946 from Collaroy and the Dover Heights WWII radar stations (see Figure 2 for Sydney localities mentioned in the text), using the 200 MHz broadside radar antennas there, and confirmed the association between solar radio emission and sunspot activity reported previously by Hey and Alexander. This research was led by the inspirational Dr J.L. (Joe) Pawsey (Figure 3a), who headed the Division of Radiophysics' radio astronomy group. The other members of the team were Lindsay McCready and Ruby Payne-Scott (Figure 3b), who has been described by Goss and McGee (2009) as the world's first female radio astronomer.[4]

The limitations of the wartime radars were soon realized, and in March 1946 a 200 MHz Yagi antenna that could track the Sun throughout the day was installed at Dover Heights. At the same time similar Yagi 200 MHz antennas were also placed at the North Head radar station at the entrance to Sydney Harbour,

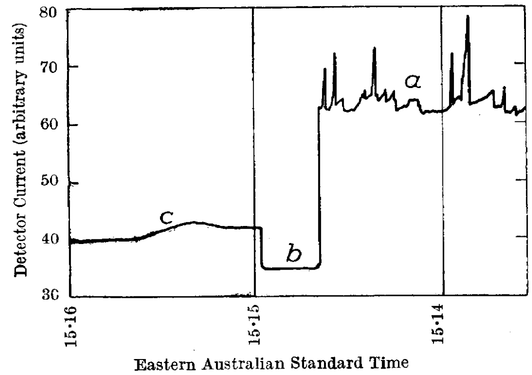

Figure 5: A 200 MHz record showing for the first time that noise storms are circularly polarized. a) = RH polarization, (c) = LH polarization and (b) = background sky level when the antenna was pointed away from the Sun (after Martyn, 1946).

and at the Commonwealth Solar Observatory on Mt Stromlo, about 200 km southwest of Sydney.

These early Sydney-based observations with the radar antennas and the 200 MHz Yagis revealed the existence of two different types of energetic solar emission, dubbed 'isolated bursts' and 'outbursts', and examples of these are shown in Figure 4. At about the same time, during 200 MHz observations made at Mt Stromlo, David F. Martyn (1946) and Cla Allen[5] (1947a) found evidence of a third type of solar activity, which the latter called 'noise storms'. These were characterised by enhanced emission and short bursts. It was Martyn who first noticed that bursts associated with noise storms were highly circularly polarized (see Figure 5).

3 MULTI-FREQUENCY OBSERVATIONS

The challenge then was to learn more about these various types of solar activity, and in 1946 the Division of Radiophysics consolidated its solar program at the Dover Heights field station, where the 200 MHz Yagi

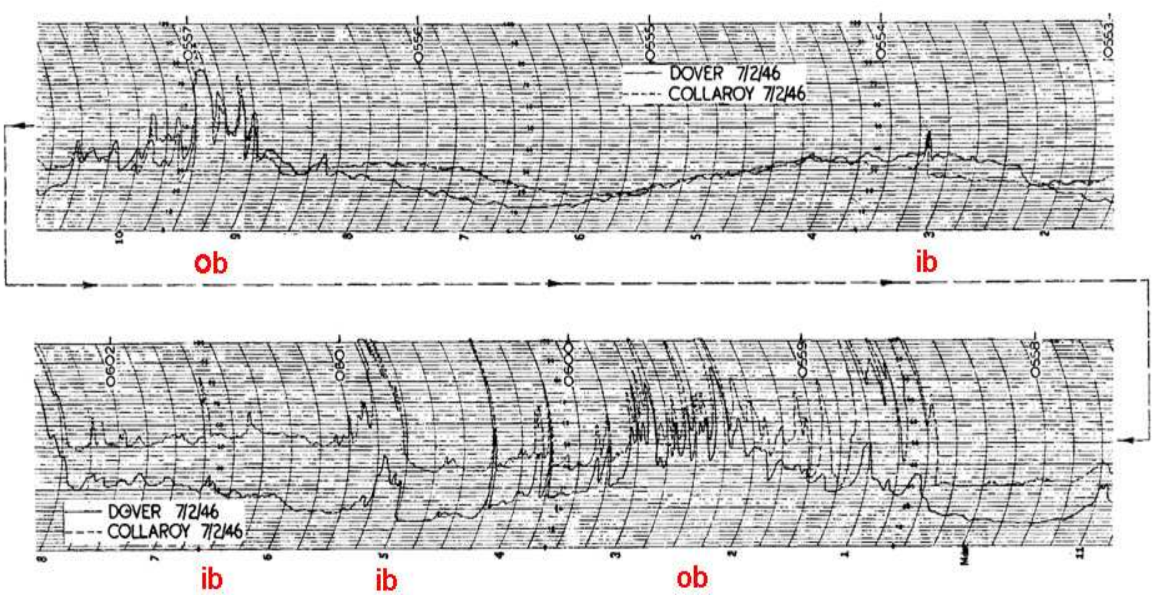

Figure 4: Chart recordings at 200 MHz made on 7 February 1946 at Dover Heights and Collaroy showing isolated bursts (ib) and outbursts (ob), examples of which are marked in red print below the chart recordings (adapted from McCready, Pawsey and Payne-Scott, 1947: 362).

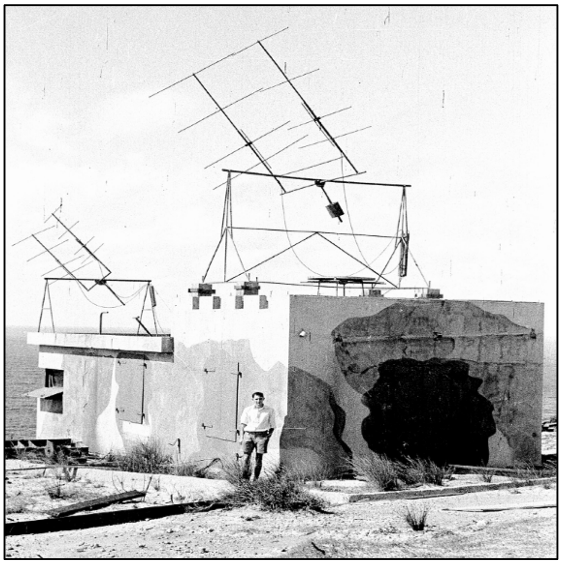

Figure 6: John Bolton standing outside the Dover Heights block house on 1 May 1947. On the roof can be seen the 60 MHz (left) and 100 MHz (right) twin Yagi antennas; the 200 MHz Yagis are hidden from view (courtesy: ATNF Historic Photographic Archive).

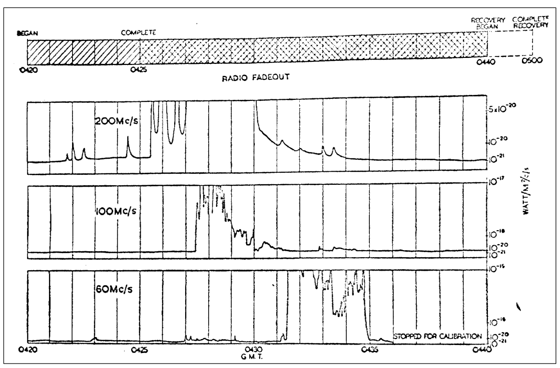

Figure 7: The outburst recorded simultaneously at three frequencies on 8 March 1947, and showing delays between the starting times different frequencies (after Payne-Scott et al., 1947).

Figure 8: The WWII experimental radar that was used by Lehany and Yabsley at 200, 600 and 1200 MHz to monitor solar emission (courtesy: ATNF Historic Photographic Archive).

was joined by 60 MHz and 75 MHz Yagis (see Goss and McGee, 2009). Judging from later developments, all three antennas were located on the roof of the small concrete building shown near the left hand margin in Figure 1, and Payne-Scott was now in an excellent position to begin a multi-wavelength assault on solar radio emission. In November 1946 she was joined by John Bolton and Bruce Slee (Bolton, 1982), and the 75 MHz antenna was replaced by a 100 MHz Yagi. It was only in early 1947 that the radar antenna on the roof of the concrete block house close to the sea cliff was removed, and the three Yagi aerials were relocated to this new site (see Figure 6).

Isolated bursts continued to be observed in 1946, but their detection at more than one frequency posed some interesting interpretive problems. For instance, on 12 August 1946 McCready (1946b) reported to the Division's Propagation Committee that

> Two large sunspots have been on the sun lately. Almost continuous observations have been made from 22nd July to 12th August, dawn to sunset on 200, 75 and 60 Mc/s … Sometimes there appears to be a lag at lower frequencies in individual bursts.

This possibility of a time delay between burst onset at different frequencies was confirmed in a remarkable fashion on 8 March 1947 when a very large bipolar sunspot appeared on the limb of the sun. Bolton, Payne-Scott and Stanley observed an intense 'outburst' at all three frequencies, which lasted for about 15 minutes. Although the 200 MHz receiver at Dover Heights was not working at the time, a record of the outburst was obtained at the Commonwealth Solar Observatory and was used in their analysis. The outburst showed a systematic delay of several minutes between its commencement at 200, 100 and 60 MHz (Figure 7) suggesting the possibility that the source moved outwards through the corona. Based on their observations of onset times at the different frequencies, Payne-Scott, Yabsley and Bolton (1947) estimated an outward velocity for the outburst of approximately 500 km/s, following Martyn's (1947) suggestion that the radio emission at each frequency escaped from the corona at a height where the refractive index reduced to zero (see Section 7.2, below).

On the evening following this unique event a prominent aurora was observed in Sydney. Payne-Scott et al. (1947) speculated that the outburst might be caused by particles travelling outwards through the corona with sufficient speed to arrive at the Earth a day or two later and initiate the auroral display.

The importance of this outburst was immediately recognized by Pawsey (1949) who later wrote:

> One of the interesting speculations concerning the origin of some of the largest radio disturbances, which are called *outbursts*, is that these may be due to explosions on the Sun which hurl great masses of gas upwards, some with so great a velocity as to escape from the Sun. Incidentally, terrestrial magnetic storms and auroras are supposed to be caused by the arrival at the Earth of such masses of gas. In the Sun, these gases would move upwards and if, as is suspected, a particular wavelength of radiation is associated with each level in the solar atmosphere, we should expect to observe different wavelengths excited in succession. Some of the greatest outbursts have shown just such delays between the onsets at different wavelengths.

Inspired by these successful investigations at Dover Heights, Pawsey (1947a) was keen to expand the solar monitoring program and in mid-1947 he installed Fred Lehany and Don Yabsley at the Division's Georges Heights field station near the entrance to Sydney Harbour (see Figure 2) where they used an experimental WWII radar antenna that operated at 200, 600 and 1200 MHz (Figure 8). Between 18 August and 30 November they detected many bursts at 200 MHz, but energetic emission was only occasionally recorded at the two higher frequencies (see Lehany and Yabsley, 1948; 1949).

Late in 1947 the Yagis at Dover Heights were being used intensively for non-solar work (see Bolton, 1982; Slee, 1994), so Payne-Scott decided to transfer to the Hornsby Valley field station on the northern outskirts of Sydney (Figure 2),[6] where she continued her investigation of solar bursts using 60, 65 and 85 MHz Yagis, an 18.3 MHz broadside array and a 19.8 MHz rhombic aerial. Observations were conducted between January and September 1948 and these revealed two types of variable high-intensity emission which Payne-Scott (1949: 215) termed 'enhanced radiation' and 'unpolarized bursts'. She describes the 'enhanced radiation':

> The intensity reaches a high level and remains there for hours or days on end; there are continual fluctuations in intensity, both long-term and short-term … Superimposed on it may be bursts … for the great part of its life the enhanced level shows circular polarization of one sense or the other. (Payne-Scott, 1949: 216-217).

The 85 MHz observations were made with crossed Yagis, so that circular polarization could be studied. Examples of enhanced radiation recorded at 60 and 85 MHz on 30 August 1948 are shown in Figure 9.

Apart from the enhanced emission, many 'unpolarised bursts' were recorded, and these showed

> … a very good correspondence on different frequentcies, though their shapes and relative amplitudes may vary considerably ... A characteristic unpolarised burst shows a finite rise time, rounded top, and slow decay … (Payne-Scott, 1949: 219-220).

Unpolarized bursts generally occurred in groups—single bursts were rare—and they often exhibited double peaks, suggesting that the second peak "… may be an echo of the original disturbance." (Payne-Scott, 1949: 222). Payne-Scott was also particularly interested in the starting times of the bursts at different frequencies:

> The occurrence of time delays between the arrival of "corresponding" unpolarized bursts [previously referred to as isolated bursts] on different frequencies is confirmed, the higher frequency commonly arriving earlier, with delays of about 0.7 second between 85 and 60 Mc/s and 9 seconds between 60 and 19 Mc/s.

An example from her paper is shown in Figure 10.

What Payne-Scott was not able to do though was confirm the earlier findings relating to the 8 March 1947 outburst:

> … on the question of longer delays, the present author has never since, in the recording of hundreds of bursts, obtained any evidence for delays of the order of minutes. Either this case reported earlier was very unusual, or the record was misinterpreted; as the relative amplitudes of different portions of a complex burst may be different on different frequencies, such an interpretation of a single case is quite possible. (Payne-Scott, 1949: 223).

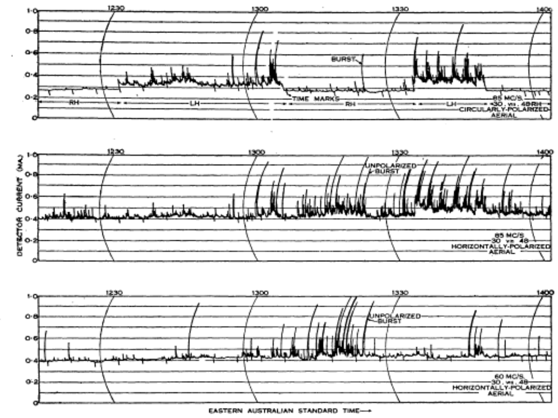

Figure 9: Examples of 'enhanced radiation' with superimposed bursts of short duration at 85 MHz (top and middle) and 60 MHz (bottom), recorded on 30 July 1948. The 85 MHz records indicate that the enhanced radiation shows left-hand circular polarization (after Payne-Scott, 1949: 218).

Long before the end of 1948 a confusing picture had emerged regarding the energetic burst emission received from the Sun at frequencies between 65 and 200 MHz, on the basis of observations made at Collaroy, North Head, Dover Heights, Georges Heights and Hornsby Valley in suburban Sydney, and at the Commonwealth Solar Observatory near Canberra. On record were isolated unpolarised bursts, outbursts, noise storms and enhanced emission (which was sometimes accompanied by polarised bursts). The relationship between these various types of emission, and particularly between noise storms and enhanced emission containing polarised bursts, was obscure. Clearly, what was needed was a radiospectrograph which could provide an instant profile of the emission across a wide frequency band at any one point in time.

In the next section of this paper we follow the development of this instrument by examining early archival material and relevant publications. We were also fortunate to be able to discuss this project with John Murray, who was one of the original members of the team that designed and operated the Penrith radiospectrograph.

4 THE 'SPECTRUM ANALYZER PROJECT'

The first reference to using a radiospectrograph in the Division's solar program is found in the Minutes of the

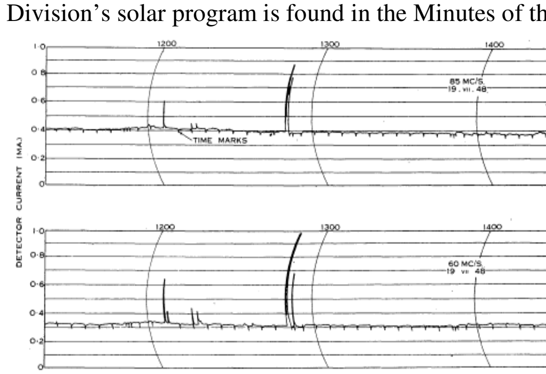

Figure 10: Examples of 'unpolarized bursts' at 85 MHz (upper) and 60 MHz (lower), recorded on 19 July 1948 (after Payne-Scott, 1949: 216).

Figure 11: Aerial photograph taken in 2006 of land near the Penrith Railway Station. The white outline defines the Department of Defence land which was acquired in 1946. The Division of Radiophysics Penrith field station was located about 300m to the north of the railway station in or near the current car park (courtesy: Penrith Municipal Council).

Propagation Committee Meeting held at Radiophysics on 8 July 1946. While discussing the possibility of extending solar observations to 200 MHz at Brisbane, Lindsay McCready (1946a) reported that: "General opinion however favoured a spectrum analyser style of approach, with all frequencies being studied at the same place." But more than a year was to pass before there was progress in this direction.

Thus, on 23 September 1947 McCready (1947a) reported to Pawsey's Radio Noise Group:

> Object.
>
> To investigate in detail the frequency–time distribution of intensity over a range of frequencies of the order of 2/1.
>
> Basic Question.
>
> Normal extent in frequency of disturbances of different types and any systematic delays between disturbances on different frequencies.
>
> Region of interest:
>
> (a) About 100 Mc/s where bursts are very common.
> (b) Between 200 and 600 Mc/s where bursts disappear.
>
> Proposed Techniques:
>
> Spectrum analyser – arrangement with alternative displays.
>
> (1) Similar to Class A with visual observation = cine photography.
> (2) Intensity modulation with f and t as axes.
>
> Plans:
>
> Begin on 100 Mc/s using rhombic aerial.
>
> Personnel:
>
> McCready + Medhurst (part time) until he leaves then new man. (Cf. Pawsey, 1947b).

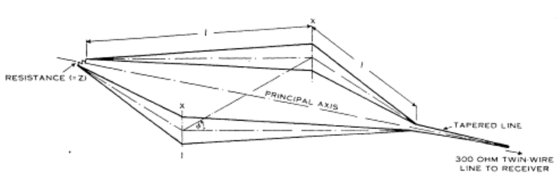

Figure 12: The rhombic aerial (after Wild and McCready, 1950: Figure 1).

The 'new man' was Paul Wild who arrived soon afterwards. From the minutes of the Noise Committee given below it appears that surplus war equipment was found to be unsuitable for solar observations and was replaced by an in-house designed 70-130 MHz receiver which used the semi-butterfly tuning condensers from one of the P58 search receivers.

On 16 October McCready (1947b) and Wild reported to the Noise Committee:

> A P58 English search receiver covering the range 200-600 MHz has been borrowed from Electrotech. It is proposed to modify this and to obtain another model if possible.
>
> Wild is looking into the theory of Rhombics for U.H.F. operation.

On 14 November McCready (1947c), Wild and Medhurst reported:

> The P58 search receiver (280-610Mc/s) has been tested. Its noise factor is 20 db. While it may still be useful, it is considered advisable to proceed with another RF unit designed for a noise factor of 10 db, to avoid delays in waiting for large magnitude bursts.
>
> In the meantime a 200 to 600 Mc/s rhombic is being constructed for use with the P58 receiver during periods of intense bursts at 200 Mc/s, when it is hoped to find the region where they disappear.
>
> An additional P58 receiver has now been obtained and it is proposed to modify this to cover the 70-140 Mc/s range pending the completion of a better receiver.

On 6 January 1948 McCready (1948a) and Wild reported:

> The 200-600 Mc/s Rhombic has been completed.
>
> MacAlister has commenced design of polar axis mount for 70-140 Mc/s Rhombic.
>
> P58 search receivers are not sufficiently sensitive for average bursts.
>
> Wild will commence design of a 70-140 Mc/s RF unit shortly.

In an undated letter to Pawsey, who was then in England, McCready (1948b) wrote:

> Rhombic is under construction and the motor tuned R.F. unit (MkI) is almost ready. The remainder of the show is straight forward & the new chap Murray is very useful and appears to be able to handle it, in good engineering fashion at any rate.
>
> Should you come across any suitable butterfly type condensers over there we could use them. Even drawings would save time. Such things will have to be made in our own workshop.
>
> At the moment we are using a semi-butterfly type pinched from some P58 English Search receivers (B.T.H) and only attempting to cover 70-140 Mc/s until we establish & finalise receiver details.

John Murray, who is first referred to in this letter, joined Radiophysics in January 1948 and was given the task of completing the radiospectrograph display and helping Bill Rowe assemble the receiving equipment (Murray, 2007).

On 20 February 1948 McCready (1948c) and Wild reported:

> Design of rhombic aerial mount completed and orders placed for timber etc.
>
> Exp. Tuneable RF unit (70-140Mc/s) has been completed. Good sensitivity has been obtained and consideration now being given to the design of a high speed mechanical drive for this unit.
>
> Tentative breadboard models of oscillograph amplifiers, slow speed time bases etc. were completed by Medhurst before he left.

In a letter to McCready dated 5 May 1948 Pawsey wrote from England:

> Spectrum presentation. I would like to see you try this in a simple manner first – e.g. 30 Mc/s spread near 100 would be a first rate initial experiment. The point I wish to clear is the delay question.
>
> I find some people over here do not believe our sequence "high frequency precedes low frequency" is correct.
>
> Surely the move is to push on with what you can make easily.

In a letter from McCready (1948d) to Pawsey dated 25 July 1948:

> I'm having a hectic time trying to get our rhombic installed on a temporary basis at Penrith pending proper tests for site noise etc.
>
> Difficulties are organisational & personal rather than technical (e.g. retaining unofficially good relations with a farmer etc).
>
> Regret the slow progress on the spectrum analyser but it is due to many causes.
>
> Finally I have little time to attend to detail & secondly my staff tend to be a little too thorough & of the perfectionist type.
>
> All very well in due course but as you've already said "Do it simply first to check general features etc & then see if it is worth developing a properly engineered model".
>
> However I think you'll find Wild & Murray a very keen & useful physicist and engineer respectively on your return.

This prediction proved to be true with the events which followed.

5 THE PENRITH FIELD STATION AND THE RADIOSPECTROGRAPH

5.1 Selection of the Penrith Site

The site chosen for a new field station at which to conduct these solar observations was on Department of Defence land which was acquired in 1946 (Penrith Library staff, pers. comm., 2007). It was within easy walking distance (~300 metres north) from the Penrith railway station which, at that time, contained a large shunting yard for steam locomotives travelling over the Blue Mountains (see Figure 11). The site was located on the western outskirts of suburban Sydney (see Figure 2). It was easily accessible by train and was relatively free from radio interference (Murray, 2007).

5.2 Method of Operation

The radiospectrograph operated for about 8 hours per day from February through to July 1949, and burst radiation from the Sun was collected with the broad-

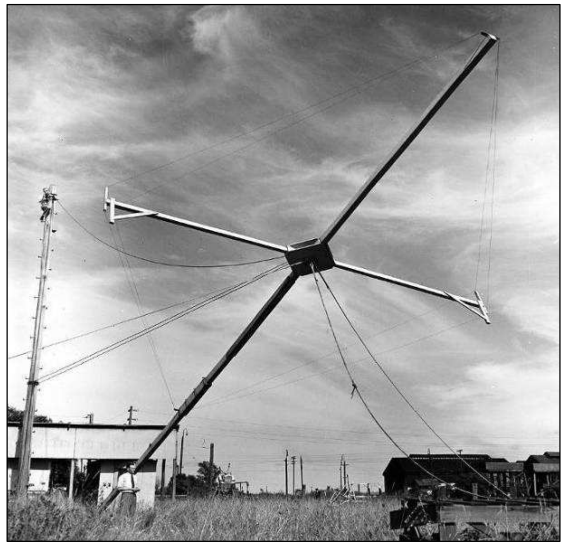

Figure 13: Photograph of the rhombic aerial and pulley system with Bill Rowe standing nearby. In the background to the right are the railway locomotive shunting sheds (courtesy: ATNF Historical Photographic Archive).

band rhombic aerial which was connected to a receiver that was rapidly 'swept' over the 70-130 MHz frequency range. The tuner was mechanically driven so that the frequency sweep occurred in 0.07 second, and repeated about three times per second, giving a time resolution for recording of 4 scans per second. The spectrum was displayed on a cathode-ray tube in the form of a graph of received power (vertical axis) versus frequency (horizontal axis), called in radar terms an A-scan, and was then photographed.

5.3 The Rhombic Aerial

The aerial was of rhombic design (see Figure 12) with sides (l) of 6.4 m (3λ at 100 MHz) and $\Phi = 56.4°$, giving an impedance (resistance) of 670 ohms and an effective area of almost 12 m^2 at the central frequency. A tapered line three metres long transformed this resistance to 300 ohms, which matched into a two-wire line connected to the receiver that was located some distance away.

The antenna was designed by Paul Wild and constructed with a wooden frame under the supervision of the Division's Keith McAlister, a mechanical and electrical engineer who became well known over the years

Figure 14: The rhombic aerial's polar mount, with right ascension and declination scales (courtesy: ATNF Historical Photographic Archive).

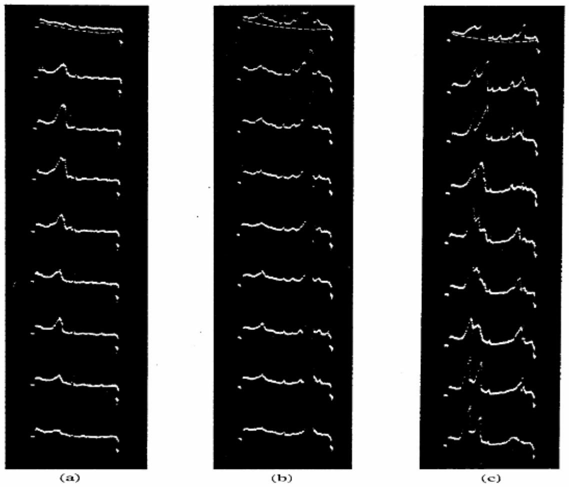

Figure 15: A-scans of three storm bursts, each section of 3 seconds duration. Frequency varies from 70 MHz on the left hand side to 130 MHz on the right. Scans are separated by ⅓ second. The dotted lines show the background level in the absence of storm continuum. (a) shows a typical storm burst from start to finish; (b) part of a large storm burst; and (c) storm bursts during a period of very high activity (after Wild, 1951: Plate 1).

for the design and construction of low-cost antennas at various Radiophysics field stations. Wild derived the theoretical effective receiving area or 'gain' of the aerial from first principles, with some help from Chris Christiansen (Wild and McCready, 1950: Appendix I).

During observations the principal axis of the rhombic aerial was pointed towards the Sun in order to receive maximum signal. This was achieved by moving the aerial by hand every twenty minutes using a rope and pulley system. The aerial and associated ropes can be seen in Figure 13. The aerial rotated about a polar axis which was embedded in a concrete footing, as shown in Figure 14. The principal axis of the

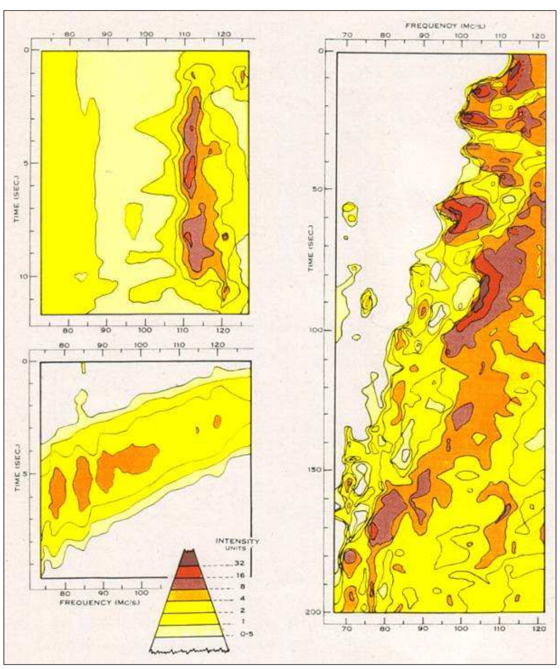

Figure 16: Dynamic spectra of Type I (top left), Type III and Type II (right) bursts (after Wild and McCready, 1950: Plate 2).

rhombic antenna was tilted in declination every few days to keep the Sun in the main lobe of the aerial. At night the aerial was lowered onto the supporting trestle shown near the bottom right-hand corner of Figure 13 (Murray, 2007).

5.4 The Receiving System

According to Wild and McCready (1950),

> The receiver was of conventional superheterodyne design with a single stage of radio-frequency amplification. The local oscillator and the input circuits of the radio-frequency amplifier and the mixer were tuned by 'slit-stator' condensers on a single shaft which was rotated by a motor at about three revolutions per second … By using split-stator condensers, the need for making electrical contacts with rotating shafts was avoided.

The split-stator condenser referred to was probably the semi-butterfly type salvaged from one of the P58 search radar receivers (see the letter from McCready (1948b) to Pawsey, discussed in Section 4).

The intermediate-amplifier operated at 10 MHz with a bandwidth of 300 kHz. The signal was then detected, amplified and fed to the 'y-plate' of the cathode ray tube for display.

5.5 The Display

The display on the screen was a graph of receiver output (vertically) versus frequency (horizontally). This 'A-scan' was photographed with a hand-held Zeiss 16 mm movie camera, which meant that during times of solar activity the equipment hut was kept in darkness (Murray, 2007). Examples of 3 seconds continuous recording during three noise storms are shown in Figure 15.

The photographic records were then converted into time-frequency diagrams for analysis as shown by the examples in Figure 16. Intensity contours were plotted on a logarithmic scale. In a subsequent paper Wild (1950a) referred to these diagrams as 'dynamic spectra' because they showed variations in intensity with time.

6 THE SPECTRAL CLASSIFICATION OF SOLAR BURSTS

By 1950, Wild and McCready had sufficient data to present papers on the first spectral classification of solar radio bursts at metre-wavelengths, which greatly helped remove the confusion introduced by the earlier single frequency records, as Wild (1985) correctly recalled.

The most outstanding result from this groundbreaking investigation was the ability to recognize three distinct types of solar bursts. According to Wild and McCready (1950) the dynamic spectra of the observed bursts were often complicated with widely-different features, but analysis showed that many conformed to one of three specific spectral types which they named Types I, II and III.[7] Typical examples of these Types were shown in Plate 2 of Wild and McCready (1950) and are reproduced here in Figure 16.

6.1 Type I Bursts

Wild and McCready (1950: 393) wrote:

> Plate 2a is typical of bursts which occurred in hundreds during restricted periods, called "noise storms" by Allen [1947]. Such periods usually last for hours, or even days, and were marked by a high, slowly-varying background continuum above which the bursts appeared. Bursts of his type rarely occurred as isolated phenomena. The type is characterized by its narrow spectrum, a few megacycles per second wide … The lifetime of the bursts is sometimes less than one second and sometimes as long as 20 seconds.

These storm bursts were the predominate type of activity observed at Penrith during the operation of the radiospectrograph. Other bursts occurred occasionally either singly or in small groups.

6.2 Type II Bursts

According to Wild and McCready (1950: 393):

> Plate 2b illustrates a type of burst of comparatively rare occurrence. In this type, the spectrum at any instant near the start shows a distinct "cut-off" in frequency, little or no radiation being received at frequencies immediately below a critical frequency. The critical frequency varies with time and, on the average, drifts gradually towards the lower frequencies at a rate of ¾ (Mc/s.) $sec.^{-1}$ The bursts last for several minutes … Of five such bursts observed, three coincided with a large solar flare or sudden short-wave communication fade-out.

6.3 Type III Bursts

Of the other thirty or so sporadic bursts or groups recorded none coincided with a reported flare or fade-out. They were of short duration (about 3 to 30 seconds) and broad bandwidth (≥15 MHz). Less than half conformed to this third distinct spectral type.

Again, according to Wild and McCready (1950: 394):

> In this type, illustrated in plate 2c, the frequency of maximum intensity drifts rapidly (at a rate of the order of 20 (Mc/s.) sec^{-1}) towards the lower frequencies. The bandwidth of these bursts at any instant is not usually less than about 50 Mc/s. They last for a few seconds.

6.4 Relation between Spectral Types and Bursts Recorded at Single Frequencies

Comparing their results with earlier observations made by the Radiophysics group, Wild and McCready (1950) noted that Payne-Scott (1949) had established that metre wavelength solar bursts could be divided into two broad groups according to whether or not the radiation was circularly polarized:

(a) '<u>Enhanced radiation</u>' which occurred during noise storms was closely associated with large sunspot groups and was circularly polarized. It appeared on single-frequency records as a slowly-varying background radiation with superimposed short bursts of similar polarization. The bursts showed little or no correspondence at frequencies differing by a few megahertz and were clearly the storm bursts of spectral Type I mentioned above.

(b) Radiation which was not circularly polarized occurred as sporadic bursts which lasted for several seconds, or in extreme cases, for several minutes. The bursts were often observed almost simultaneously at widely-spaced frequencies.

When larger sporadic bursts occurred at the time of solar flares they were called 'outbursts' (Allen, 1947a). Wild and McCready (1950) were able to establish that at least some of these outbursts could be identified with spectral Type II bursts, especially those that showed onset time delays at widely-spaced frequencies (such as the 8 March 1947 event).

Other sporadic bursts, called 'isolated bursts' by Pawsey (1950) were of shorter duration than outbursts and, according to Wild and McCready showed diverse spectral features but at least some of them conformed to spectral Type III (characterized by a rapid drift from high to low frequencies). The fast frequency drift also explained the time delays of several seconds found at spaced frequencies in 'unpolarized' bursts by Payne-Scott (1949) and mentioned above in Section 3.

The reason Payne-Scott (1949) did not detect more delayed outbursts is probably due to the complex nature of the flare event at metre wavelengths. Often more than one Type III burst preceded the Type II burst, making recognition difficult on single frequency records.

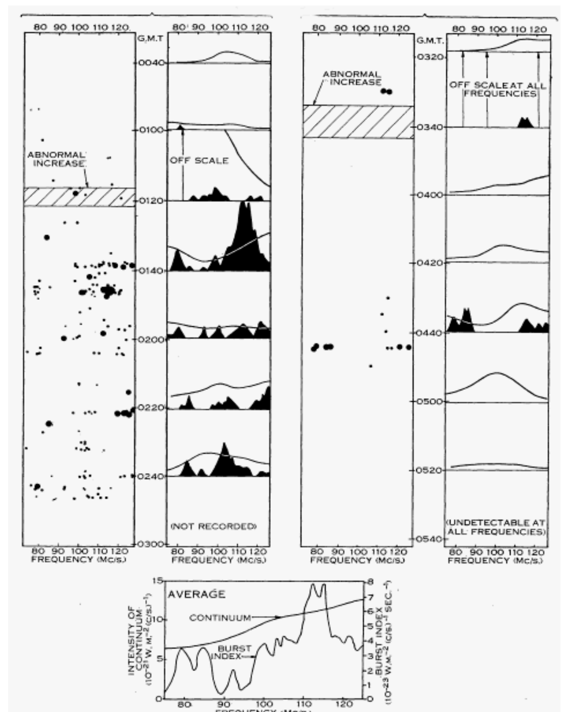

Figure 17: The LH plot shows the distribution of Type I storm bursts recorded on 14 April 1949 and the RH plot shows the continuum spectrum and the 'burst index'. The bottom plot shows the averaged spectra (after Wild, 1951: Figure 2). The burst index gives a fair indication of the mean-intensity distribution of the Type I bursts.

7 DETAILED ANALYSIS

7.1 Type I Bursts

The Penrith dynamic spectrum of Type I bursts (Figure 16 top left) explained why these bursts were not correlated on spaced-frequency records such as those obtained by Payne-Scott (1949). Wild (1951) then investigated the possibility that the enhancements accompanying Type I bursts was merely a composite of many unresolved bursts.

It was suggested earlier by McCready, Pawsey and Payne-Scott (1947) and also by Ryle and Vonberg

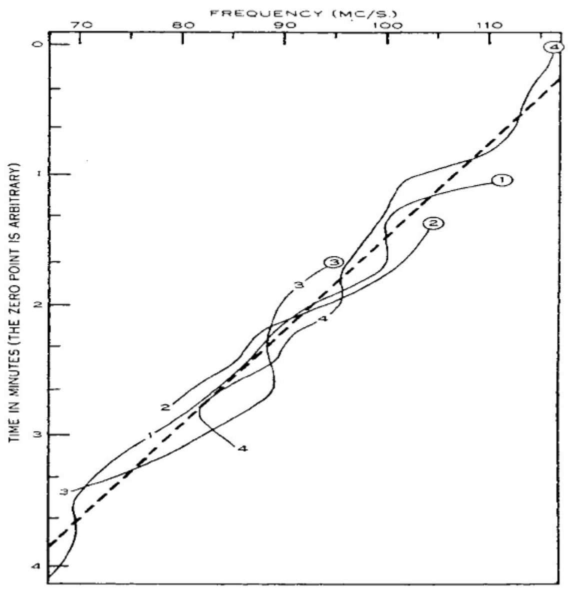

Figure 18: Smoothed curves of the variation with frequency of the low-frequency cut-off of the four type II bursts (after Wild, 1950a: Figure 1).

(1948) that the background continuum may be the result of a large number of storm bursts, with only the larger ones being recognized as distinct phenomena. This hypothesis is supported by (1) the observed circular polarization of both bursts and continuum, and (2) the good general daily correlation of occurrence of the two components.

On the other hand, Wild pointed out that the opposite view—that the two components are fundamenally different—is suggested by (1) the usual small degree of fluctuation in the background continuum; (2) the lack of correspondence between the spectrum of the continuum and the integrated spectrum of the bursts (see Figure 17); and (3) the fact that during some periods a high continuum level is observed without appreciable burst activity and at other times bursts occur without detectable continuum.

Wild (1951) concluded that more observations of noise storms were needed to resolve this question.

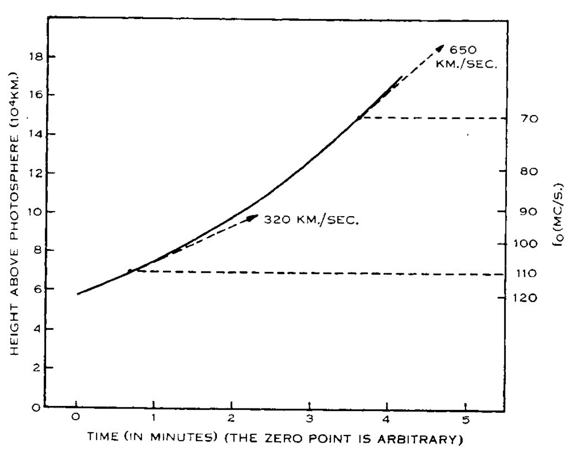

Figure 19: The curve shows the motion of the disturbance moving outwards through the solar corona producing a frequency drift corresponding to the dotted line of Figure 18 (after Wild, 1950a: Figure 2).

7.2 Type II Bursts

Wild (1950a) analysed the frequency drift of four of the five Type II bursts recorded at Penrith, and his results are reproduced in Figure 18. Points on the curves correspond to the position of the low-frequency 'cut-off' edge which he found to be a distinct feature of Type II bursts. The four curves were superimposed by adjusting their starting points. The dotted line represents a constant drift rate of 0.22 MHz per second. The diagram shows that the average drift rate of each of the four bursts was close to this value and that the drift rate was constant with frequency.

Martyn (1947) had suggested that solar bursts were due to plasma oscillations and this suggestion was adopted by Payne-Scott et al. (1947) in their analysis of the outburst shown in Figure 7.

Wild (1950a) also used this 'plasma hypothesis' to interpret the frequency drift rate of the Type II outburst shown in Figure 16. He identified the cut-off frequency of the outburst with the local plasma frequency, $f_{0,}$ where the refractive index for electromagnetic waves reduces to zero. In the absence of a magnetic field, f_0 is given by:

$$f_0^2 = e^2 N / \pi m \qquad (1)$$

where N is the electron density of the medium, e is the electronic charge (cm^{-3}) and m is the electronic mass. Values of N, obtained from an optically-derived electron density model for a spherically-symmetrical corona by Baumbach and modified by Allen (1947b), were used to produce the height-versus-time plot of Figure 19.

Finally, Wild (1950a) considered two known coronal phenomenon as possible candidates for the outburst disturbance. First he examined 'surge-prominences', but he discarded these because they were observed to rise and then fall back towards the solar surface whereas the outburst showed a tendency to accelerate outwards through the corona. Instead, he was of the opinion that the most likely cause was the fast particles that were known to be emitted from the Sun at the time of flares, and which caused magnetic storms with sudden commencements here at the Earth about one day later. Indeed, two of the four Type II bursts analysed represented in Figure 18 were found to be associated with geomagnetic storm commencements 28-29 hours later. This idea had previously been suggested by Payne-Scott et al. (1947) and Pawsey (1949) to explain the outburst of 8 March 1947. Later it was found that the Type II event was caused by a magneto-hydrodynamic shock wave.

7.3 Type III Bursts

Wild (1950b) considered three possible mechanisms for the rapid frequency drift of maximum intensity towards lower frequencies which is characteristic of Type III bursts (such as shown in Figure 16):

(a) Selective group retardation of the radiation from a localized, instantaneous disturbance in the corona. Jaeger and Westfold (1950) had found that such a disturbance may be capable of producing a radio burst of short duration at the Earth, where the higher frequencies would arrive before the lower ones, due to group retardation effects near the plasma level.

(b) The outward motion, through the corona, of a localized source that excites plasma oscillations of continuously-decreasing frequency (similar to the mechanism discussed above for Type II outbursts).

(c) Some mechanism in which the wave frequency is controlled by an external magnetic field.

Wild dismissed mechanism (c) as a possibility because of the absence of observed circular polarization in Type III bursts. Then to decide between (a) and (b), he analysed the decay rate and frequency drift of the simple Type III bursts observed, and noted that the time profiles of these showed a gradual rise to a maximum value followed by slower decay which appeared to be approximately exponential in form (as found earlier by Payne-Scott 1949, and Williams 1948). Wild showed that the mean value of the normalized decay constant for Type III bursts tended to decrease with decreasing frequency (see Figure 20). This result cannot be easily explained by mechanism (a), above, but it can be explained by mechanism (b) if it is accepted that the decay constant is related to the electron-atom collision frequency (Westfold, 1949), which would decrease as the disturbance moved outwards through the corona (Smerd, 1950).

To test the frequency drift of mechanisms (a) and (b) further Wild constructed the diagram which is reproduced here in Figure 21. Clearly the observations do not fit mechanism (1). On the other hand, mechanism (2) gives much better agreement. Here the line OB shows the prediction for an outward-moving source of constant velocity in a Baumbach-Allen atmosphere, where the numbers on the line refer to velocities in 10^4 km/sec. The other lines, labeled n = 0, 1, 2, and 3, refer to a curvature of the intensity ridge line of the burst if the drift rate is proportional to f^n. The scatter of points on the graph suggests that a small acceleration of the source occurred as it moved outwards through the corona.

However, it should be noted that when more realistic density models for the corona became available further analyses indicated that the outward-velocity of the Type III burst remained more or less constant.

From the above analysis Wild (1950b: 554) concluded that:

> With the assumed electron density distribution, velocities of between about 2×10^4 and 10^5 km./sec would be required to account for the observed drift rates … Corpuscular streams with these velocities have not been observed in the solar atmosphere, but in any case such streams would likely to be highly ionized and may consequently escape optical detection.

8 LATER REMINISCENCES

In his recollections of the early days of Australian radio astronomy, Dr E.G. (Taffy) Bowen (1984), who was the Chief of the Division of Radiophysics at that time, wrote:

> It happened that during the war the Division—as part of a secret within a secret—had been involved in the construction of receivers for surveillance of enemy radio and radar transmissions.
>
> The basic method of carrying this out was to scan rapidly over a 2:1 frequency range and to cover the whole band of usable frequencies in a series of 2:1 steps.
>
> Within the Division there was a substantial store of such receivers. These were ready made for spectral analysis of the noise from the Sun and they were quickly pressed into service.
>
> In the inventive hands of Lindsay McCready and Paul Wild, a "radio spectrometer" evolved which was to dominate the field of solar studies for the next twenty years.

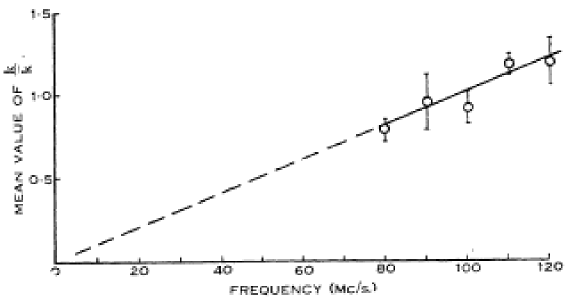

Figure 20: Plot of the average normalized decay constant versus frequency for five Type III bursts (after Wild, 1950b: Figure 4).

Although it is true that the Penrith radiospectrograph was built on the principles developed earlier for wartime radar, the archival records and publications used in this study reveal that Bowen's claim that wartime equipment was quickly pressed into service was not entirely correct. These spectrum analysers were found to be unsuitable for solar observations. Instead, new equipment—including a broadband rhombic antenna matched to a swept-frequency receiver which was coupled to a photographic display—had to be designed and constructed before being installed at the Penrith field station in 1948.

As we have seen, this took careful planning and experimentation by a number of skilled personnel under the leadership of Joe Pawsey and his deputy Lindsay McCready, who had formed the Solar Noise Group within the Division back on 15 January 1946 (Bowen, 1946).

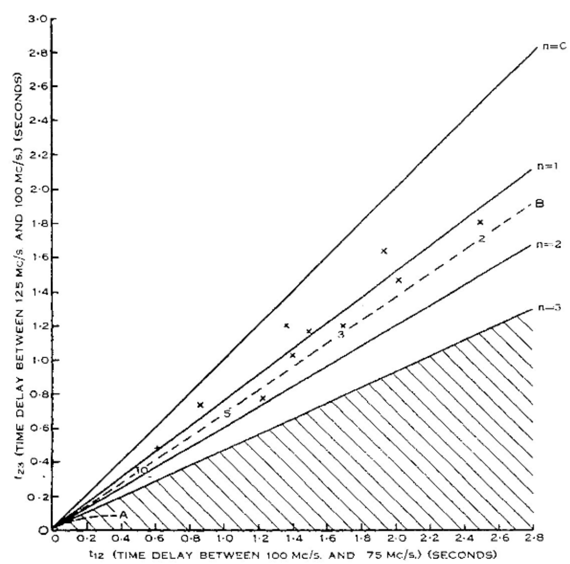

Figure 21: Diagram for studying the frequency drift of Type III bursts. Ten Type III bursts are shown by crosses. The line OA shows the predicted results of selective group retardation in a Baumbach-Allen coronal electron density model. The shaded region shows selected group retardation in any atmosphere (after Wild, 1950b: Figure 6).

Figure 22: View of the receiver hut and three crossed-rhombic antennas at the Dapto field station (courtesy: ATNF Historic Photographic Archive).

Another somewhat contentious issue which drove the development of the Penrith radiospectrograph was the question of whether time delays occurred between the onsets of solar outbursts at different frequencies.

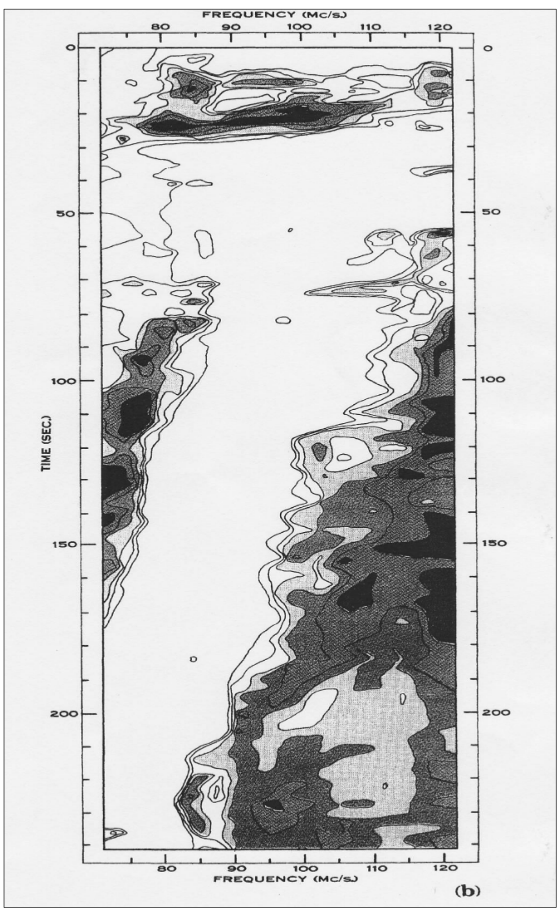

Figure 23: Dynamic spectral record of a type II burst showing probable fundamental and second harmonic structure. Only the trailing edge of the fundamental band and the leading edge of the second harmonic band were recorded. At the top of the record is a type III burst (after Wild, 1950a: Figure 2a).

Years later, when he was the Chief of CSIRO, Paul Wild wrote about his early days at Radiophysics:

> The situation around 1948, when I joined the Sydney group of investigators led by Joe Pawsey, was one characterized by mystery, incredulity and intense interest. A whole new field of research lay ahead with obvious objectives: to disentangle the conglomeration of phenomena; to interpret and understand them; and to put the results to use in the mainstream of research for solar physics, astronomy and physics.
>
> Before the 'origin of species' could be identified there had to be an exercise in taxonomy. Already Pawsey and his colleagues at Sydney had found that, in addition to the polarized storm radiation, there were different kinds of unpolarized bursts: there were large outbursts lasting 10 or 20 min which accompanied large flares, and there were short, sharp 'isolated' bursts lasting a few seconds ...
>
> A new clue was discovered when Payne-Scott et. al (1947) noted systematic time delays in the starting time of bursts, high frequency preceding low. In the case of the isolated bursts these delays were typically a few seconds and were thought to be due to the difference in travel time …
>
> In the case of outbursts, one event was recorded with long delays (a few minutes) between frequencies, and the possibility was suggested that the delay was due to the outward movement of the source. However, in a subsequent extended series of observations Payne-Scott (1949) found no further evidence of similar delays and was inclined to believe that the long delays of that one event was fortuitous. She stressed the difficulty of identifying corresponding features of a complex burst at different frequencies …
>
> An obvious next step, therefore, was to develop a radiospectrograph to record the intensity of the solar emission as a continuous function of frequency and time. (Wild, 1985: 8).

9 PROLOGUE

Following the success at Penrith the radiospectrograph was extended to cover the 40 to 240 MHz frequency range and three different rhombic aerials were installed at a new field station at Dapto (Figure 22), south of Sydney (see Figure 2), in 1952. Fundamental and second harmonic structure was observed in both Type II and Type III bursts, lending support to the 'plasma hypothesis' and Wild's interpretation of the frequency drifts.

It is interesting to note that an example of a Type II burst with harmonic structure was partially recorded by the Penrith radiospectrograph (Figure 23). Although the restricted frequency range does not show the complete burst, it is likely that the trailing edge of the fundamental band and leading edge of the second harmonic were recorded.

The 'plasma hypothesis' was finally confirmed by Wild and Sheridan (1958) when they constructed a swept-frequency interferometer to measure the heights of the sources of solar bursts (Figure 24). The positions agreed with the plasma levels of coronal density models, derived from white-light eclipse observations.

Thus the dynamic spectra, when converted to height -versus-time plots, gave an instant snapshot of coronal activity when other means of observing the corona were not available. Later observations from spacecraft identified the Type III electron streams and the Type II shock waves as they travelled out into interplanetary space. Today, radiospectrographs are still used as part of the global watch on space-weather, because of the disruptive effects massive solar ejections can have on communications and GPS satellites.

10 CONCLUSION

The Penrith radiospectrograph was built to solve the problem of time delays between burst onset at different frequencies. Although the principles involved in building a radiospectrograph were known from war-time radar it took careful planning, experimentation and innovative design to produce a successful instrument.

In 1949 this led to the first spectral classification of solar bursts at metre wavelengths. The discovery of streams of ionised particles travelling outwards through the corona at speeds of 10^4–10^5 km/sec and flare-initiated disturbances moving at speeds of 500 to 1000 km/sec heralded the advent of space research and space weather.

11 NOTES

1. The Division had been set up by the CSIR (Council of Scientific and Industrial Research) in 1939 to develop radar for Australia and the South Pacific. When the war ended the Division experimented with various peace-time research options before deciding to focus primarily on radio astronomy, cloud physics and rain-making. The CSIR also reinvented itself, in 1949 becoming the CSIRO (Commonwealth Scientific and Industrial Research Organisation). For details of these developments see Sullivan, 2005 and 2009.
2. Sullivan (1984) has shown that the term 'radio astronomy' only began to gain international visibility in about 1948. Prior to this, terms like 'solar noise' and 'cosmic noise' were widely used.
3. Penrith was merely one of a large number of radar stations, field stations and remote sites used by Radiophysics staff for solar, galactic and extra-galactic research between 1945 and 1965. For a succinct summary of this work see Orchiston and Slee (2005).
4. In 2005 one of the authors of this paper (WO) published a paper titled "Dr Elizabeth Alexander: first female radio astronomer", and assigned her the title of the world's first female radio astronomer on the basis of her New Zealand-based investigation of 200 MHz solar radio emission during 1945. At that time we were aware that Ruby Payne-Scott and Joe Pawsey had made earlier attempts to detect galactic emission (in 1944), but they were unsuccessful, whereas Alexander did carry out successful radio astronomical observations in 1945 and report on her work in reports and in one brief post-war research paper (see Alexander, 1946). Given these differing circumstances we feel that Alexander and Payne-Scott should be assigned equal billing in the 'first female radio astronomer' stakes (cf. Goss and McGee, 2009).
5. The Commonwealth Solar Observatory's foray into radio astronomy is discussed in Orchiston, Slee and Burman (2006: 51-53) and by Frame and Faulkner (2003). Dr David Martyn's interest in radio astronomy stems from the fact that he was at one time Chief of the Division of Radiophysics, but he was unceremonially removed from the post and seconded to the Commonwealth Solar Observatory. His colleague, Dr Cla Allen, was a solar physicist, but war-time research he carried out into the causes of short-wave radio fadeouts whetted his appetite to investigate solar radio emission.
6. For information about this relocation to Hornsby Valley see Goss and McGee (2009: Chapter 8).
7. Sullivan (2009: 304, footnote 24) has noted that initially, Wild considered using an α, β and γ classification, but he quickly dropped it in favour of I, II and III.

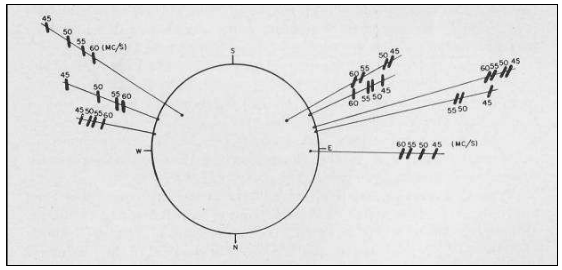

Figure 24: Dapto swept-frequency interferometer observations of the source heights of Type III bursts at different frequencies (after Wild, Sheridan and Neylan, 1959: 382).

12 ACKNOWLEDGEMENTS

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Ronald Stewart recently completed a Ph.D. in the Centre for Astronomy at James Cook University, Townsville, Australia. His thesis topic was "The Contribution of the Division of Radiophysics Penrith and Dapto Field Stations to International Solar Radio Astronomy". Ron was a member of the Radiophysics Radio Astronomy Group from 1963 to 1985 and the Australia Telescope National Facility from 1986 to 1996. He has published over 100 research papers in radio astronomy, and is a member of the IAU Working Group on Historic Radio Astronomy.

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Dr Wayne Orchiston is an Associate Professor in the Centre for Astronomy at James Cook University, Townsville, Australia. His main research interests relate to Cook's voyage, Australian, British, French, Indian, New Zealand and U.S. astronomical history, with emphasis on the history of radio astronomy, comets, historically-significant telescopes, solar eclipses, and transits of Venus. He has published extensively, and has edited the book *The New Astronomy. Opening the Electromagnetic Window and Expanding our View of Planet Earth* (2005). He also has a book on early Australian radio astronomy, co-authored by Woody Sullivan, which will be published by Springer in 2010. He is the founder and currently is the Vice-Chairman of the IAU Working Group on Historic Radio Astronomy.

Dr Bruce Slee is an Honorary Associate at the Australia Telescope National Facility in Sydney, and an Adjunct Professor in the Centre for Astronomy at James Cook University, Townsville, Australia. He continues to research topics which have engaged his attention for more than sixty years. He was one of the original discoverers of the first discrete radio sources and participated in one of the first metre-wave sky surveys for radio sources, followed by measurements of their angular sizes with medium base-line interferometers. His other interests include scattering in the interplanetary medium, radio emission from active stars, absorption in the interstellar medium, pulsar research, surveys of clusters of galaxies, radio relics in clusters and, in more recent years, the history of Australian radio astronomy. He is a member of the IAU Working Group on Historic Radio Astronomy.

LETTERS TO THE EDITOR

Dear Associate Professor Orchiston,

Re: Montgomery et al.'s paper on "Michell, Laplace and the Origin of the Black Hole Concept"

I was very pleased with the recent article on Michell and Laplace (Montgomery et al., 2009). May I add that Laplace's article is reprinted in my Zach collection book *Astronomie der Goethezeit* (Brosche, 1998), a second edition of which has appeared. Also, you should notice the book by Jean Eisenstaedt (2005) titled *Avant Einstein* ..., .where Michell and Laplace are treated extensively. Finally, you may be interested to see that the germs for such ideas were more widely distributed. For example, our writer and scientist, G. Ch. Lichtenberg (1742–1799), also made pertinent notes, but did not publish his thoughts during his lifetime (see Brosche, 1993).

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THE HARVARD RADIO ASTRONOMY STATION AT FORT DAVIS, TEXAS

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Abstract: The Harvard Radio Astronomy Station at Fort Davis, Texas, came into operation in 1956 as a radio extension of the U.S. Air Force Sacramento Peak Observatory. The location near Fort Davis was chosen for the low level of man-made radio signals. Initially the receiving equipment at the site included a 28-ft diameter antenna and covered the range 100-580 MHz. The receivers swept through this band approximately three times per second, recording the spectrum of solar radio activity. In subsequent years the frequency range was extended to cover all or parts of 10 MHz to 4 GHz. All recorded solar bursts were identified according to five principal spectral types, and lists including times, durations, and frequency ranges of all solar activity were published. Studies of the bursts included analyses of their relationships to flares and other optical solar phenomena, and also their relationships to geophysical phenomena, including magnetic storms and polar blackouts. An 85-ft diameter antenna was installed in 1963, which during 1970-1974 was used for solar observations in the range 580 MHz to 4 GHz. Otherwise this antenna was used for non-solar radio astronomy, including lunar occultations of radio sources, measurements of flux densities at 5 GHz, investigations of the Galactic Center, and similar projects. The solar program was closed in late 1982 after 26 years of continuous operation. After 1974 the 85-ft antenna was used mainly in a program of VLBI network observations conducted by astronomers from Caltech and NRAO. In 1991 it was replaced by an antenna of the VLBA program of the NRAO. This paper describes some details of the antennas and receivers, and results of the solar studies. It also includes a brief discussion of the non-solar observations other than the VLBI program.

Keywords: Solar radio burst, radio spectra, sweep-frequency observations, solar burst classification, radio-quiet site, flare associations, geophysical associations.

1 REQUIREMENT FOR A SOLAR RADIO PROGRAM

By the mid-1950s it had become apparent that solar activity, which was well known in the optical spectrum from sunspots and solar flares, also included bursts of emission at radio frequencies. Australian observations (Wild and McCready, 1950) had shown that most of the more intense solar radio emissions could be observed at frequencies around one hundred megahertz. Also, it was known that measurement of the spectra of the bursts, i.e. the intensity of the emissions as functions of both frequency and time, allowed most of the bursts to be classified into several types, presumably related to different mechanisms of generation. It was clearly important to extend solar observations in the U.S. to include the radio range, and thereby increase the fraction of time for which solar radio data were available. The planned International Geophysical Year (IGY), 1957-1958, for which full 24-hour monitoring of the Sun was of basic importance for study of atmospheric and ionospheric phenomena, provided further impetus for the radio extension. It was therefore proposed to include the radio domain within the observations at the U.S. Air Force Solar Observatory at Sacramento Peak, New Mexico. The U.S. Air Force thus provided the initial funding for the project. Professor Donald H. Menzel of Harvard College Observatory, an authority on solar astronomy, played a leading role in the establishment of the solar radio project.

The specifications for the U.S. observing equipment, based on the astronomical requirements and the available technology, resulted in the choice of a 28-ft (8.4-m) diameter parabolic antenna, equatorially mounted to track the Sun across the sky, with receiving equipment that would sweep through a range of 100 to approximately 600 MHz, several times each second.

2 CHOICE OF THE FORT DAVIS SITE

Dr Alan Maxwell, an experienced solar radio observer, was chosen to lead the U.S. radio project. In 1947-1948 he had made measurements of solar emission at 100 MHz in New Zealand as the subject for a Master's thesis (Orchiston, 2005, see Figure 8, p. 86) and then performed more extensive solar radio studies at the Jodrell Bank Radio Observatory of Manchester University, U.K. From practical experience with solar observing at meter wavelengths, Maxwell had learned the importance of avoiding interference from transmissions of services such as communication, broadcasting, etc. This was a particularly important consideration for the U.S. observations, which were intended to make measurements of the spectra of radio bursts over a wide frequency range. Thus Maxwell decided that locating the radio equipment in a sheltered valley would be much preferable to the mountaintop site of the observatory at Sacramento Peak. Henry Smith, a solar astronomer at Sacramento Peak, suggested to Maxwell that the ranching country near Fort Davis, in west Texas, would be a good area to investigate in his quest for a radio-quiet site. Marlyn Krebs, the Technical Manager of the McDonald Observatory on Mt. Locke near Fort Davis, provided further help in locating Cook Flat, a valley near the base of Mt. Locke just four miles from Fort Davis. This proved to be an excellent choice, and the Sproul family, whose ranch included a large part of Cook Flat, allowed Harvard University to lease a one-acre site for the solar radio observatory. The elevation of the site is 1600 m and the location is latitude 30° 38′ 08″ N., longitude 103° 56′ 42″ W. To reach the site from Fort Davis, take Highway 118 west which branches off about one mile north of the town center. Then after approximately four miles turn north on Sproul Road,[1] which is unpaved, and proceed for about 1.5 miles. The Harvard site was on the left-hand side of the road, opposite the VLBA antenna (which was installed later—see Section 12, below).

3 OBSERVING INSTRUMENTATION

When Maxwell took up his position with Harvard College Observatory in 1955 orders had already been placed for a 28-ft. diameter equatorially-mounted antenna from D.S. Kennedy Co. of Cohasset, MA, a feed system covering 100-600 MHz from Jasik Labs. of Westbury, NY, and receivers from Airborne Instruments Laboratory Inc. (A.I.L.) of Mineola, NY. In 1956, Maxwell oversaw the erection of a small laboratory building at Cook Flat and the installation of the antenna and receiving system. Electric power was extended to the site and also an emergency motor generator was installed. A photograph of the station taken about 1958 is shown in Figure. 1. Space for offices and a photographic dark-room was rented in the Limpia Hotel building (which was not then in use as a hotel) in the Fort Davis town center. The program of routine observations of the Sun began the same year and was to run continuously through to 1982.

The initial frequency range was divided into three bands for efficient coverage by the antenna feeds. The feed design is described in detail by Jasik (1958), and consisted of a pair of half-wave dipoles for the 100-180 MHz band, a single dipole with a corner reflector for 180-320 MHz, and a horn for 320-580 MHz. The three feeds were ingeniously designed as a single structure with a common electrical center.[2] In each band a single linear polarization was received. For meridian pointing the polarization of the mid-frequency band was horizontal. Polarization of the two outer bands was orthogonal to that of the mid-frequency one, to minimize cross coupling. Receivers for the three bands were mechanically tunable using rotating capacitors driven at 200 rpm by electric motors. Thus the receivers swept in synchronism across each band approximately three times per second, as described by Goodman and Lebenbaum (1958). There were three rotating capacitors in each receiver, one each for the two amplifier stages and one for the local oscillator. The amplifiers used Western Electric (WE) 416B coaxial-type triodes in grounded-grid configuration.

The receiver outputs were displayed on three cathode ray tubes and continuously recorded on 35-mm film. The cathode ray tubes each had a vertical trace that swept downward as the associated receiver swept from the low to the high end of its range. The intensities of the traces were modulated in proportion

Figure 1: The 28-ft. diameter antenna and solar laboratory building as they appeared in 1958. The small antenna near the center of the picture, consisting of two dipoles with reflectors, was used with a 70 MHz fixed-frequency receiver and chart recorder. It provided a real-time indication of the state of solar activity, which was useful since the outputs of the spectral receivers could not be examined until the film was developed. Note that the dome of the McDonald Observatory, approximately 4 miles distant, is just visible on the horizon near the right-hand edge of the picture (Photograph supplied by A. Maxwell, Harvard College Observatory).

to the signal strengths from the receivers. The three display tubes were mounted with vertical alignment of the traces, and facing into a light-proof enclosure. A camera in which the film moved continuously in a horizontal direction recorded the three traces. As a result, the film showed three bands with time varying horizontally along the length of the film, and frequency running from 100 MHz at the top edge to 580 MHz at the bottom. Time marks were inserted at one minute intervals and frequency calibration signals every 20 min. Intensity calibration using a noise source was performed every three days when the 35-mm film was changed. Each evening after sunset the antenna was moved to the sunrise position and the whole system set to start automatically at sunrise. Further general descriptions of the instrumentation are given by Maxwell (1958), Maxwell et al. (1958), Thompson (1959b), and Maxwell (1971). Examples of the records and descriptions of the types of bursts observed are given in Section 5.

4 PROJECT STAFF IN THE EARLY YEARS

In addition to Alan Maxwell, the staff at the observatory during the first year included Govind Swarup and Samuel J. Goldstein Jr. (see Figure 2). Swarup left the Fort Davis project in late 1957 and went to Stanford University where he worked on the solar cross as a graduate student of R.N. Bracewell. He later returned to India where he had a distinguished career in radio astronomy, and was responsible for the conception and construction of two major instruments (Swarup 2006). Goldstein was interested in the angular sizes of solar bursts and built a two-element interferometer at the Fort Davis station. This instrument used two rhombic antennas 1 km apart on an east-west line, and a broadband receiver that covered approximately 105-140 MHz. Measurements on Type I and Type III bursts were made (Goldstein, 1959). Use of the interferometer was discontinued after Goldstein left for Stanford in 1958 where he too was a Ph.D. student of R.N. Bracewell. He later joined the Astronomy Department at the University of Virginia.

In August 1957, I (Dick Thompson) joined Maxwell's group. Like Maxwell, I had obtained a Ph.D. in radio astronomy from the University of Manchester. I remained with the project until November 1962 when I also joined the Radio Astronomy Institute at Stanford, and subsequently moved to the NRAO. Michael P. Hughes, a mathematician and very capable radio engineer, also from the U.K., joined the group in 1960. He moved to Stanford in 1966 to take a Ph.D. and subsequently had a teaching career at the West Kent College of Technology, U.K. Some of the staff and friends of the Fort Davis project are shown in Figure 3.

5 CLASSIFICATION OF SOLAR BURSTS

Most of the solar bursts in the meter- and decimeter-wavelength range can be classified as one of five types. Originally, Types I, II, and III were defined by Wild and McCready (1950), Type IV by Boischot (1957), and Type V by Wild et al. (1958). Although the great majority of bursts are classified within these types, other spectral details are sometimes seen: see e.g. Boischot et al. (1960). Examples of bursts from the Fort Davis records are shown in Figures 4-7, and include the extended frequency ranges described in

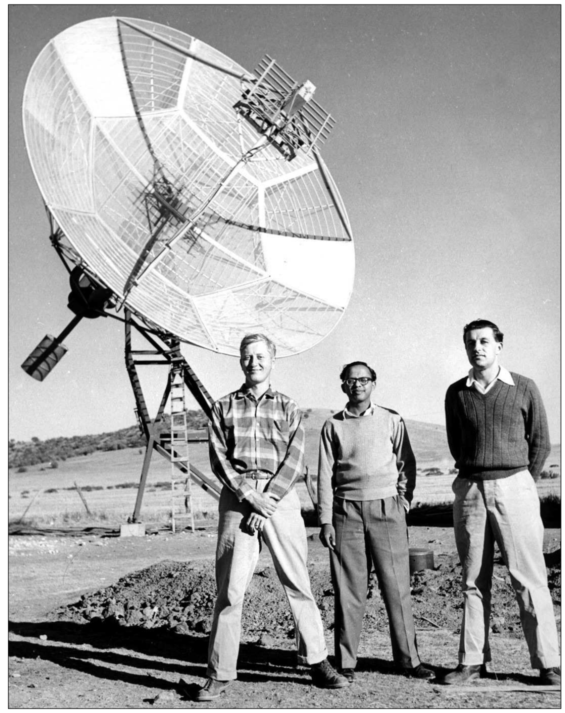

Figure 2: An early picture (1956) showing the three pioneers of the Fort Davis radio astronomy project (left to right): Sam Goldstein, Govind Swarup, and Alan Maxwell (Photograph supplied by A. Maxwell, Harvard College Observatory).

Sections 6 and 7. The five different spectral types are described below.

5.1 Type I, Noise Storm

A long series of short bursts which may continue for hours or days. These generally occur at frequencies below 200 MHz, and are superimposed upon a slowly-varying background enhancement. Individual bursts may have durations of less than one second, and often occur in clusters extending for many seconds. They are generated within the corona above active sunspot regions.

Figure 3: A farewell gathering in the solar laboratory on 26 October 1962, just prior to my leaving the project (left to right): myself; Mike Hughes; lab. assistant Charlie Murray; Bob Sproul, on whose ranch the site is located; Donald McIvor, a rancher who also had land in Cook Flat; and an unidentified person. Donald's mother was a member of the Locke family, who provided the site on Mt. Locke for the McDonald Observatory (Photograph supplied by A. Maxwell, Harvard College Observatory).

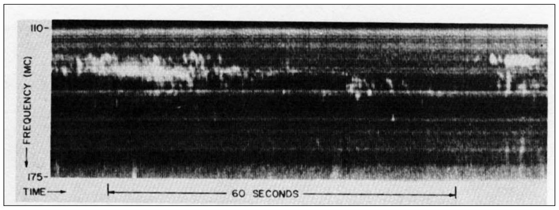

Figure 4: An example of noise storm (Type I) bursts. The enlargement is greater than in the next three figures to show the short duration of the individual bursts. The fine vertical structure extending across the frequency band is caused by the cathode-ray traces (after Maxwell, Swarup and Thompson, 1960).

5.2 Type II, Slow Drift Bursts

Strong bursts lasting for several minutes, usually starting in the frequency range 200-700 MHz and drifting down to less than 100 MHz. Frequency structure in the form of a fundamental and second harmonic is usually present. Type II bursts are attributed to fast-mode MHD (magneto-hydrodynamic) shock fronts moving outward through levels of decreasing plasma frequency within the corona.

5.3 Type III, Fast Drift Bursts

Relatively common bursts that start at frequencies of a few hundred MHz. Burst lifetimes are a few seconds, within which the maximum intensity drifts rapidly downward in frequency. They often occur in clusters that last for a few minutes. A type of fast-drift burst, in which the spectrum initially drifts downward in frequency and then turns upward again, was discovered at Fort Davis by Swarup. These appear on the Fort Davis records as an inverted letter U, and are known as

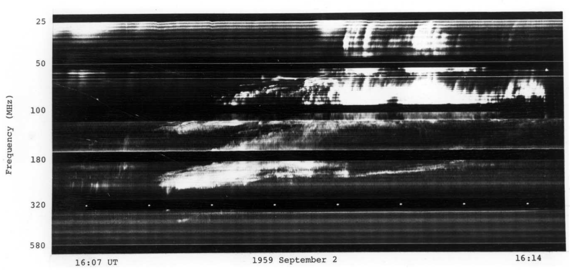

Figure 5: A Type II burst showing fundamental and harmonic frequency components. The white dots near the 320 MHz frequency level are one-minute time marks. Type III bursts can be seen between 16:11 and 16:13 UT in the 25-110 MHz range (Figure supplied by A. Maxwell, Harvard College Observatory).

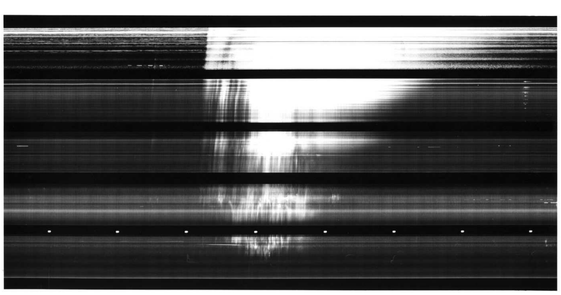

Figure 6: A group of Type III bursts accompanied by Type V continuum. The frequency range is 25-580 MHz as in Figure 4, and the time marks run from 19:25 to 19:32 UT on 4 February 1960 (Figure supplied by A. Maxwell, Harvard College Observatory).

'U-bursts' (Maxwell and Swarup 1958). U-bursts are believed to be generated by excitations that begin to move outward through the solar corona, but are guided by loops in the solar magnetic fields causing them to turn and move down toward the solar surface. They occur much less frequently than the usual Type III bursts.

5.4 Type IV, Continuum Emission

These appear as strong continuum emission with mainly smooth spectral features, but sometimes showing pulsations. They typically extend from a few hundred MHz to a few GHz and may last for several hours. They are usually associated with major outbursts on the Sun, and at their start are often accompanied by a Type II burst.

5.5 Type V

A short continuum burst, with duration increasing with decreasing frequency up to about 10 min, and usually accompanying T ype III bursts. Type IV and V emissions are attributed to the gyro-synchrotron mechanism.

5.6 The Fort Davis Observations

Each film record from the Fort Davis station was carefully analyzed, and the times and frequency ranges of all bursts were listed, along with their classification (as given above). Intensities were classified on a scale of one to three as described in Thompson (1961a). Summaries of these data were sent to the Sacramento Peak Solar Observatory and the National Oceanic and Atmospheric Administration (NOAA), and were published in the CRPL[3] (Boulder) Series F, Part B, *Monthly Bulletin of Solar-Geophysical Data*, and in the *IAU Quarterly Bulletin of Solar Activity*. Also, detailed information on radio emissions from specific solar flares was provided to a large number of individual investigators. The solar program covered the period October 1956 to October 1982, or approximately two cycles of the sunspot number activity, as shown in Figure 8.

6 FURTHER DETAILS OF THE SOLAR INSTRUMENTATION

When I joined the Fort Davis group in 1957, my first important task was to replace the couplings in the drive shafts of the capacitors on the three sweep-frequency receivers. These had become worn after more than a year of constant rotation for ~12 hours each day, resulting in some loss in sensitivity which was restored by realignment of the tuning. Thereafter, this procedure became a routine yearly maintenance item. By late 1957, it was clear from the records of solar bursts that interesting spectral structure was being missed by the low frequency cutoff at 100 MHz in the records. Two more receivers, covering 25-50 MHz and 50-100 MHz, were obtained from A.I.L. These were mechanically tuned as in the 100-580 MHz receivers. The vacuum tubes for the tuned input stages were WE 417A triodes, which (unlike those for the 100-580 MHz receivers) were conventional tubes with electrode connections through base pins. For the 25-50 MHz receiver, the intermediate frequency (IF) stages included a crystal filter of width 40 kHz to contain the response to the strong interfering signals encountered at these lower frequencies. The antennas for the new receivers were fixed bow-tie dipoles[4] in front of a plane reflecting screen with a fixed pointing direction toward the meridian at zero declination. The 25-50 MHz dipole was horizontally polarized and the 50-100 MHz one was orthogonal to it. These were able to pick up solar bursts over a wide range in hour angle. To accommodate the two new receivers, a new recording system with six cathode ray tubes and a camera using 70-mm film were obtained.[5]

The effective shielding of the site from FM, TV, and other signals in the 50-100 MHz range was demonstrated by the occurrence on the film records of occasional short bursts of interference as a result of reflections from meteor trails (Thompson 1961b). Typically about ten signals would be seen across the 50-100 MHz band, starting at approximately the same time, but with durations varying inversely as the square of the frequency. The overall duration of such a burst was usually a few seconds to two minutes. They were particularly noticeable during the Perseid meteor shower. In the same band there were also occasional periods of interference lasting for minutes to hours, attributable to reflection from sporadic-E in the ionosphere.

In 1959 a receiver covering 2100-3900 MHz was added which made use of the sixth cathode ray tube. When designing the 100-580 MHz feed system, Henry Jasik had first built a 1/6.82 scale model for test measurements, in which the 300-600 MHz horn of the full-scale feed was represented by a 2-4 GHz horn (Jasik 1958). As an extra benefit he added this small horn to the full-scale feed package, and it was brought into use from January 1960 to December 1961 with a new receiver obtained from A.I.L.[6] The input stage of this receiver was a Schottky diode mixer with a local oscillator using a backward-wave oscillator tube. Both sidebands from the mixer were accepted, and the IF response was 100 kHz to 5 MHz. The response to received signals was a band of width 10 MHz with a small gap in the center. This system was commonly referred to as a 'zero-IF' receiver because the center frequency of the received band was not offset from the local oscillator frequency. For further details see Thompson (1961a). In 1966, a receiver covering 10-25 MHz was added, for which a log-periodic antenna was obtained. This was pointed at a fixed elevation of 60° but could be adjusted in azimuth. Problems with observations in this low band are caused by ionospheric absorption and by the number of communication signals. Solar emissions were recorded, particularly during strong outbursts, but in general the 10-25 MHz band did not provide much useful data.

7 FURTHER EXPANSION OF THE SOLAR FREQUENCY RANGE

Because the site was substantially free from interfering signals at frequencies above a few tens of MHz, Maxwell realized that it would also be a good location for non-solar radio astronomy. An 85-ft. (25.9-m) diameter equatorially-mounted antenna was obtained in 1962 from the Blaw-Knox Co. of Pittsburg, PA, and the Harvard site at Cooke Flat was extended to 4 acres in order to accommodate the antenna and a new laboratory building, as shown in Figure 9.

Although it was not primarily intended for solar

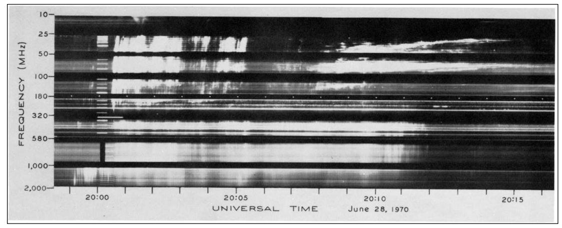

Figure 7: A large radio outburst in which there is a group of Type III bursts between 20:00 and 20:05 UT and a Type II burst between 20:08 and 20:15 UT. The frequency coverage shown is 10 to 2000 MHz, and in the range from about 400 MHz to 2000 MHz there is strong Type IV continuum radiation (Figure supplied by A. Maxwell, Harvard College Observatory).

work, from March 1970 to March 1974 the 85-ft antenna was used for solar observations in the bands 580-1000 MHz, 1-2 GHz, and 2-4 GHz, as shown in Table 1. There were then as many as nine solar observing bands, so, when observations were made in more than six bands, the original three-band recording system with its 35-mm film camera was used in addition to the six-band system. During the period of solar observing with the 85-ft antenna, solar activity (as indicated by the sunspot numbers) was declining from the maximum of 1969 toward the minimum of 1976, as shown in Figure 8. No information has been found about the receivers used in these three bands covering 580 MHz to 4 GHz, but they were probably the 'zero-IF' type with a log-periodic feed. Solar bursts in these three highest frequency bands were mostly of the continuum Type IV classification, sometimes showing intensity pulsations with periods in the range 1-200 sec, as investigated by Maxwell and Fitzwilliam (1973).

Table 1: Frequency ranges and the corresponding antennas used in the solar program.

Frequency Range	Antenna
10 – 25 MHz	Log-periodic, fixed elevation 60°, adjustable in azimuth.
25 – 50 MHz	Broadband dipole with plane reflector, fixed elevation 60°.
50 – 100 MHz	Broadband dipole with plane reflector, fixed elevation 60°.
100 – 180 MHz	28-ft. diameter tracking paraboloid.
180 – 320 MHz	28-ft. diameter tracking paraboloid.
320 – 480 MHz	28-ft. diameter tracking paraboloid.
580 – 1000 MHz	85-ft. diameter tracking paraboloid.
1000 – 2000 MHz	85-ft. diameter tracking paraboloid.
2000 – 4000 MHz	85-ft. diameter tracking paraboloid.

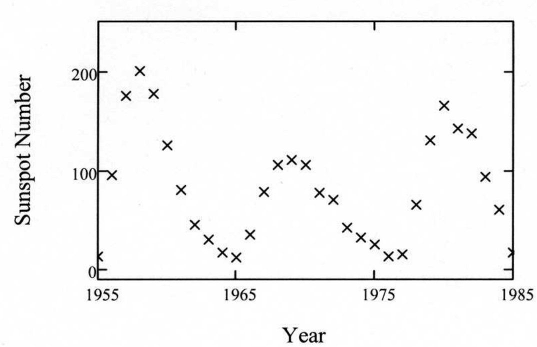

Figure 8: Yearly averages of the sunspot number. The Fort Davis observations spanned the years 1956-1982.

During 1977-1978 a new sweep-frequency receiver for the 50-100 MHz band, based on a commercial (Hewlett Packard) spectrum analyzer, was tested and found to perform well. In late 1979 and early 1980 all of the mechanically-tuned solar receivers were replaced with spectrum analyzer systems. Sensitivity with the new receivers was very similar to that with the old system, and an example of a record with the new system can be found in Maxwell et al. (1985).

From October 1956 to October 1982, the period in which solar observations were made at Fort Davis, there were sunspot maxima in 1958, 1969, and 1980 (see Figure 8). The years 1962-1966 and 1973-1977 were periods of low solar activity, and in some years as few as two Type II bursts were recorded. The frequency range 50-320 MHz was generally adequate to record events during such times. Thus the frequencies covered at any time depended upon the level of solar activity as well as the receivers available. Table 2 shows the frequency bands principally used at different times.

8 STATISTICS AND OPTICAL ASSOCIATIONS OF THE SOLAR BURSTS

In addition to providing data on all solar radio outbursts that occurred during daytime hours at Fort Davis, a number of studies of the statistics of the various types of bursts were made. These included the association with optical solar phenomena and geophysical events. Some of the more important results are summarized below.

Type I (noise storm) events, which persist for hours or days, generally occur when there is an active region on the Sun, but no statistically-significant association was found between their intensity and the occurrence of other types of radio outbursts or flares. Type II (slow drift) bursts often occur as part of a large outburst which starts as a group of strong Type III (fast drift) bursts and may be accompanied by continuum emission of Type IV or V. Such major radio events are usually associated with solar flares (Swarup et al., 1960; Maxwell and Thompson, 1962).[7] On the assumption that the emission occurs at the local plasma frequency, the radial velocity of the disturbances that produce Type II bursts was generally found to be within the range 700-1800 km/s, decreasing with frequency (i.e. with increasing coronal height). In relating the frequencies of bursts to the level in the solar corona, values used for the electron density (over active regions) as a function of height were ten times the quiet-Sun values given by the Baumbach-Allen or Saito models, and twice those of the Newkirk model, as explained by Dryer and Maxwell (1979). In the case of Type III (fast drift) bursts, about 50% were found to occur during times when a flare was present on the Sun, but examination of the statistics indicated that the number of such bursts causally associated with a flare was closer to 20%. Hughes and Harkness

Figure 9: The site in 1964. From left to right: the solar laboratory, the 28-ft. antenna, the 25-50 and 50-100 MHz dipoles and the 70 MHz monitoring antenna, the 85-ft. antenna, an extendable tower for access to the focus of the 85-ft. antenna, and the new laboratory building for the 85-ft. antenna. The figure near the 85-ft. antenna is laboratory assistant C. Murray (Photograph supplied by A. Maxwell, Harvard College Observatory).

(1963) examined the frequency variation with time in Type III bursts and estimated the radial component of velocity of the exciter of the plasma oscillations to be 40% of the speed of light. Both electron streams and electron plasma shock waves were discussed as the cause of Type III bursts, but subsequent analysis has eliminated the shock wave mechanism.

Bursts with continuum spectra (Types IV and V) are generally attributed to gyro-synchrotron radiation. Of these, the Type IV events often have durations of one or more hours and can extend to frequencies up to several GHz (Thompson, 1962; Thompson and Maxwell, 1962; Maxwell et al., 1963). Most Type IV bursts recorded at Fort Davis were associated with large solar flares, 85% of which were within 60° of the solar meridian, indicating some restriction on the angle of emission of the radiation. Type V continuum bursts typically closely follow an intense group of Type III bursts. They were found to be strongest at frequencies below about 300 MHz. The duration increased with decreasing frequency and generally did not exceed a few minutes. Type V bursts were found to be associated with flares in more than 70% of cases. Detailed statistics of the various burst types can be found in the references given above. In general, associations of Type II and Type IV bursts with strong (class 3) flares were unambiguous, but with less energetic events the associations were often less clear.

In the periods 1972-1973 and 1979-1981, during or following sunspot maxima, large solar events recorded at Fort Davis resulted in a number of publications with respect to the generation of MHD shock-fronts by solar flares and their relation to Type II bursts (Maxwell and Rinehart, 1974; Dryer and Maxwell, 1979; Maxwell and Dryer, 1982; Maxwell and Dryer, 1982-1983, Wu et al., 1983; Maxwell et al. 1985). These included theoretical studies of the propagation of fast-mode MHD shock waves in the solar plasma, and are one of the more important results of the solar program.

9 ASSOCIATION OF SOLAR BURSTS WITH GEOPHYSICAL PHENOMENA

Several papers were written on the association of bursts with geophysical events. The speed of disturbances associated with Type II bursts suggested an association with magnetic storms, i.e. the increases in the index of magnetic activity at the Earth often accompanied by auroral phenomena and Forbush decreases in the cosmic ray count. These occur approximately 30 hours after certain solar flares. An analysis of the Type II bursts that occurred during 1957-1958 resulted in the conclusion that bursts of this type are causally associated with the emission of auroral particle streams and associated phenomena (Maxwell, Thompson and Garmire, 1959; Thompson and Maxwell, 1960b). Further investigation has indicated that the association is stronger when the Type II burst is accompanied by Type IV emission. Similarly, the speed of the disturbances associated with Type III bursts suggested that if the mechanism involves particle streams that are subsequently emitted from the Sun, these might be detected as variations in the cosmic ray flux at the Earth. However, analysis of the Fort Davis Type III data indicated no correlation with increases in the general cosmic ray level as recorded at the neutron monitor pile at Climax, Colorado (Thompson, 1959a; Thompson and Maxwell, 1960b).

Another type of solar emission that is detected at the Earth is in the form of protons with energy of some tens of MeV, which at the time of the Fort Davis observations were sometimes referred to as low-energy cosmic rays. These cause increased ionospheric attenuation of radio waves at high latitudes, resulting in conditions referred to as polar blackouts. The time delay between the solar outburst and the onset of the blackout is approximately 0.7 hr. The Fort Davis data showed a strong correlation between the occurrence of Type IV continuum emission and polar blackouts, especially in cases where the associated flare was in the western hemisphere of the Sun (Thompson and Maxwell, 1960a). This predominance of the western hemisphere in the related outburst positions suggests that the solar particles follow a curved path in space, guided by magnetic fields. For further discussion of the relationships between solar radio bursts, particularly Type II and Type IV, and the emission of solar protons with various energy ranges, see Maxwell (1963) and particularly Maxwell et al. (1964). Studies of how the radio emission is related to particle emissions and geophysical phenomena are among the most interesting and important results of the Fort Davis solar program.

Table 2: Time periods in the solar program and the corresponding frequency ranges observed.

Observing Period	Frequency Range
October 1956 – December 1958	100 – 580 MHz
January 1959 – December 1959	25 – 580 MHz
January 1960 – December 1961	25 – 580 MHz and 2.1 – 3.9 GHz
January 1962 – December 1962	25 – 580 MHz
January 1963 – March 1965	50 – 320 MHz
April 1965 – December 1966	25 – 320 MHz
January 1967 – February 1970	10 – 580 MHz
March 1970 – April 1970	10 – 1000 MHz
May 1970 – March 1973	10 – 2000 MHz
April 1973 – March 1974	10 – 4000 MHz
April 1974 – January 1978	25 – 320 MHz
February 1978 – October 1982	25 – 580 MHz

10 THE NON-SOLAR PROGRAM WITH THE 85-FT ANTENNA

Installation of the 85-ft antenna at the site was completed by the end of 1962, and a new laboratory building was erected for the associated control and receiving equipment. The main purpose of the antenna was to allow an expansion of the astronomical program, particularly during periods of low solar activity.

Before leaving the project in December 1962, I built a simple receiver for first tests of the new antenna at a frequency of approximately 950 MHz. The receiver input was switched at 94 Hz between the antenna output and a 50-ohm load at ambient temperature, using a switch (see Figure 10) with a design similar to one that Gordon Stanley had shown me at Caltech's Owens Valley Radio Observatory. The Fort Davis station had only minimal workshop facilities, so improvization was sometimes necessary. Marlyn Krebs kindly provided the aluminum box parts for the switch, and I found some metal parts in the household plumbing supplies at the Fort Davis hardware store which I used for the transmission line and stub elements. The switch isolation at 920, 950, and 980 MHz was 21, 31, and 19 dB, respectively. The input stage of the receiver was a 1N21F Schottky diode mixer, and the IF was 30 MHz with 5 MHz bandwidth. The IF input stage had a noise figure of approximately 0.7 dB using low-noise WE437A and WE417A vacuum tubes in a cascode circuit.[8] A gain modulator driven at the switching frequency allowed the signal levels with the two positions of the input switch to be balanced. The receiver was used for observations of lunar occultations at 950 MHz and appeared in several Fort Davis publications.

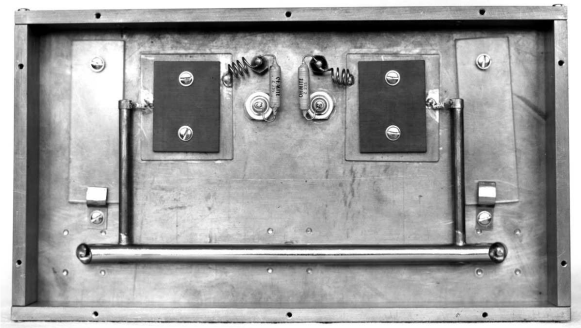

Figure 10: Input switch for a 950 MHz receiver made for initial observations with the 85-ft. antenna. The horizontal conductor in the lower part of the picture forms a 50-ohm line with respect to the mounting plate, which acts as a ground plane. A connector at one end of this line goes to the antenna and at the other end to a 50-ohm load. A connector at the center of the line goes to the receiver input. The two vertical stub lines are each a quarter wavelength long and are attached to the 50-ohm line at points a quarter wavelength from the central connector. (At radio wavelengths, a quarter wavelength of line effectively converts a short circuit into an open circuit, and vice versa.) The effective electrical lengths of the stubs can be adjusted by pieces of polystyrene sheet, the edges of which can be moved between the stubs and the ground plane. The top end of each stub is connected through a diode to a plate that forms a capacitor with the ground plane. Two square wave switching voltages, applied in opposite phase to these plates, cause the stubs to be alternatively open-circuit or capacitively shorted to ground. Thus the receiver input is alternately connected to the 50-ohm load or to the antenna. A switch designed on the same principles but using coaxial elements is described by Orhaug and Waltman (1962) (Photograph by the author).

In early 1963, a state-of-the-art receiver for 5 GHz with a parametric amplifier, obtained from A.I.L. (Hughes et al., 1965), was installed with a 5 GHz feed system from Jasik Labs. The input of this receiver was switched between the primary feed horn and a reference horn that could be pointed towards the antenna to produce a reference beam, or toward the cold sky at high elevation angles.

Publications show that the 85-ft antenna was being used regularly in non-solar projects by mid-1963. These included observations of occultations of sources by the Moon (Hughes, 1965; Taylor, 1966; Moffet et al., 1967; Maxwell and Taylor, 1968) and of the Crab Nebula by the Sun (Hughes et al., 1964). For most of the lunar occultations the data were recorded on paper tape and transferred to punched cards at Harvard for further analysis. Other programs included mapping of the Galactic Center (Maxwell and Downes, 1964), the Galactic Plane (Altenhoff et al., 1970), and star-forming regions, including Cygnus X (Downes and Rinehart, 1966). Measurements were made of flux densities at 5 GHz for Galactic and extragalactic sources (Maxwell and Rinehart, 1966; Hughes, 1967), including planets (Hughes, 1966). Most of the published work with the 5 GHz receiver involved observations made before 1970.

In 1972, a U.S. program of very long baseline interferometry (VLBI) observations was initiated, in which the 85-ft antenna at Fort Davis was frequently used (Cohen et al., 1975). Other antennas included in these observations were the 30-m antenna at the Owens Valley Radio Observatory and the 40-m antenna of the NRAO in Green Bank. The Fort Davis location was particularly useful for VLBI since it provided intermediate baselines when combined with other radio astronomy antennas, many of which were located in the North-East or West-coastal regions of the U.S. After April 1974, the 85-ft antenna was used entirely for non-solar observations, mostly for VLBI. The VLBI program used frequencies 10.69 and 10.71 GHz, i.e. a wavelength of ~2.8 cm.

11 FURTHER DETAILS OF THE OBSERVATORY STAFF AND STUDENTS

Alan Maxwell lived principally in Fort Davis through the years 1956-1973 and then moved to Cambridge, MA. He continued to direct the solar operations which were carried out by technical staff at Fort Davis and included analysis of the film records. He retired in 1983. In addition to members of the research staff mentioned above, Daniel E. Harris was involved mainly with the non-solar activities during 1970-1973. Graduate students who completed work for Ph.D. theses at the station included Samuel J. Goldstein (Stanford Ph.D.), Joseph H. Taylor (as a Harvard graduate student, 1968-1969), Dennis Downes (as a Harvard undergraduate and graduate student 1964-1970), and David B. Shaffer (Caltech Ph.D.). Joe Taylor was later awarded the Nobel Prize for his work on relativistic effects of gravitation using timing of binary pulsars at the Arecibo Observatory. Other students from Harvard who worked at the station included Peter Stone, Stephen Cole, Gordon Garmire, William E. Howard III, Richard L. Harkness Jr., Richard J. Defouw, Larry Goad, Tom Wilson, Peter Cummings, Andrew Fraknoi, and Jim Fitzwilliam. Several other scientists spent time at Fort Davis as visitors. Figure 11 shows the 85-ft laboratory with some of the people mentioned above.

From 1976 to 1991, the VLBI programs were successively managed by John Ball, Paul Sebring, Jesse James, and J.D. Williams. Electronic technicians who worked at the station include Dino Parenti, Newell Sanford, Richard H. Ellis, and Paul Whitfield. Almost always one of the young people from Fort Davis, while a student at the high school or at Sul Ross State College in Alpine, had a job as laboratory assistant. Of these Ron F. Rinehart remained as a staff member through 1964-1975 and participated in observing programs.

12 CONCLUSION OF THE HARVARD SOLAR PROJECT

The solar observations continued until December 1982, after which the program was discontinued. All of the film records were sent to the National Oceanographic and Atmospheric Administration (NOAA) at

Boulder (CO) for archival storage. The VLBI program continued until October 1991,[9] when the NRAO's Very Long Baseline Array (VLBA) (Napier et al., 1994) took over with a new 25-m antenna at Cook Flat, specifically for that program. The VLBA antenna is located within a few hundred meters of the location of the original 85-ft antenna, which was demolished. The Fort Davis location thus remains an active radio astronomy site.

13 NOTES

1. At one point Sproul Road crosses the usually-dry bed of Limpia Creek. The creek sometimes flowed for a few hours after a thunderstorm in the mountains, and experience showed that at such times it was not always easy to judge whether the observatory pickup truck could make the crossing successfully!
2. The tripod feed-support structure on the 28-ft antenna was made of fiberglass, and was probably not designed for a feed as heavy as the 100-580 MHz structure. After about three years, cracks in the fiberglass were noticed near the centers of the feed support members. As on many occasions, Marlyn Krebs produced an answer to the problem. He improvised splints made from short lengths of oil-well casing, which provided the required support and remained in place on the antenna throughout its working lifetime.
3. CRPL (the Central Radio Propagation Laboratory) became part of ESSA, and later part of NOAA.
4. A photograph of the 25-100 MHz antennas in Thompson and Maxwell (1959) shows initial tests in which the dipoles were too close to the reflecting screen. Their positioning was subsequently re-adjusted. Broadband feeds for frequencies below 100 MHz would have been too large and too heavy to use on the 28-ft antenna.
5. This recording system was designed by Dr Richard Dunn, a scientist at the Sacramento Peak Solar Observatory.
6. The frequency range for this receiver was 2.1-3.9 GHz, i.e., just less than a factor of two to avoid second harmonic responses at the mixer input. The same receiver may have been used during 1973-1974 on the 85-ft antenna to cover the nominal band 2-4 GHz (see Table 2).
7. Note that the associations referred to here are based on the timing of the radio and optical outbursts since the Fort Davis radio telescopes did not measure positions of the solar bursts on the Sun.
8. A grounded-cathode triode followed by a grounded-grid triode.
9. During the period from 1982 until the ending of the Harvard program in 1991 the Fort Davis station was referred to as the Agassiz station for official Harvard purposes.
10. The list of references does not include those associated with the VLBI program, but otherwise is believed to be complete, or close thereto, for publications concerning the equipment and observations at the Fort Davis site. Not all of the listed references are mentioned in the text.

14 ACKNOWLEDGEMENTS

The original funding for the Fort Davis station including the two antennas and laboratories was provided by the U.S. Air Force through the offices of the Sacramento Peak Observatory. This funding also covered the solar program through 1973. Dr J.W. Evans, Director of the Sacramento Peak Observatory, and Dr Edwin W. Dennison, who monitored the Fort Davis contract, provided much assistance to the project. From 1974 until it ended in 1983, the solar program was funded by the NSF Atmospheric Sciences Division, the NASA Solar Physics Division, and the NOAA World Data Center. Funding for non-solar programs from 1962 through 1972 and for the VLBI astronomical programs from 1972 through 1991 was provided by the NSF Astronomical Sciences Division. Funding for the VLBI geodetic programs was provided by the NOAA National Geodetic Survey.

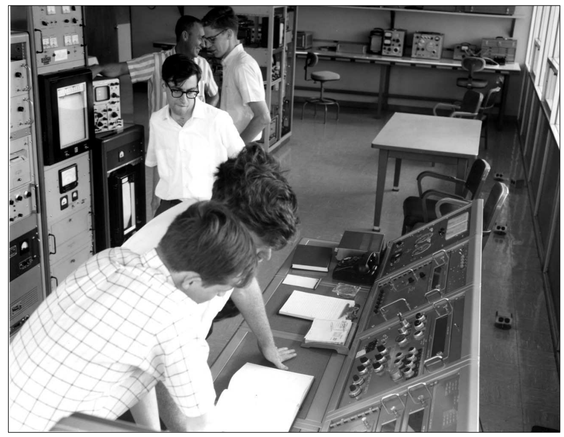

Figure 11: The 85-ft. antenna laboratory with control console and equipment racks. From front to rear the people are: Harvard undergraduate students L. Goad and T. Wilson, graduate students D. Downes and J.H. Taylor, and electronic technician N. Sanford (in the striped shirt) (Photograph supplied by A. Maxwell, Harvard College Observatory).

Many local people were most helpful and hospitable, especially in the early years of the project, particularly the Sproul, McIvor and Miller families. This was especially appreciated by those of us who had moved to Fort Davis shortly after arriving in the U.S., which included Maxwell, Swarup, Hughes and myself. Although the town of Fort Davis had no mayor, Mr. Barry Scobee, a Justice of the Peace, local historian, and newsman, essentially filled that position. He provided much advice and support for the Harvard staff. Marlyn Krebs of the McDonald Observatory was a great help on numerous occasions.

Finally, many thanks are due to Alan Maxwell, who provided Tables 1 and 2, photographs of the site and the records of solar bursts, information on students at the site and many other details. Figure 4 is reprinted here with the permission of Harvard University Press. Govind Swarup and Michael Hughes also provided invaluable help with recollections of the equipment and observations.

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A. Richard Thompson is a graduate of the University of Manchester, and in 1956 obtained his Ph.D. for work at the Jodrell Bank Experimental Station, where as a student of R. Hanbury Brown, he developed a long-baseline radio interferometer for measurement of angular widths of radio sources. From 1956-1957 he worked with E.M.I. Electronics, Middlesex, on missile guidance and telemetry. He then joined the staff of Harvard College Observatory as a Research Associate, working on the solar program at the Harvard Radio Astronomy Station, Fort Davis, Texas. In 1962 he moved to Stanford University as a member of R.N. Bracewell's radio astronomy group. During 1966-1972 he also held a visiting appointment at Caltech's Owens Valley Radio Observatory. In 1973 he joined the National Radio Astronomy Observatory (NRAO), and served in various engineering and management positions in the VLA and VLBA projects. From 1978 to 1998 he was also active in frequency coordination for radio astronomy and was a member of U.S. Study Group 7 of the International Telecommunication Union (earlier Study Group 2 of CCIR) and Chairman of the U.S. Working Group on Radio Astronomy. Between 1980 and 1991 he was a member of the Committee on Radio Frequencies of the National Academy of Sciences. He is first author of the book *Interferometry and Synthesis in Radio Astronomy* (Wiley, 1986, 2nd edition 2001), and is currently an emeritus scientist at NRAO.

LETTERS TO THE EDITOR

Dear Associate Professor Orchiston,

Re: Montgomery et al.'s paper on "Michell, Laplace and the Origin of the Black Hole Concept"

I was very pleased with the recent article on Michell and Laplace (Montgomery et al., 2009). May I add that Laplace's article is reprinted in my Zach collection book *Astronomie der Goethezeit* (Brosche, 1998), a second edition of which has appeared. Also, you should notice the book by Jean Eisenstaedt (2005) titled *Avant Einstein* ..., .where Michell and Laplace are treated extensively. Finally, you may be interested to see that the germs for such ideas were more widely distributed. For example, our writer and scientist, G. Ch. Lichtenberg (1742–1799), also made pertinent notes, but did not publish his thoughts during his lifetime (see Brosche, 1993).

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HIGHLIGHTING THE HISTORY OF FRENCH RADIO ASTRONOMY. 5: THE NANÇAY LARGE RADIO TELESCOPE

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Abstract: The large radio telescope (Le Grand Radiotélescope) at the Nançay radio astronomy field station of Paris Observatory was built between 1958 and 1966 on the model of the Ohio State University radio telescope, with which a large collecting area was obtained at low cost. The Nançay radio telescope, with a surface area of 7,000m^2, is a meridian instrument which can observe equatorial sources for 30 minutes on each side of the meridian transit of the source. We describe the origin and the construction of this instrument. We also describe the evolution of the focal systems and give an outline of the first spectral and continuum observations obtained with the radio telescope in the wavelength range 6 to 32 cm.

Keywords: radio telescope, radio interferometer, Nançay, radio astronomy, incoherent scatter

1 INTRODUCTION

Radio astronomy in France started after WWII with small instruments, mostly solar, at the Physics Laboratory of the École Normale Supérieure and at the Institut d'Astrophysique in Paris (see Orchiston and Steinberg, 2007). Thanks to the availability of two 7.5-m Würzburg antennas taken from the Germans, the group at the École Normale Supérieure began galactic radio astronomy in 1954 (Orchiston et al., 2007). Meanwhile, the group at the Institut d'Astrophysique built a 2-element interferometer at the Haute Provence Observatory which was used between 1959 and 1967 to catalogue radio sources at 300 MHz (ibid.). But radio astronomy then ceased at the Institut d'Astrophysique, and the interferometer was dismantled.

In 1953, a field station was established at Nançay, 190 km south of Paris, by the École Normale Supérieure, and the radio astronomy group moved to the Meudon site of the Paris-Meudon Observatory the following year. In 1955, two Würzburg dishes located at Marcoussis, south of Paris, were transferred to Nançay and mounted equatorially on carriages which could be moved along a 1,480m long E-W, 6m wide, railway track, and along a similar 380m long N-S track. This variable-baseline interferometer became operational in 1959, and operated in the continuum at 1,420 MHz (details are in Orchiston et al., 2007). A 169 MHz solar interferometer was put into operation at Nançay in 1956, and a small 3cm solar interferometer which was moved earlier from Marcoussis to Nançay was enlarged in 1958 (see Orchiston et al., 2009).

Elsewhere in the world large single-dish radio telescopes and interferometers were being erected for galactic and extra-galactic studies at about this time. For example, in England the Jodrell Bank 76-m Mark I Radio Telescope was completed in 1957 (Lovell, 1968; 1973), and in Australia the 64-m Parkes Radio Telescope and the Mills Cross at Hoskinstown near Canberra were completed in 1961 and 1965 respectively (see Robertson, 1992; McAdam, 2008). The Cambridge University radio astronomy group was also busy building interferometers (e.g. see Scheuer, 1984; Smith, 1984). The period was favourable for large projects in France, which was under the leadership of General Charles de Gaulle, and it is natural that the radio astronomers there were dreaming of a large instrument for non-solar work. This eventually materialized as the Nançay 'Grand Radiotélescope' (see Figure 1). In this paper we investigate the origin and development of this instrument.[1]

2 INTERFEROMETER OR LARGE PARABOLIC RADIO TELESCOPE?

The French group at the École Normale Supérieure and Observatoire de Paris-Meudon had considerable experience in radio interferometry. As early as 1952 solar fringes were obtained at 3cm by Jacques Arsac and Jean-Louis Steinberg, with the latter proudly announcing "I think we are the first." (Steinberg, 1952; our translation).[2] Several solar radio interferometers were subsequently installed at Marcoussis, and later at Nançay (Pick et al., 2010). It is not surprising, therefore, that at the beginning of 1955 some members of the group proposed to build a large interferometer for non-solar studies, consisting of two 25-m diameter altazimuth-mounted antennas, similar to the Dwingeloo Radio Telescope (see Van Woerden and Strom, 2007), but movable on E-W and N-S railway tracks. The project was unanimously accepted by the radio astronomy group and co-signed by its head, Jean-François Denisse, and by Steinberg who was still at the École Normale Supérieure (Denisse and Steinberg, 1955). The main science driver was to observe the 21cm line of interstellar atomic hydrogen, discovered in 1951 (Ewen and Purcell, 1951; Muller and Oort, 1951), and the scientific reason for an interferometer was as follows (Denisse and Steinberg, 1955; our translation):

> At present, the major problem is to obtain a better resolution in order to solve the problems of structure [of the radio sources] … Since 1946, interferometers have been used in England and in Australia, with two or more antennas on a rather long baseline. Provided that the distance between the antennas can vary in a quasi-continuous way, a two-antenna interferometer is in principle equivalent in resolving power to a continuous antenna with the same total length.

However, at the beginning of 1956 Denisse came up with new ideas when he compared the interferometer with two other options:

(1) a fully-steerable paraboloid, which was rejected on the grounds that "… given the required surface quality [for observing at 21 cm] and the present technical possibilities, one can only build for a reasonable price dishes with a surface smaller than about 900m^2 (a diameter of about 30 metres) …; and

(2) "… a [fixed] parabolic mirror illuminated by a flat mirror movable around a horizontal axis: this is a meridian instrument, less versatile than the other one, but which can be built with a much larger surface area at low cost. (quotations are cited by Darmon, 1981: 42; our translations).

One argument against the interferometer was that

> … taking into account the structure of the ground in Nançay (sand + clay), the cost of the railway track is a significant part of the total cost of the project which is more than 500 million [old] francs … (cited by Darmon, 1981: 43; our translation).

This sum was equivalent to about €10 million in 2008.[3] This new railway track, with concrete foundations, was judged necessary to support the heavy 25-m antennas on their carriages, but the argument was rather weak because the problem of foundations was the same for any type of radio telescope. Moreover, the reservations expressed about steerable paraboloids seem odd since the Jodrell Bank Radio Telescope was almost completed and the Australians had decided to build the Parkes Radio Telescope. A better reason—which was difficult to acknowledge officially—was that French industry was unable or unwilling to build high-precision steerable paraboloids (even though this was possible in other countries), but the radio telescope simply had to be built in France given the political climate at the time.

Meanwhile, the scientific objectives had also changed. Denisse was impressed by the results obtained on distant galaxies with the 5-m Hale Telescope on Palomar Mountain, and in particular by Baade and Minkowski's (1954) identification of Cygnus A with a faint, distant radio galaxy, and he wrote:

> [Cygnus A] is at a distance of 200 million light years. This radio source is more than 1,000 times stronger than most of the other radio sources in which similar objects are certainly present: so on average they must be located 30 times further away, i.e. at 6 billion light years.
>
> This conclusion is also confirmed by the fact that no remarkable optical objects can be seen in the direction of even very intense radio sources, so one must expect that most of them are located beyond the range of large telescopes. (Denisse, 1958: 2; our translation).

Then he went on to say that it would be of great importance to obtain the distances of these sources, and that the only direct method for this would be to observe the 21-cm hydrogen line, which had recently been discovered in absorption in Cygnus A (Lilley and McClain, 1956). Thus, "The very large radio telescope which will be constructed at Nançay field station was conceived in order to calibrate the radio universe

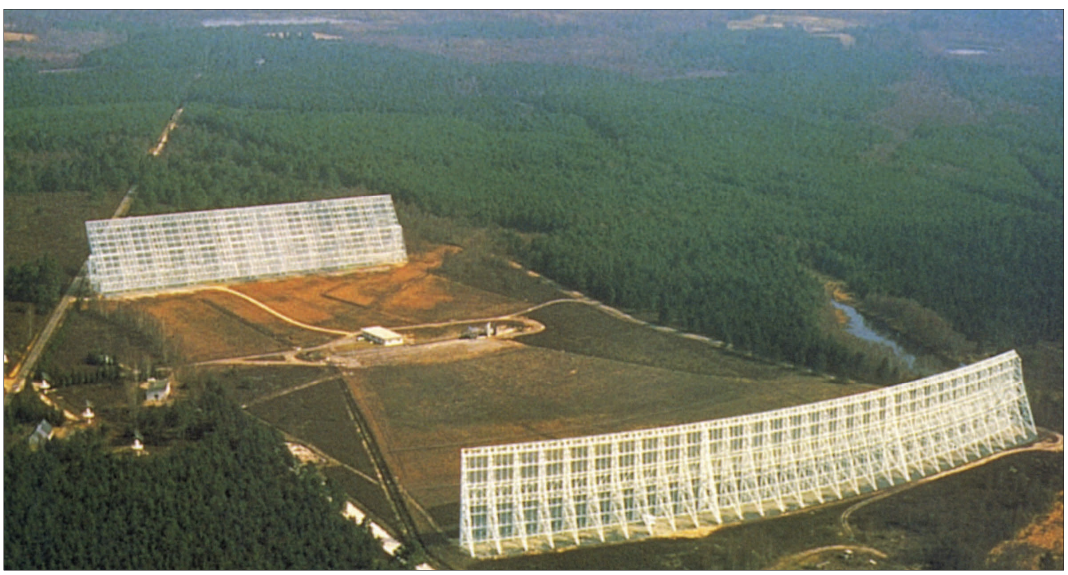

Figure 1: Aerial view of Le Grand Radiotélescope at Nançay.

...” (Denisse, 1958: 3; our translation).

Curiously, Denisse did not explicitly mention observations of the hydrogen line in emission in galaxies, which were to become the main target of the Nançay radio telescope; but H-line observations had been made of only a handful of external galaxies at that time, and presumably he thought that it would be easier to detect the line in absorption. Then he proceeded to say that a very large collecting surface was needed for sensitivity, and also in order to limit confusion when observing faint sources. Confusion was then considered a major topic, being the subject of intense debate between the Cambridge group and Mills’ team in Australia in regard to radio source counts and their cosmological significance (e.g. see Mills, 1984; Sullivan, 1990).

The two-element meridian radio telescope built between 1956 and 1963 by John D. Kraus (1910–2004) and his students at the Ohio State University Radio Observatory was taken by Denisse as a model for the Nançay instrument, because it had a large surface area and had been constructed for a modest cost. This instrument (Kraus, 1986: 86-88) consisted of a fixed curved E-W reflector 110m wide and 21m high, illuminated by a tiltable flat E-W reflector 104m wide and 31m high located to the north. The two reflectors were joined by a flat conducting ground plane, the distance between the mirrors being 153m. Two 1,415 MHz rectangular fixed horns, for observations in the switching-position mode, were placed at the focus of the curved mirror, 18m from its apex. The dimensions of these beams, defined by diffraction, were 40′ N-S and 8′ E-W at this frequency, and they were separated by 40′. The Ohio radio telescope was used for a continuum survey of the whole accessible sky at 1,415 MHz, and later for a Search for Extra-Terrestrial Intelligence (SETI) with a single horn feed which was able to track a source. This novel radio telescope was dismantled in 1998.

Denisse succeeded in convincing his colleagues to adopt this concept rather than the interferometer. Later interviews with several French radio astronomers point to a perceived problem with interferometry which may have played a part in this change of heart: the need to calculate a Fourier transform in order to obtain an image from observations with a variable-baseline interferometer. For example, Arsac said:

> For [radio] interferometry one used Fourier transforms as in optics. Before computers, there was a room at the Institut d’Optique on Boulevard Pasteur in Paris, where ladies were computing Fourier series by hand all day.
>
> Prior to 1958, it was not easy to do interferometry. In 1959, I fought to obtain a computer for the Observatory. This computer [an IBM 650] was purchased and I headed the Computing Centre at the Paris Observatory until 1965. On the other hand there was also a theoretical problem with the [mathematical validity of the] Fourier transform. The theory of distributions outlined by [Laurent] Schwartz at this time allowed us to solve the problem of the Fourier transform. (cited in Darmon, 1981: 44-45).

Remember that these discussions were taking place in 1956, when these problems had yet to be solved.

The choice of a large Kraus-type French radio telescope was approved by the Comité de Direction de la Station de Nançay at a meeting on 29 June 1955. Since the Chairman of this Committee also happened to be the Directeur Général de l’Enseignement Supérieur—who headed a large part of publically-funded research in France—this decision was seen as an official endorsement, and the project could begin.

It is interesting to note that the idea of a large interferometer was not completely abandoned since the Comité de Direction also recommended that a large steerable antenna operating at decimetre wavelengths be built, which would allow very long baseline interferometry (VLBI)[4] and could be used together with the other new radio telescope at Nançay as an interferometer in order to obtain a better resolving power in the N-S direction. This did not materialize because at its meeting on 14 May 1958 the Comité recommended that

> … this construction should be replaced by a relatively cheap increase in the surface area of the two [Würzburg] antennas … [at Nançay, which function as] an interferometer on a railway track: [and] the sum of 4 million francs [equivalent to 65,000 Euros] is proposed for the 1959 budget in order to carry out this transformation. (Comité …, 1958; our translation).

Needless to say, this plan was never carried out. Meanwhile, the idea of using the large Nançay Radio Telescope and a moveable 40-m antenna was revived by French radio astronomers in 1968 (Blum, 1968: 9), but once again without success.

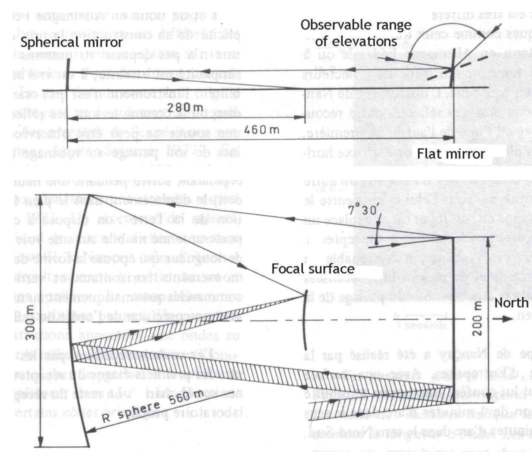

Figure 2: Principle of the Nançay large radio telescope: elevation (top) and ground plan (bottom).

3 BUILDING THE FIRST SECTION OF ‘LE GRAND RADIOTÉLESCOPE’ AT NANÇAY

The plan was to build a French radio telescope modelled on Kraus’ instrument (see Figure 2), but on a considerably larger scale. The mirror would be a portion of a sphere 300m wide, 35m high and of 560m radius, while the tiltable plane mirror would be made of ten 20m × 40m elements in parallel, giving a surface 200m wide and 40m in the other direction. Both surfaces would be made of metallic mesh. An important change with respect to the Ohio design was that the tiltable mirror would be located not far from the centre of the sphere (actually 460m from the surface) and that the plane would be somewhat distorted on the E-W edges, by displacing slightly the axes of the two ex-

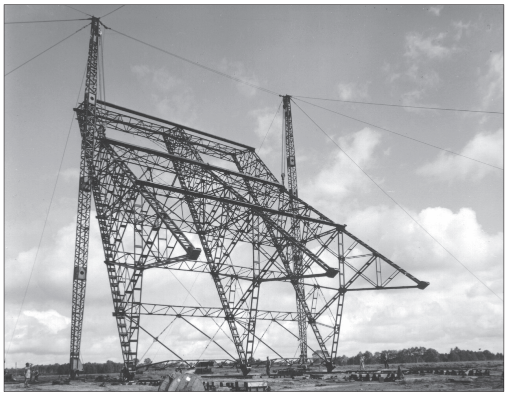

Figure 3: Two 10m-wide elements of the fixed mirror, which were assembled on the ground, are hoisted together.

treme elements on each side with respect to the axes of the six central panels. This configuration was calculated by Arsac and François Biraud, and is similar to that of the optical Schmidt telescope where the spherical aberration is corrected by a deformed plate located near the centre of curvature of the spherical primary mirror. For the radio telescope, this would give a diffraction-limited image on a curved focal surface (of 280m radius) concentric with the spherical mirror, allowing observations to be made of sources up to 7.5º on either side of the meridian plane. By tracking the path of the image of a source on this focal surface, it would then be possible to integrate its flux for an hour for a source located at Dec. = 0°, and for longer for sources with other declinations.

There are advantages and drawbacks to this design when compared to that of a fully-steerable parabolic antenna.

The main advantage is the low cost per unit area. Another one is the easy accessibility and lack of weight limitation for focal equipment.

The main disadvantage is the fact that this is a meridian telescope with an integration lime limited to about 30 minutes on either side of the meridian crossing. This makes the scheduling of the telescope difficult, with a poor time-efficiency, and the limitations in hour angle in practice forbid VLBI with other radio telescopes. Also, the elongated lobe renders measurements of linear polarization almost impossible, and makes it difficult to compare Nançay results with those obtained with circular antennas. Because the focal antenna is close to the ground, some thermal noise from the ground enters through the side lobes if special care is not taken. Kraus solved this problem by covering the ground with a flat reflecting surface, but this is expensive, and runs the risk of creating 'ghosts' of strong sources. Similarly, the focal horn 'sees' in its main lobe whatever happens to stand behind the bottom of the plane mirror when this is inclined. At Nançay, these significant contributions to the system noise were only drastically reduced in the late 1990s when appropriate measures were introduced. A final disadvantage of the two-mirror design is that it would be extremely expensive to replace the reflecting surfaces by better ones for observations at shorter wavelengths, whereas this is common practice with large steerable paraboloids.

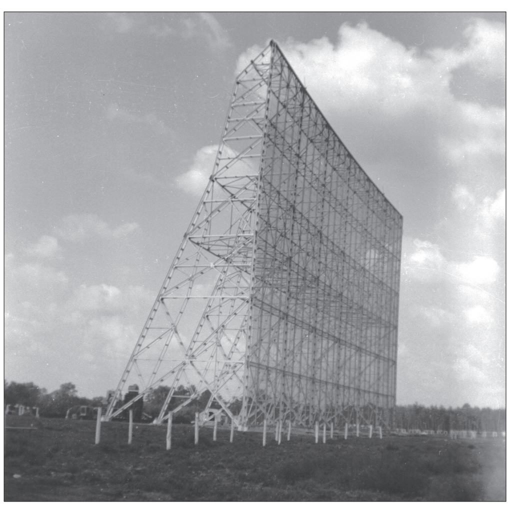

Figure 4: The first section of the fixed concave mirror is completed.

It seems that the limitations of a meridian radio telescope were underestimated in the beginning, and that the other disadvantages of the design were completely overlooked. The low cost per unit surface area was the decisive argument, as can be seen from the following, somewhat naïve, statement:

> The voluntary limitations on the universality of the large Nançay mirror will render its usage secure. Moreover, it could fit in this way within the present scientific budget of France. It is in a way a cousin of the 1.97m [sic] Rosse [optical] reflecting telescope which was built a century earlier than its universal brother, the 1.93m reflector at Haute Provence, because one accepted its limitations around the meridian. (Heidmann, 1961: 49; our translation).

It turned out to be very easy to obtain a substantial amount of money for the new instrument: 155 million francs (equivalent to €2.9 million in 2008) were assigned in the budget for 1957. Three million of this total was used for preliminary studies including tests in wind tunnels, and contract submissions were then invited from French companies. Surprisingly, only one answered positively, and this was the Compagnie Française d'Entreprises (CFE), which was created by Gustave Eiffel around 1880 as Entreprises Métropolitaines et Coloniales, and then merged with the Moisant-Laurent-Savey Company, only to be purchased by Usinor-Sacilor in 1959. The CFE had considerable experience in large concrete and metal constructions, and the Director of its Industrial Department, Jean Roret (1925–2005), was personally interested in the radio astronomy project. A contract with CFE was signed in December 1958 for 152 million francs (€2.5 million), and work started in their Rouen plant and at Nançay in May 1959.

This contract price was only sufficient to build the first section of the radio telescope, one-fifth of the total, consisting of a fixed 60m × 35m portion of a spherical mirror and two tiltable flat panels covering 40m × 40m in total. This was supposed to be completed within 14 months. A further amount of 32 million francs (€500,000) was obtained in 1960 for the buildings, the first focal antennas, the receivers and an electrical generator, the local municipal power supplies being insufficient for moving all ten panels of the completed radio telescope at the same time.

Figures 3, 4, 5 and 6 illustrate the erection of both mirrors. The reflecting surface, a square wire-netting initially foreseen as an 18mm × 18mm mesh but finally realised as a 12.5mm × 12.5mm one, was fixed to steel cables which were attached to the structure and were adjustable. This structure was completed by the end of 1961, with a slight delay. The surface of the concave mirror was checked by the Division des Travaux Spéciaux of the Institut Géographique National (IGN), headed by J. Commiot, and found to be significantly better than the contract specifications: 5-6mm r.m.s. instead of the required 10mm. A fixed set of parabolic antennas was installed at the focus for 21, 13 and 6cm, with small antennas and uncooled receiver front ends, mixers and intermediate-frequency amplifiers at their foci (Figure 7). On 23 January 1962 the radio telescope was officially inaugurated, with several speeches, including one by Denisse as head of the Nançay field station. One can sense there was some bitterness when he spoke about the 64-m Parkes Radio Telescope (which had just been completed):

> [When our Nançay radio telescope was decided] … the Australians were studying the present paraboloid at Parkes which at the same time is both accurate and has an imposing surface area: 3,000m^2. At the present time it is certainly the best radio telescope in existence, and it is operated by a staff of exceptional quality. (Denisse, 1962: our translation).

It is true that at this time the French radio astronomy group was still small and busy using the various solar instruments at Nançay. Moreover, the construction of the new radio telescope was only overseen by a single mechanical engineer, Marcel Parise (Figure 8).

Furthermore, an unexpected problem arose: pointing of the tiltable panels, as measured on their axes, was largely in error. Not only was the measuring equipment inadequate, but there was also some distortion when the panels were inclined (and there was no computer to perform the structural analyses at this time). The problem was completely beyond the comprehension of the CFE staff, and it was agreed that it had to be solved by the radio astronomers. This was done by attaching graduated rulers perpendicular to the mesh along one of the edges of the panel, and observing them with a small telescope equipped with a graduated vertical circle attached to the rotation axis. This way the distortion was measured, and a correction was then applied through a mechanical cam inserted between the end of the axis and the encoder. The encoder was supplied by Ferranti Ltd., a UK company.[5]

During the measurements, another problem was discovered: the distortion was not the same when the inclination increased or decreased, pointing to mechanical hysteresis in the panels. This forced the panel to always move in the same way, with increasing inclination. It remained to be seen if the inclination of the edges of the panels where the measurements were performed was representative of the average inclination of the whole surface. This was checked by IGN staff, who used a theodolite to measure from the ground the positions of nine points of the panel surface for different inclinations. The results were satisfactory, but it was discovered that the surface, which was

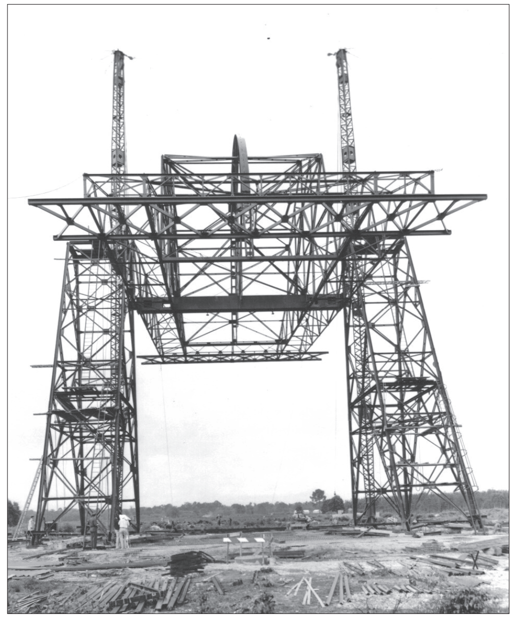

Figure 5: One 20m-wide panel of the tiltable mirror, which was assembled on the ground, is hoisted into place.

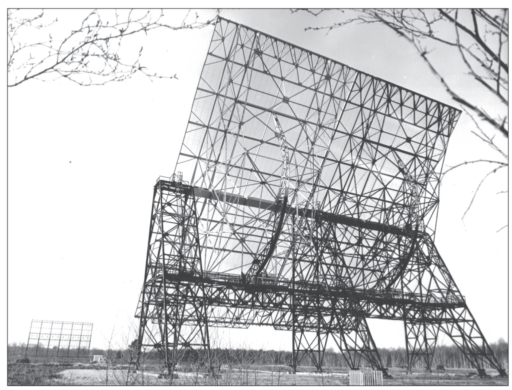

Figure 6: The first completed section of the tiltable flat mirror. Each panel is driven by a pinion acting on a chain placed along the half-circle.

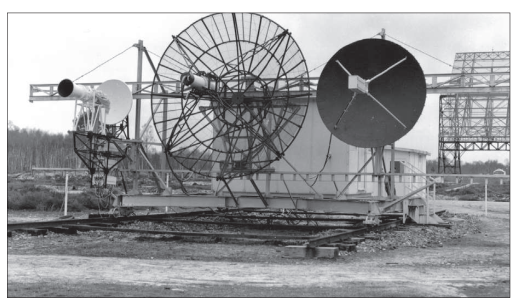

Figure 7: The focal equipment of the first section of the radio telescope. The focal diffraction spot forms on paraboloids which concentrate the radiation on circular horns followed by the high-frequency stages of the receivers (see, also, Figure 8). The intermediate frequency signal is sent to the focal laboratory shown at the back of this photograph. The whole is moveable on N-S rails for focussing. From left to right are devices for 6, 21 and 13cm respectively. The tiltable mirror in visible in the background.

Figure 8: Marcel Parise adjusting the focal system for 21cm.

approximately flat for an inclination of 45º, became concave in the N-S direction by 8mm at the middle of the panel for an inclination of 90º, while it became concave by 5mm in the E-W direction. The usual rule of thumb that the deviations of the final wave surface should be better than $^1/_{10}$ of a wavelength for good results showed that the Nançay Radio Telescope should be good at 21cm and 18cm, fair between 9cm and 13cm and quite poor at 6cm.

With a few exceptions, all of the measurements, analyses and designs of the new instrumentation were done by Steinberg and Michel Ginat, with help from James Lequeux and a few others (Steinberg, 2004). It is only upon reading Ginat's Ph.D. thesis (1966), which is devoted to this work, that one realises just how complex and difficult this task was.

Once the final section of the radio telescope was operational, some continuum observations were made of extended galactic sources at 1,430 MHz and 2,315 MHz (Bottinelli and Gouguenheim, 1964; Heidmann, 1965) and of a few large galaxies at 1,430 MHz (Heidmann, 1963). But since the rest of the radio telescope was then under construction, this effectively prevented further observations from being made.

4 THE COMPLETION OF THE RADIO TELESCOPE

Given the success of the first section of the radio telescope it was relatively easy to raise the money for the rest of the instrument. A new contract was set up between the Ministry of Public Education and the CFE and the construction proceeded without any major problems. Figure 9 illustrates a step in the erection of the second part of the radio telescope. The completed instrument was officially inaugurated by the President of the Republic himself, General de Gaulle, and the Minister, Christian Fouchet, on 15 May 1965.

Of course it was necessary to calibrate the inclination of all of the panels in the same way as for the first two, and this lengthy process was only finished in 1966. This work, along with other geodetic measurements, was the subject of Ginat's Ph.D. thesis (1966). Also, in order to save money, encoders were only installed on the axes of panels 2, 5, 6 and 9, and the other panels were slaved to these master panels

Figure 9: The fully-tiltable mirror during construction.

thanks to a simple but effective electromagnetic proximity system designed by Biraud: panels 1 and 3 to panel 2; panel 4 to panel 5; panel 7 to panel 6; and panels 8 and 10 to panel 9. The pointing of the panels and the necessary controls were designed by the staff, especially by Ginat and Steinberg. Despite the passage of the years, this system is still working at present, after only minor changes.

One also had to deal with motion of the carriage (or rather the carriages, as two were constructed), in order to track the displacement of the image due to diurnal motion. This required both a vertical motion and a motion along a curved railtrack, both depending upon the declination of the source. Money was available to build the mechanical and hydraulic parts of the carriages (the motion being secured by hydraulic motors and jacks), but not for controlling the motions, a problem whose difficulty had been underestimated. There was no computer to drive real-time servos so one needed a custom-made computer. The only European firm able to do this at a reasonable cost was Ferranti Ltd., which had also supplied the encoders for the flat mirrors as stated earlier and the control desk of the radio telescope (Figure 10). Lequeux was in charge of defining the needs, writing the contract and following the construction and installation of the drive system. The necessary funds came from a convention (agreement) signed in 1963 between the Paris Observatory and the Centre National d'Études Spatiales (CNES) which agreed to pay, on the basis that artificial satellites would be tracked by the radio telescope (something which never occurred). This was arranged by Steinberg, who was in the process of setting up a Laboratory of Space Radioastronomy at Meudon whilst continuing his work at Nançay, and had excellent relations with the CNES. The position of the focal antenna as a function of time was computed with the IBM 7040 in Meudon, whose output was a punched tape. This tape was sent to Nançay and fed into the Ferranti equipment, which was housed in several big cabinets which filled a sizable fraction of the control room. The total cost was 320,000 new francs (€400,000).

The first H-line receiver was built by Émile-Jacques Blum, with help from Jean Delannoy, Émile Le Roux and Leonid Nicolas Weliachew (Blum et al., 1966), and placed on one of the carriages (Figure 11). This was a correlation receiver, a concept invented by Blum and derived from his studies of interferometers (Blum, 1959). The principle is as follows: if one splits the signal from the antenna and feeds each of two identical receivers with half of this signal, a correlation of the outputs of these receivers will give a DC output proportional to the power received by the antenna, the noises in the receivers being uncorrelated. Thus, the output is essentially unaffected by variations in the receiver gains, which were very troublesome at this time. For this purpose, Blum used a correlator that he originally designed for his solar interferometer (Figure 12). Of course fluctuations in receiver noise are still present, but it can be shown that the signal/noise ratio of the system is comparable to or better than that of the permutation receivers of Robert Dicke and Martin Ryle which were largely in use at this time. A problem with this system is that splitting the antenna signal in a hybrid circuit like a magic T requires an-

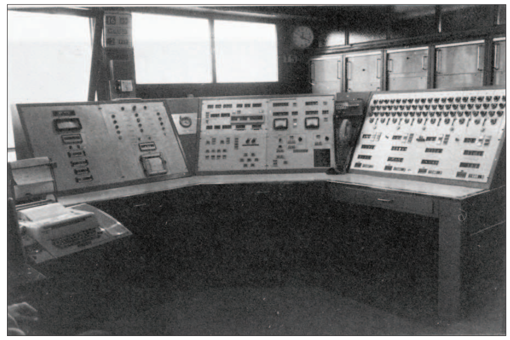

Figure 10: The control room of the radio telescope, circa 1966. The controls on the left activated the generating set for powering the tiltable mirrors; those in the central part controlled the tracking of the focal carriage; and those on the right controlled the motions of the tiltable panels. Notice the panels in the background which housed part of the electronics of the Ferranti equipment.

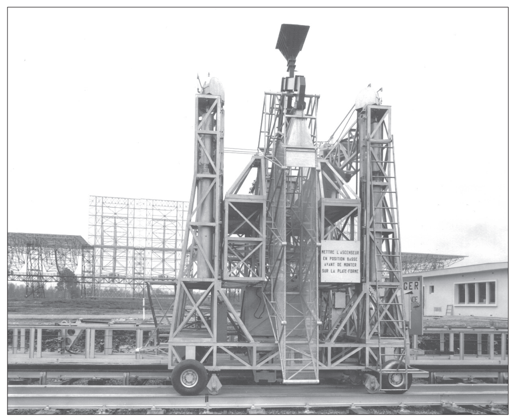

Figure 11: The focal carriage for observing the H-line. The signal is received by a hog horn whose dimensions (2m × 0.4m) match the diffraction spot. Notice the smaller vertical horn which feeds the other input of the hybrid circuit (magic T) of the correlation receiver (see the text, and Figure 13). The cabin contains the front end, the mixer and the amplifier for the intermediate frequency, which is sent by cables to the focal laboratory towards the rear of the photograph.

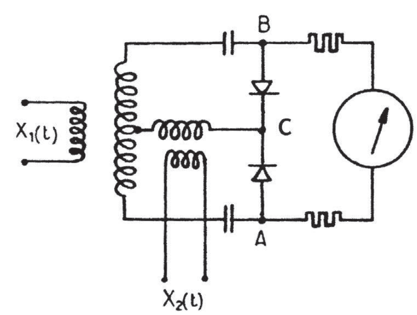

Figure 12: Blum's correlator. $X_1(t)$ and $X_2(t)$ are the input signals from two antennas of an interferometer or from the two halves of the signal of the antenna for a correlation receiver. The voltage between A and C is proportional to $[X_1(t) + X_2(t)]^2$ with a quadratic detecting diode, and that between B and C proportional to $[X_1(t) - X_2(t)]^2$, if the senses of the transformers are well chosen. Hence the voltage between A and B is the difference of these two quantities, which is proportional to $4X_1(t)X_2(t)$, the correlated product.

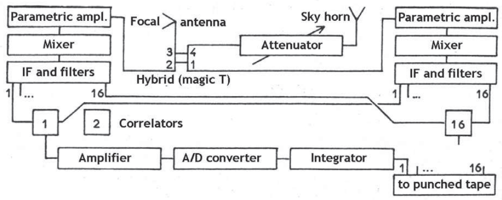

Figure 13: Principle of the 21cm line correlation receiver. For a description see the text.

other input for balancing the impedances (Figure 13). This input comes from a horn which is looking at the sky, followed by a variable attenuator whose noise must balance the noise from the antenna. Another possibility, which has also been used in some correlation receivers, was simply to insert a unidirectional circuit between each half of the antenna signal and the input of the corresponding receiver.

For all these receivers, the incoming signal was sent to the mixer after amplification by a parametric amplifier.[6] The locally-made parametric amplifiers did not work very well and were soon replaced by commercial ones. The first 21cm line receiver was uncooled and had a system temperature of 350K, including 35K of ground noise for low declination sources. It had 15 frequency channels, each 280kHz (59km/s) wide, which were only suitable for extragalactic observations, and a continuum channel 5MHz wide. The signals were digitized and integrated, and the results were entered on punched paper tape. This tape was sent to Meudon and its content was transferred onto punched cards by an IBM 1401 computer, then the reduction was performed with the Meudon IBM 7040, with an output on paper (Figure 14) and on punched cards. This complicated system was replaced in 1969-1970 by a Digital Equipment PDP 8 computer located in the control room of the radio telescope.

Another carriage (Figure 15) bore three horns for continuum observations at 21, 11.3 and 6.2cm, and the

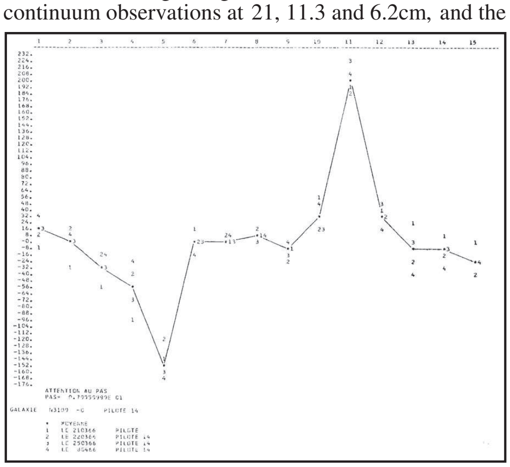

Figure 14: One of the first observations of an extragalactic 21cm line with the completed radio telescope. This is a listing from the Meudon IBM 7040 computer. The 15 frequencies of the multi-channel back end are in abscissae. The positive signal (2K of antenna temperature) is the 21cm line from the galaxy NGC 3109, and the negative one is a residual from the galactic line emission in this 4-hour ON-OFF observation (after Bottinelli et al., 1966).

corresponding receivers. It seems, however, that the 21cm continuum receiver was never implemented, and that the observers simply used the broad channel of the line receiver instead.

In 1968 the total cost of the radio telescope with the focal building and all of the auxiliary instrumentation that we have just described was estimated at 15 million francs, corresponding to €16.7 million in 2008. As suggested by a referee, it is of interest to compare this cost with that of contemporary large radio telescopes. This comparison can only be approximate, because of difficulty in obtaining the actual total costs and because of uncertainties in the exchange rates and in the conversion into 2008 Euros. For Jodrell Bank (the Mark I Lovell Telescope) and Parkes the estimates did not include the first receivers and auxiliary equipment, so we added 20% to these estimates. We do not include the Ohio Radio Telescope because this was essentially a home-made instrument. Our results are presented below in Table 1.

These results must be weighted by the shortest wavelength observable with the different radio telescopes. At the time of their completion, Jodrell Bank and Arecibo were worse than Nançay, while Parkes was better. Also, Arecibo has a limited observing range around the zenith, whereas Jodrell Bank and Parkes are fully steerable. Overall, it appears that the choice of a meridian combination for Nançay saved money, but that the best deal was clearly Parkes, a radio telescope which was built by German industry (MAN-Krupp). For political and industrial reasons it was not possible for France to obtain such an instrument.

After the completion of Le Grand Radiotélescope most of the scientists who had worked so hard on its pointing, focal tracking and receivers partially lost interest in the instrument, with the exception of Biraud and Weliachew. Thus, in 1965 Le Roux left astronomy; during 1967-1968 Blum spent a sabbatical year at the NRAO in Charlottesville (West Virginia) becoming familiar with millimetre techniques; and in 1967 Delannoy moved to the Bordeaux Observatory in order to build an experimental 8mm interferometer. Meanwhile, Steinberg worked full-time in his Space Radioastronomy Laboratory at Meudon, and in 1966 Lequeux (with a few colleagues) founded an infrared laboratory at Meudon, before going to Caltech in 1968-1969 in order to observe with the Owens Valley Radio Observatory interferometer. Ginat was killed in a mountain accident on 1 April 1968. Blum had taken over from Denisse as Director of the Paris Observatory's Radioastronomy Department and the Nançay field station in 1964, and he remained in charge until 1973, but he never used Le Grand Radiotélescope, working instead on millimetre receivers. He was succeeded by Lequeux, who occasionally used the large radio telescope but was mostly busy with other tasks, especially (with Blum, Weliachew and Pierre Encrenaz) in setting up a large millimetre interferometer which materialized in 1979 as one of the elements of the German-French-Spanish Institute for Millimeter Radio Astronomy (IRAM).

Presumably all of these scientists were exhausted by the considerable tasks they had to achieve in order to bring Le Grand Radiotélescope to fruition. Denisse understood that building such a large instrument in a difficult industrial climate was at the very limit of the potential of a small group with little technical preparation, and so in 1966 he created the Institut National d'Astronomie et de Géophysique (INAG), with a Technical Division, in order to handle major projects. On the other hand, some members of the staff thought that the Nançay radio telescope would soon be superseded by others, like the Effelsberg 100-m steerable parabola, which was completed in 1972. Whether they were right or wrong will not be discussed here, but long-standing unease was experienced by the staff, which later resulted in a splitting of the Radioastronomy Department into 'millimeter' and 'decimeter' radio astronomers. In any case, the use of Le Grand Radiotélescope was left to the younger generations.

5 IMPROVEMENTS AND USE OF THE NANÇAY RADIO TELESCOPE

As with any new facility, Le Grand Radiotélescope at Nançay has been continually improved over the years. Little has changed to the actual radio telescope itself, but the Ferranti system to tilt the panels and move the focal carriages was replaced by a computer in 1969-1970. Many more changes were made to the receivers and the focal carriages. It is difficult to track all of them, and we will only report on some of them. We will also briefly describe some of the early observations which were made with this radio telescope.

A 15MHz continuum channel and fifteen 60kHz channels were first added to the H-line receiver, and the high-frequency parts were cooled. In 1973 there were thirty-two 60kHz channels and sixty-four 6kHz (1.3km/s) channels, and the receiver temperature was down to 120K in 1975. Unfortunately, the correlated response of each pair of frequency channels turned out to be very sensitive to the shape of the bandpass of these channels, so that chromatism was a problem for line observations. This, together with the cost of having all the electronics in duplicate, led to abandoning this type of receiver and also the parametric preamplifiers around 1985, and they were replaced by cooled High Electron Mobility Transistors (HEMT) in the front-ends. An autocorrelator was substituted for the filter banks. However, many useful scientific results were produced before these changes occurred, in particular the H-line detection of a large number of galaxies (see in ADS the many papers by R.J. Allen, C. Balkowski, L. Botttinelli, P. Chamaraux, B.F. Darchy, E. Gérard, L. Gouguenheim, M. Guélin, J. and N. Heidmann, I. Kazès, R. Lauqué and N. Weliachew).

A new impetus to this major program of the Large Nançay Radio Telescope came from the discovery of the Tully-Fisher Relation between 21cm line width and absolute magnitudes and diameters of galaxies (Tully and Fisher, 1977), which offered a way of deriving distances of galaxies independent of redshift and allowed the Nançay observers to obtain a value of 68 ± 8 km s^{-1} Mpc^{-1} for the Hubble Constant (Fouqué et al., 1990), which is close to the currently-adopted figure of 71 ± 4 km s^{-1} Mpc^{-1} obtained from COBE and WMAP observations.

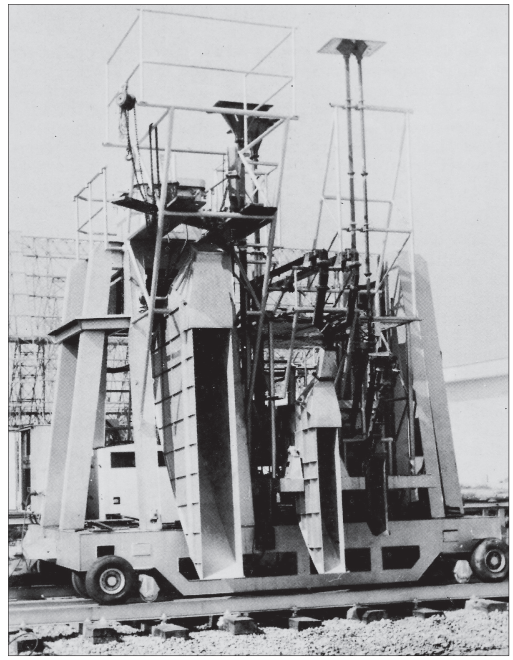

Figure 15: The carriage for the continuum receivers. From left to right are the hog horns for 21, 11 and 6cm respectively. The height of the largest horn is 2m.

There was also an extensive program involving galactic 21cm absorption (Lazareff, 1975; Crovisier et al., 1978), during which many observations of continuum sources were also made. Although more subject to contamination by residual line emission than observations with interferometers, these results were quite useful as a means of measuring distances to continuum sources. One of the original programs was to observe 21cm absorption in front of pulsars whose distances were unknown at the time (Guélin et al., 1969). In this case, the difference between the line seen during the pulse and between the pulses gives a pure absorption profile, hence a relatively good estimate of the distance. This was the beginning of an interest in pulsars, which developed considerably later for the purpose of timing their pulses, and is at present a major program of the radio telescope.

The 21cm line receiver was also used in 1975 and later for observations of radio recombination lines, in particular the 166α lines of carbon and sulphur (Cesarsky et al., 1976). The receiver was used in total power detection instead of the usual correlation mode.

Table 1: Cost comparisons for major early radio telescopes.

Radio Telescope	Date of cost Estimate	Cost (original currency)	Cost (2008 €)	Area (m^2)	Cost per unit area (2008 €/m^2)
Nançay	1968	1.5×10^7 Francs	1.67×10^7	7000	2400
Jodrell Bank	1957	8.4×10^5 £	1.58×10^7	4500	3500
Parkes	1963	1.5×10^6 US$	9.7×10^6	3200	3000
Arecibo	1963	9×10^6 US$	5.8×10^7	70700	800

Figure 16: The focal carriage bearing the 21, 18 and 9cm hog horns in the 1980s.

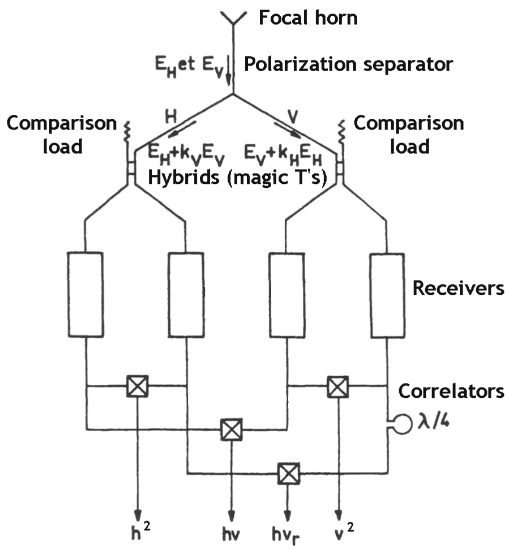

Figure 17: Principle of a correlation-receiver set-up for measuring polarization. The four outputs give the power in the vertical linear polarization component v^2, that in the horizontal one h^2, the product hv, and the product hv_r with a $\pi/2$ phase shift. The fraction of circular polarization in the signal is $2hv_r/(h+v)$.

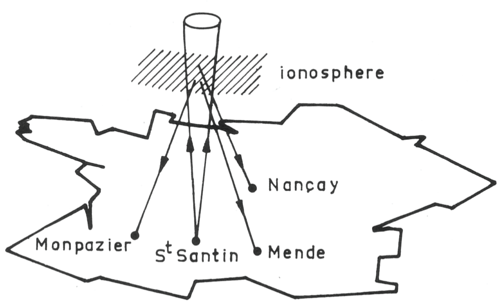

Figure 18: Principle of the incoherent scattering ionospheric sounder. An emitting antenna in Saint Santin near Decazeville sends out a monochromatic wave vertically. The scattered radiation is received in Nançay, and in two other receiving stations equipped with 25m diameter paraboloids near Mende and Montpazier, which were added in 1973.

An interesting event was the arrival at Nançay in 1971 of an 18cm line receiver built in the Soviet Union at the Sternberg Institute and the Space Research Institute in Moscow. This was made possible through cooperation between Intercosmos (the Soviet Space Agency) and the French CNES. The receiver (Paschenko et al., 1971) operated in the frequency-switching mode, and had in its front end an uncooled parametric amplifier on loan from the Max Planck Institut für Radioastronomie in Bonn. The back end had 16 × 20kHz channels 3.6km/s wide. The system temperature was initially 250K, but in 1972 it dropped to 150K thanks to cooling. In 1974 three channel banks were added, each with 32 filters of respective widths 10, 6 and 6kHz. This receiver was used until 1986 when the front-end was replaced by a cooled HEMT one (and the receiver temperature was 40K after this change), and the filters were replaced by an auto-correlator in common with the 21cm receiver. The main program with this equipment was to observe OH-IR stars, OH lines in the Galaxy and OH in comets. These progressively became major programs for the radio telescope, especially the cometary part following the detection of OH in Comet Kohoutek (Biraud et al., 1974; and for a bibliography see Crovisier et al., 2002). Later the radio telescope was turned to external galaxies and several OH megamasers were discovered (Bottinelli et al., 1986).

A 9cm cooled HEMT receiver for observation of the CH lines was constructed in the 1980s for galactic and cometary studies, and these lines were also detected in external galaxies (Bottinelli et al., 1991). For this, a new carriage was built with three focal hog horns working at 21, 18 and 9 cm (Figure 16).

While most of the research conducted with the radio telescope related to line observations, there were also some continuum observations. An early observing program with the continuum channel of the 21cm line receiver was devoted to normal galaxies (de la Beaujardière et al., 1968). The 11cm correlation receiver was used to detect emission from Saturn and Uranus and to obtain an upper limit for that from Neptune (Gérard, 1969). Jupiter and Saturn were observed in 1972-1973 at 21, 11.1 and 6.2cm, with respective system temperatures of about 100, 200 and 300K (Gérard and Kazès, 1973). Biraud made an heroic attempt to measure the polarization of quasars at 11.1cm using a correlation receiver set-up suggested by Blum and represented in Figure 17. The linear polarization could not be observed with any accuracy, but circular polarization was detected in PKS 1127-14 (Biraud, 1969).

One original early program in the continuum was the observation of radio source scintillations due to the heliospheric plasma at 11cm and other wavelengths (Bourgois, 1969, and follow-up papers).

It should be noted the Le Grand Radiotélescope was also used for a substantial fraction of the time for observing incoherent scattering in the ionosphere, just like the Arecibo Radio Telescope (see Cohen, 2009). This resulted from an agreement between INAG and the Centre National d'Études des Télécommunications (CNET). As shown in Figure 18, a powerful monochromatic beam at 32cm was sent vertically by an antenna located 300km south of Nançay, and the scattered radiation was received by the Nançay Radio Telescope with a hog horn followed by a line receiver

(Figure 19). The two beams of the emitting and receiving antennas defined a volume in which the density and temperature of ions and electrons were measured, as well as the velocity and direction of the wind (thanks to the Doppler effect). The range of elevations explored by changing the inclination of the plane mirror was 95 to 700km.

Between 1995 and 2000 a complete remodelling of the focal installations of the Nançay Large Radio Telescope took place, the so-called FORT Project (for Foyer Optimisé pour le Radio Télescope décimétrique de Nançay). A new carriage (Figure 20) was built on a new railtrack, and the hog horns were replaced by an ensemble of two eccentered concave mirrors feeding one or the other of two corrugated horns according to the wavelength. This system (Figure 21), designed by staff from the CSIRO in Australia (Granet et al., 1997; 1999), completely covers the frequency range 1.0 to 3.5GHz and has low sidelobes. An efficient system of metallic mesh in front of the focal system and behind the tiltable mirror drastically reduces the effects of the ground and the trees behind the tiltable mirror. New front ends were installed in enclosures at 20K and the system temperature is now ~35K over the whole range of received frequencies. A new focal laboratory was built outside the radio beams. All this gave a new life to what is now a venerable radio telescope.

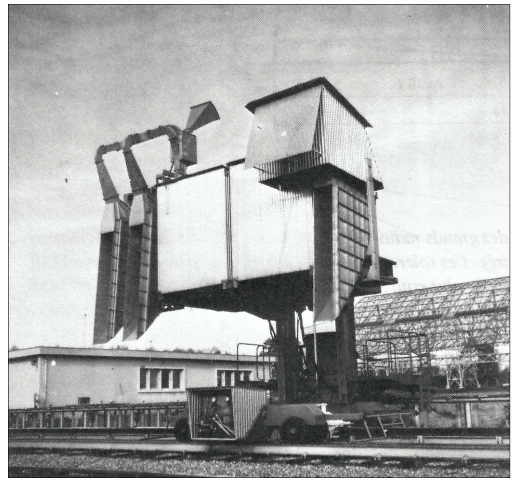

Figure 19: A focal carriage with two radio astronomy hog horns for 18 and 21cm (left) and a hog horn for receiving the signal of the incoherent ionospheric scattering project at 32cm (right), in the late 1970s.

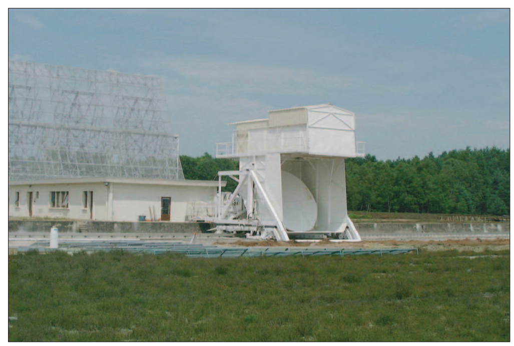

Figure 20: New focal carriage of the radio telescope, circa 2000. The old focal laboratory was still in operation at this time, but has since been replaced by a new one located outside the radio beam.

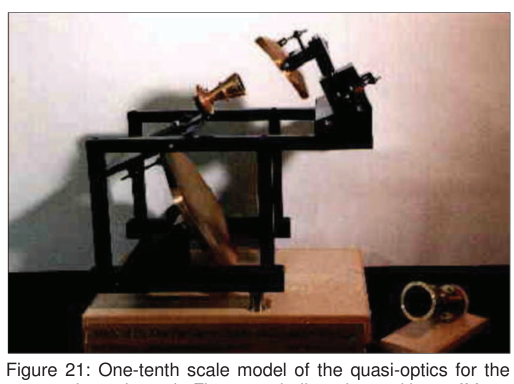

Figure 21: One-tenth scale model of the quasi-optics for the new carriage shown in Figure 20, built and tested by staff from the CSIRO in Sydney, Australia. There are two corrugated circular receiving horns, each one covering approximately half of the total frequency range. One is in position, and the other is lying on the floor.

6 CONCLUDING REMARKS

The construction of Le Grand Radiotélescope at Nançay took place in a favourable economic and political climate. But the context was not as favourable when techniques were concerned, because French industry was not prepared to manufacture large metallic structures with any accuracy, and because on-line computers were not yet available. Moreover, the Paris Observatory radio astronomy group only had one mechanical engineer, so this forced the radio astronomers to do work for which they had little training or preparation. To their credit, they succeeded, but they were exhausted by these efforts and the instrument was delayed for two years: although the structure was completed and inaugurated in May 1965, the radio telescope only began working properly at the end of 1967. With its surface area of 7,000m^2, comparable to that of the Effelsberg and Greenbank 100-m diameter paraboloids, it was one of the largest radio telescopes in the world, Arecibo excepted. But unlike its competitors, the Nançay Radio Telescope could not operate below 9cm.

The Nançay site was relatively free of man-made radio interference at the beginning, but like any other, it now suffers badly from this plague. Today, sophisticated techniques are required to allow any sensitive observations, especially at decimetre and meter wavelengths. These techniques are in force at Nançay, but just how long observations will be possible there at these wavelengths is a major question. The Square Kilometer Array (SKA) project, for which the direction of observation will be changed instantaneously as a function of interference, is clearly the way to go for decimetre radio astronomy.

7 NOTES

1. This project was initiated under the auspices of the IAU Historic Radio Astronomy Working Group in 2006, and four papers have been published to date. The first deals with Nordmann's attempt to detect solar radio emission in 1901 (Débarbat et al., 2007);

the second with early solar eclipse observations (Orchiston and Steinberg, 2007); the third with the Würzburg antennas that were at Marcoussis, Meudon and Nançay (Orchiston et al., 2007); and the fourth with early solar research till the mid-1950s (Orchiston et al., 2009). A sixth paper, on post-1956 solar research at Nançay (Pick et al., 2010) will be published later this year and a seventh paper, on the birth of the IRAM project, is currently in preparation.

2. Steinberg was referring to fringes at centimetre wavelengths; all previous interferometry was at metre and decimetre wavelengths.
3. When mentioning the prices associated with the Grand Radiotélescope Project we have tried to convert them into 2008 Euros, based on a comparison of the cost of living at that epoch and in 2008. This conversion was established by the Institut National de la Statistique et des Études Économiques (INSEE), and is available through the following web site: http://www.insee.fr/fr/themes/indicateur.asp?id=29&type=1&page=achatfranc.html
4. This is not explicitly mentioned in the recommendation, but VLBI was just beginning at this time in Canada and the USA, and the French radio astronomers were certainly aware of this.
5. This was one of the few instances where French industry could not supply the required product. Ferranti Ltd. was based in Dalkeith, near Edinburgh, in Scotland.
6. For the concept of parametric receivers see the Wikipedia article on 'Parametric oscillator'.

8 ACKNOWLEDGEMENTS

We wish to thank Nicole Cornilleau-Wehrlin and Bertrand Flouret (Paris-Meudon Observatory) for providing access to photographs of the radio telescope and the focal equipment. The Nançay radio astronomy field station holds the copyright to all of the photographs published in this paper.

We also thank staff at the Library of the Paris-Meudon Observatory for their efficiency and their kindness, and the Astrophysics Data System (ADS) for making many historical documents freely available. Finally, we are grateful to Professor Richard Strom (ASTRON and James Cook University) for reading and commenting on the manuscript.

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Dr James Lequeux started research in radio astronomy in 1954 as a young student, and after a long military service obtained his Ph.D. in 1962. He and Jean-Louis Steinberg produced the first French text book on radio astronomy in 1960. After a career in radio astronomy and in various fields of astrophysics, his post-retirement interests turned to history, and his 2005 book, *L'Univers Dévoilé*, is a history of astronomy from 1910 to the present day. He published a scientific biography of Arago in 2008, and a biography of Le Verrier in 2009. James is affiliated with the LERMA Department at the Paris Observatory.

Dr Jean-Louis Steinberg began working in radio astronomy with J.-F. Denisse and E.-J. Blum at the École Normale Supérieure after the War. On his return from the 1952 URSI Congress in Sydney, he began developing the Nançay radio astronomy field station, and from 1960 through to 1965 he and M. Parise led the design and construction at Nançay of 'Le Grand Radiotélescope'. In 1965, he began developing space research at Meudon Observatory. In 1960 Jean-Louis and J. Lequeux wrote a text book on radio astronomy, which was subsequently translated into English and Russian. In 1962 he was appointed Editor-in-Chief of *Annales d'Astrophysique*, which he and his wife ran until 1969. For the next five years he was one of the two Editors-in-Chief of *Astronomy and Astrophysics*. Jean-Louis has authored or co-authored about 80 scientific publications, and has received several scientific prizes and awards.

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WILHELM TEMPEL AND HIS 10.8-cm STEINHEIL TELESCOPE

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Abstract: The German astronomer Ernst Wilhelm Leberecht Tempel (1821–1889) owed most of his successes to a 10.8-cm Steinheil refractor, which he bought in 1858. A lithographer, without an academic foundation, but with a strong passion for astronomy, Tempel had sharp eyesight and a talent for drawing, and he discovered with his telescope many celestial objects, including asteroids, comets (most notably, 9 P/Tempel 1) and the Merope Nebula in the Pleiades. Tempel carried his telescope with him throughout his moves in France and Italy. The telescope is now conserved in Florence, at the Arcetri Astrophysical Observatory, where Tempel was astronomer from 1875 until the end of his life. Using unpublished material from the Arcetri Historical Archive, as well as documents from other archives and published material, we trace the history of the telescope and its use during and after Tempel's life, and describe its recent rediscovery and status.

Keywords: Wilhelm Tempel, nineteenth-century astronomy, instrumentation, Steinheil, Arcetri

1 A LITHOGRAPHER WITH AN INTEREST IN ASTRONOMY

Ernst Wilhelm Leberecht Tempel was born on 4 December 1821 in Niedercunnersdorf, which at that time was in the Kingdom of Saxony. The son of farmers, he received a basic education in the village school. His teacher, Johan Kiesewalter, passed to the boy his passion for science and astronomy: local lore states they observed the sky with the naked eye from the church bell tower, where the young Tempel earned some money as a bell ringer. Kiesewalter also taught Tempel drawing, and apprenticed him to a lithographer in the nearby town of Meissen (Clausnitzer, 1989; Eichhorn, 1963). After this experience, Tempel started to wander through Europe. He worked for three years as a lithographer in Copenhagen (Tempel, 1884a), then after returning to Germany for a while he moved to Italy. In 1852 we find him in Venice, where he converted to the Catholic faith (Mutti, 1852).

During these years, he offered his drawing skills to several scientific institutes, but he was not considered for a permanent job because of his lack of an academic title (Clausnitzer, 1989; Eichhorn, 1963). However, he visited a number of astronomical observatories: probably the old observatory of Copenhagen (Clausnitzer, 1989); surely those of Marseille and Bologna. At the last two observatories, Tempel was probably employed in the making (and copying) of star charts. Among the Tempel documents stored in the Historical Archive of the Arcetri Astrophysical Observatory,[1] there is a lithographic copy of an equinoctial chart, compiled by J. Laurent (Valz, 1857a) in March 1857 under the direction of Benjamin Valz, Director of the Marseille Observatory, and engraved by Tempel. Several lithographic copies of Bishop's *Ecliptical Atlas* (Howard-Duff, 1985) are stored in the Library of the Arcetri Observatory, a few of which are annotated by Tempel, and one in particular has the note: "autogra. emprimer sur papier Bologna."

2 THE 10.8-cm (4-in) STEINHEIL TELESCOPE

In 1856, while in Marseille, Tempel (1856) wrote to the workshop of scientific instruments at the Bavarian Academy of Science in Munich, to which Carl August Steinheil had just been appointed by King Maximilian II (Brachner, 1987; Steinheil, 1856), and asked for information on the cost of refracting telescopes of 8.1-cm to 9.5-cm aperture (3–3.5 inches; the workshop used French inches: 1 inch = 2.707 cm). However, Valz advised against the purchase, and instead offered Tempel the use of the instruments at the Marseille Observatory. About a year later, Tempel was in Bologna. On behalf of Lorenzo Respighi, Director of the local observatory, he wrote again to Steinheil, asking for a 13.6 to 16.2-cm refractor for the institute (Tempel, 1858a; Steinheil, 1858a). Respighi indeed bought a 16.2-cm Steinheil telescope of 260-cm focal length (Poppi et al., 2008), and he was very satisfied with its quality (Tempel, 1858b).

In 1858 Tempel moved back to Venice, and wrote again to Steinheil about buying a telescope for himself. The purchase was defined in a series of letters in summer and autumn of 1858. Tempel chose to buy item n. 7 in the 1857 price list (Steinheil, 1857), comprising a 10.8-cm (4-in) refractor of 1.62-m focal length (5 feet), with a wooden tube and without an equatorial mount. According to the price list, the telescope was equipped with a 2.7-cm finder (24.4-cm focal length), a set of five astronomical eyepieces providing magnifications of 60, 80, 120, 180 and 240, and a 60× terrestrial eyepiece. Tempel also bought a solar filter, a 300× eyepiece, and two more wide-field eyepieces with 24× and 40× that were not in the price list. Later, he bought other eyepieces and filters, to substitute for broken ones. The telescope was identified by its production number, engraved in the brass ring holding the objective: it was N. 216 (Steinheil, 1858b).

The telescope was in Venice in December 1858, but Tempel could not use it because the wooden alt-azimuth mounting that he had ordered from a local craftsman was not yet ready (Tempel, 1858c). The telescope and its mounting can be seen in Figure 1 (left), the only photograph of Tempel next to his instrument. More technical details on the mounting can be inferred from a drawing (Figure 1, right) in one of Tempel's notebooks stored in the Arcetri Archive (which perhaps documents the project to build the mounting). A long fork rotated in azimuth on a cylindrical base, provided with three adjustable feet for horizontal positioning. A pivot for the movement in altitude was located on the fork and connected to the telescope tube by a band. A wing nut on the pivot probably kept the telescope steady in altitude. On the upper part of the fork, a ring could be closed to keep the telescope tube vertical when not in use. Surely, this mount was not easy to use: the Venetian doctor, Antonio Berti (1861), wondered how Tempel could at the same time follow the movement of the celestial sphere and make drawings (see Clausnitzer, 1989).

The telescope and its accessories cost Tempel 400 South German florins. Tempel bought it with his own savings (Berti, 1861; Schiaparelli, 1889b), perhaps from money obtained by selling some lithography tools (Clerke, 1893) or with the help of his wife (Baldelli, 1881), the Venetian Marianna Gambin (or Gambini; see Iliazd, 1964). The burden of the purchase was surely high, as the price of the telescope was close to the annual salary of an assistant at the nearby University of Padua (equivalent to about 490 South German florins; Tucci, 1960). Later Tempel thought of selling the instrument, possibly when he was experiencing economic difficulties. In February 1865 Valz wrote to him saying that "… it is a too cruel necessity that you have to get rid of the telescope." (Iliazd, 1964; our translation). In the spring of the same year, Tempel told his cousin, Gottlieb Hummel, that he had in his pocket an advertisement for the telescope, but did not have the heart to post it in a newspaper because it would harm both him and his wife (Eichhorn, 1961). Such an advertisement can be found inside one of Tempel's notebooks in the Arcetri Archive. It describes, in French, an "… excellent telescope … [from the] famous Steinheil workshop in Munich, of 48 lines [12 lines = 1 inch] aperture …" (our translation), complete with the eyepieces that we have described. The advertisement has no date, but it reports that Tempel made "… from 1859 13 astronomical discoveries." (ibid.). According to *Decouvertes Astronomiques*, Tempel considered the asteroid (81) Terpsichore his thirteenth discovery, which he made on 30 September 1864, while the fourteenth (Comet 55P/Tempel-Tuttle) was on 19 December 1865 (see Table 1). The advertisement says that the telescope is to be sold "… because of my impending departure." (our translation). This probably refers to the (vain) hope Tempel had in 1865 of being called to the Leipzig Observatory, where he had a sponsor in the High Appeal Court Magistrate and amateur astronomer, Friedrich Carl Gustav Stieber (Eichhorn, 1961). However, the telescope was not sold.

A refractor of that aperture could have been attractive not only to an amateur, but also to a professional observatory. Already in March 1859, before Tempel made any discoveries, Valz offered him a position at the Marseille Observatory, promising a dome and an equatorial mount for his telescope. However, when Tempel worked at the Observatory, from March 1860 to December 1861, a dome was not available, and he continued using his telescope—with the altazimuth mount—from the terrace of the building (Clausnitzer, 1989). Tempel found two instruments similar to his in aperture and focal length in the other two observator-

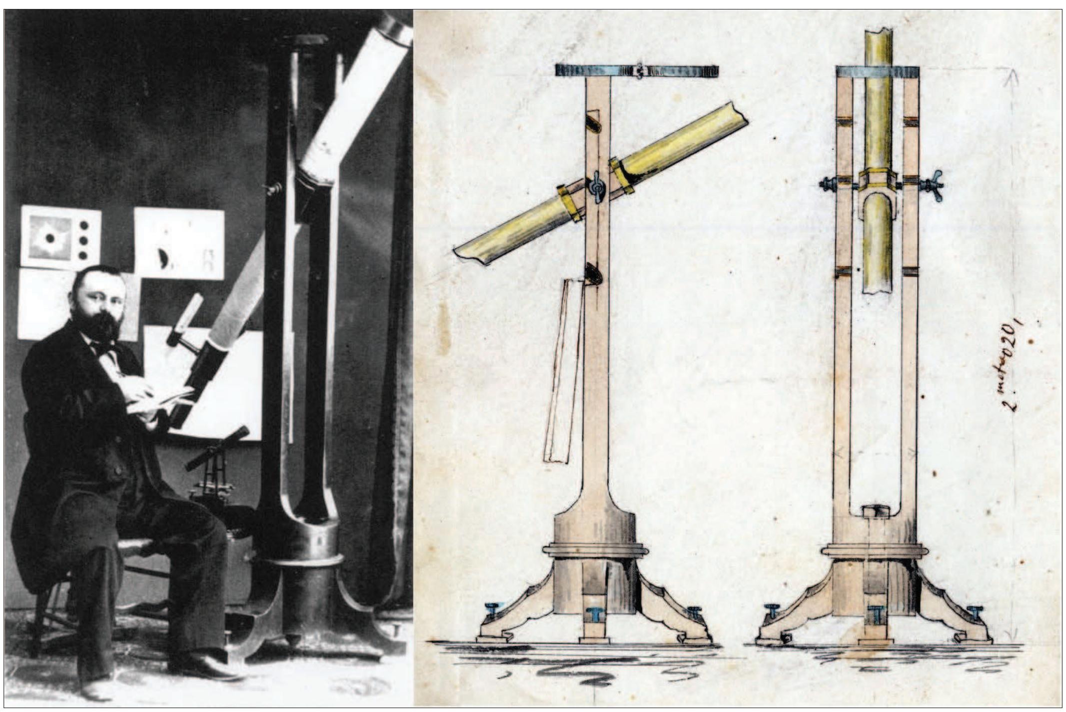

Figure 1: The left panel shows Tempel in Marseille next to his telescope, in 1868 (Clausnitzer, 1989). On the wall in the background we can recognise, to the left, the drawing of the totality phase of the solar eclipse of 18 July 1860, which was published as a lithograph in Donati (1866) and, to the right, the lithograph of the Moon presented here in Figure 6. In the right-hand panel is a drawing of the altazimuth mounting from one of Tempel's notebooks in the Arcetri Archive (series: *Wilhelm Tempel*). The height of the mounting is given as 2.02 m.

ies where he later worked, Brera and Arcetri. In Brera, there was a late eighteenth century Sisson equatorial sector equipped with an 1855 Plössl objective, the only equatorial instrument available in the Observatory until 1874, when the 22-cm Merz telescope was finally installed (Tucci and Valota, 1983). An equatorially-mounted Fraunhofer refractor, originally from the old Observatory of Florence (the *Specola*), was installed in a side dome of the newly-built Arcetri Observatory, that hosted as its main instrument the 28-cm equatorial refractor Amici I (so called by Tempel in 1875 to distinguish it from a smaller Amici telescope), which at the time was the largest telescope of this type in Italy (Schiaparelli, 1875). Therefore, at both Observatories 4-inch refractors were considered minor, even obsolete, instruments, to be replaced or already replaced with more powerful telescopes. However, Tempel used both.

3 ASTRONOMICAL OBSERVATIONS FROM VENICE AND MARSEILLE (1859-1870)

By the beginning of 1859, the new telescope mounting was ready and Tempel started observations in Venice. As recorded in the *Decouvertes Astronomiques*, he observed from the *escalier Lombard,* the winding staircase of the Palace Contarini del Bovolo (Berti, 1861; Iliazd, 1964). Observations fascinated him, so much so that he was distracted from his daily work. In the same year he wrote his cousin, Hummel, that it was too tiring to work in the daytime and also at night, since he often observed from seven in the evening to four in the morning, in the cold and damp. Thus, he asked his cousin if he knew of a benefactor able to finance him in Marseille, so that he could widen his astronomical knowledge without the need to work as a lithographer (Eichhorn, 1961). It is not clear why Tempel was worried about having to work as a lithographer in Marseille, since he had already been offered a position at the Observatory by Valz. Perhaps he wanted to cover a delay in his appointment due to some problems that are alluded to in his correspondence with Valz (Iliazd, 1964). Or maybe he was worried that his employment at the Observatory had to do more with lithography than astronomical observations, since it appears that he was employed as a 'drawing astronomer' (Berti, 1861; Iliazd 1964). While he was in Marseille, Tempel's zeal for night observations also was considerable. In November 1860, the well-known Italian astronomer Giovanni Battista Donati congratulated Tempel on the discovery of a new comet, but reminded him that he also had to work during the day, since he promised to produce lithographs of the total solar eclipse of the previous July (Donati, 1860b). A few months after the retirement of Valz, Tempel left the Marseille Observatory because of problems with the new Director, Charles Simon, and resumed working as a lithographer (see Table 2, where Tempel's career in astronomy is summarised). However, he only worked four hours during the day, thus procuring for his wife and himself a meager income (Clausnitzer, 1989). Instead, he passed long nights successfully observing the sky from the garden, the balcony, and even the windows of his houses (see Table 1).

Tempel's interests were as wide as those of any passionate amateur astronomer, and he observed all the objects that were within the reach of his instrument. However, he must have devoted most of his observing time to the search for comets and asteroids, whose discovery could bring him fame and the possibility of employment in a professional observatory (as eventually happened—see Section 4 below). In this respect, the published lists of his discoveries (Tempel, *Decouvertes Astronomiques*; Flammarion, 1874; as reproduced here in Table 1) could be seen as a sort of curriculum vitae that he could present to the scientific community. Together with the quality of his Steinheil telescope, the large number of Tempel's discoveries can be explained by his commitment to observing and by the clear skies over Marseille, which he praised several times (e.g. see Tempel, 1863; 1864b). Surely, most of his success must have been due to his 'sharp eye' (Schiaparelli, 1889b) and his ability to detect faint details, possibly a result of his experience in observing and drawing since youth.

3.1 Comets

On 2 April 1859 Tempel was in Venice when he discovered his first comet, C/1859 G1, the only one detected that year. Lacking an equatorial mounting, he derived an approximate position using Harding's Atlas (Trettenero, 1859). This atlas (Harding, 1856) was owned personally by Tempel, and is now in the Arcetri Library. In it, Tempel marked the position of the 1859 comet from the day of the discovery (Figure 2) and of many other comets and nebulae that were observed later, right up till the end of his life.

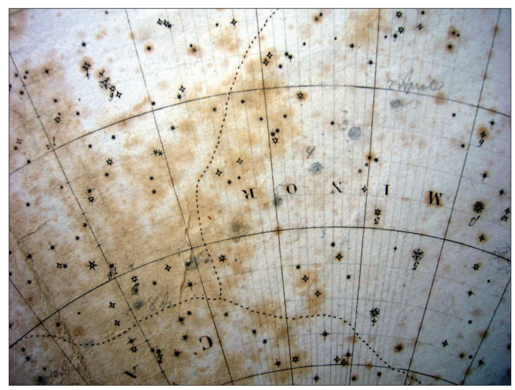

Figure 2: The path of Comet C/1859 G1 in Ursa Minor, from the day of its discovery, 2 April 1859. Tempel marked the positions in pencil on plate 27 in his personal copy of the Harding Atlas, which can be found in the Library of the Arcetri Observatory. The atlas is included in a list of Tempel's books left at Arcetri after his death, written during the reorganization of the Library in 1894 (Historical Archive of the University of Florence, Florence; Sovrintendenza, year: 1894, file: 83 bis).

In Marseille, Tempel discovered seven more comets: C/1860 U1, C/1863 V1 (Figure 3); C/1864 N1, the first comet with an observed spectrum (Donati, 1864); 55P/1865 Y1 Tempel-Tuttle (Figure 3), which was soon associated with the November Leonid meteor shower (Schiaparelli, 1867); 9P/1867 G1 Tempel 1 (Figure 3), which in 2005 was visited by the NASA mission Deep Impact (A'Hearn et al, 2005) and will be targeted by STARDUST/NexT in 2011 (Veverka et al., 2008); C/1869 T1; and 11P/1869 W1 Tempel-Swift-LINEAR.

Tempel also discovered independently other comets (see Table 1), but never as the first observer. Among

Table 1: Tempel's astronomical discoveries made with the 4-in Steinheil telescope (adapted from Tempel, 1868a and Flammarion, 1874).

No.	Name	Alternative Name	Type of Object	Discovery Date	Observing Location
1	C/1859 G1	1859	comet	2 April 1859	Venice, Escalier Lombard
2	NGC 1435	Pleiades Nebula	reflection nebula	19 October 1859	Venice, Escalier Lombard
3	C/1860 U1	1860 IV	comet	24 October 1860	Marseille Observatory terrace
4	(64) Angelina		asteroid	4 March 1861	Marseille Observatory terrace
5	(65) Cybele	Maximiliana	asteroid	8 March 1861	Marseille Observatory terrace
6	C/1862 N1	1862 II	comet	2 July 1861	Marseille, home garden
7	(74) Galatea		asteroid	29 August 1862	Marseille, home window
8	C/1863 G2	1863 III	comet	17 April 1863	Marseille, home garden
9	(79) Eurynome		asteroid	6 October 1863	Marseille, home window
10	C/1863 T1	1863 VI	comet	14 October 1863	Marseille, home balcony
11	C/1863 V1	1863 IV	comet	5 November 1863	Marseille, home garden
12	C/1864 N1	1864 II	comet	5 July 1864	Marseille, home garden
13	(81) Terpsichore		asteroid	30 September 1864	Marseille, home window
14	55P/1865 Y1	1866 I	comet	19 December 1865	Marseille, home balcony
15	38P/1867 B1	1867 I	comet	28 January 1867	Marseille, home balcony
16	9P/1867 G1	1867 II	comet	3 April 1867	Marseille, home window
17	(97) Klotho		asteroid	17 February 1868	Marseille, home window
18	7P/1869 G1 (?)	1869I, 1869a	comet	29 June & 12 August 1869	Marseille, home balcony
19	C/1869 T1	1869 II, 1869b	comet	12 October 1869	Marseille, home garden
20	11P/1869 W1	1869 III, 1869c	comet	27 November 1869	Marseille, home balcony
21	C/1870 K1	1870 I, 1870a	comet	30 May 1870	Marseille, home balcony
22	C/1871 L1	1871 II, 1871b	comet	14 June 1871	Milan, Brera Observatory
23	C/1871 V1	1871 IV, 1871e	comet	3 November 1871	Milan, Brera Observatory
24	10P/1873 N1	1873 II, 1873b	comet	4 July 1873	Milan, Brera Observatory
Other discoveries not included in the references above					
25	NGC 1398		galaxy	9 October 1861	Marseille
26	NGC 1360		planetary nebula	9 October 1861	Marseille
27	X/1871 Y1		comet	29 December 1871	Milan
28	C/1874 G1	1874 II, 1874b	comet	19 April 1874	Milan

Notes:

A progressive number is given in Tempel (1868a), up to number 17 (second edition of the sheet; Iliazd, 1964). Numbers are omitted in Flammarion (1874), although the list order is the same. In this table, numbers in bold refer to objects for which Tempel was the first observer.

Objects 6 and 7 were discovered from Tempel's address at rue Pythagore 10, those from 8 to 21 from rue Pythagore 26.

Supposedly, objects 22, 23, 24 and 28 were discovered with the Steinheil (see discussion in Section 4).

For comets, designations and discovery dates are taken from Kronk (2003), to which we refer for the bibliography. No reference is found for the observations of object 18. Flammarion (1874) reports the year 1868 but we believe it should be 1869: in the note for the object, it is said that it was discovered by Winnecke on 9 April, and that Tempel found it independently, before and after perihelion. We thus believe it was 7P/1869 G1, whose perihelion was on 30 June.

For other objects, references are provided in the text.

Table 2: Tempel's career in astronomy

Period	Location	Occupation
early 1859 – March 1860	Venice	Amateur astronomer, lithographer
March 1860 – December 1861	Marseille	Drawing Astronomer at the Marseille Observatory
January 1862 – early 1871	Marseille	Amateur astronomer, lithographer
early 1871 – early 1875	Milan	Assistant at the Brera Observatory
early 1875 – 16 March 1889	Florence	Helper, then Assistant, at the Arcetri Observatory

these is C/1870 K1, which was found by Tempel only fifteen minutes after Winnecke had made the initial discovery (Littrow, 1870).

For the comets he discovered in 1869, Tempel received the first two prizes of the Imperial Academy of Sciences in Vienna. He was given a gold medal for the first comet, and its monetary value (20 Austrian ducats) for the second (Preisertheilungen …, 1870). Tempel (1884c) believed that the reason for his success as a comet hunter was the good quality of his telescope, and in the large 2° field of the 24× eyepiece (Tempel, 1866). Schiaparelli (1889b) alluded to this excellent eyepiece when he listed the comet discoveries in Tempel's obituary.

3.2 Asteroids

In Valz's obituary which Tempel (1867a) wrote, he lists among the achievements of the former Director of the Marseille Observatory the idea of simplifying the discovery of asteroids by the use of the ecliptic and equatorial charts produced by Chacornac (1856-1863) and Laurent (Valz, 1857a; 1857b), respectively. Thus, it is not by chance, while in Marseille, that Tempel engaged in the search for these bodies. In a note dated 16 July 1860 (Arcetri Archive, Series: *Wilhelm Tempel*), he wrote, in Italian, that he was angry with Chacornac because so many stars were missing on his ecliptical charts, which made the search for a new asteroid, the 59th, very difficult. He added that he was

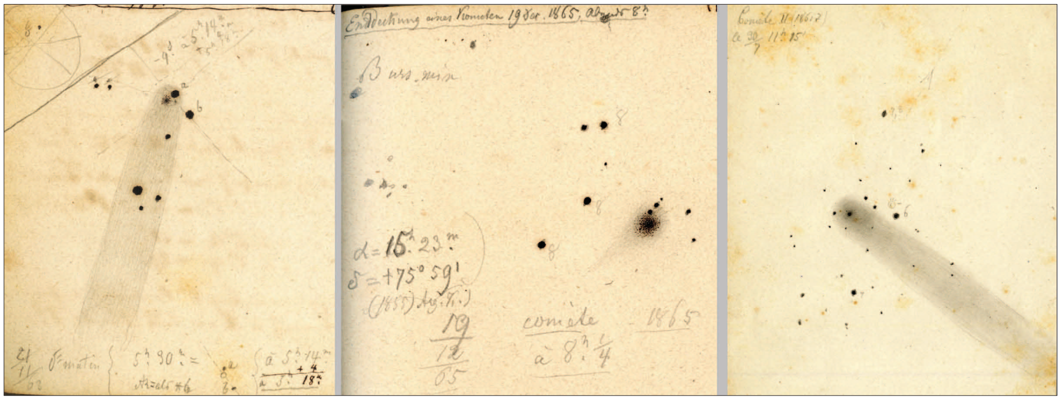

Figure 3: Drawings of comets discovered by Tempel, from his personal notebooks in the Arcetri Archive (Series: *Wilhelm Tempel*). Left: Comet C/1863 V1 on 21 November 1862. Center: Comet 55P/Tempel-Tuttle on the day of its discovery, 19 December 1865. Right: Comet 9P/Tempel 1, observed on 30 July 1867.

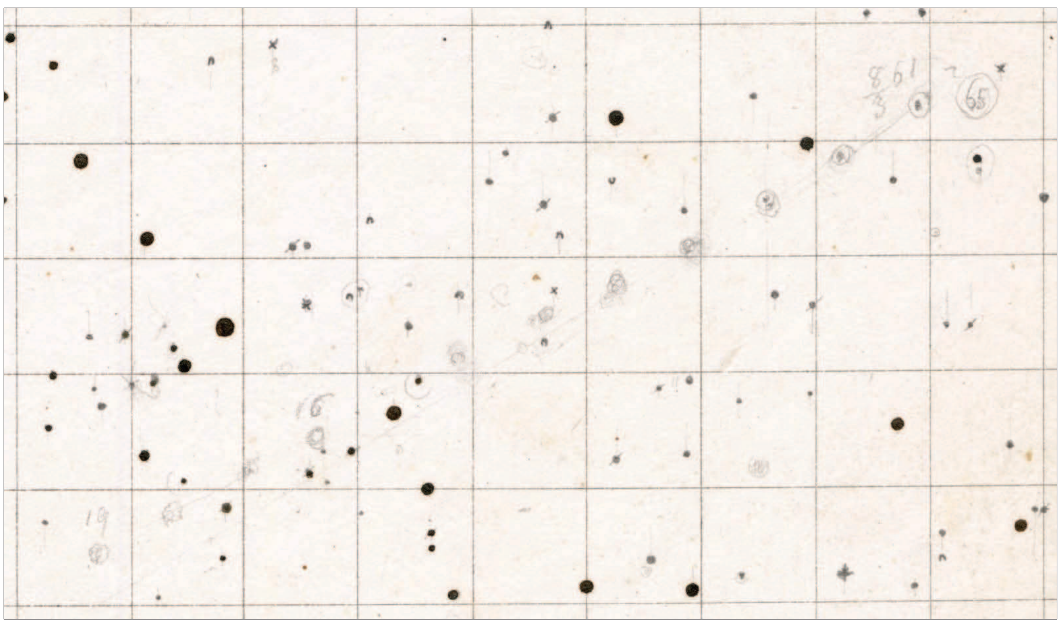

Figure 4: The path of (65) Cybele (Maximiliana) from the day of its discovery, 8 March 1861. The path is marked on what looks to be a copy of Laurent's equinoctial chart, in the Arcetri Archive (Series: *Wilhelm Tempel*). The Arcetri Archive also has a chart with the path of (64) Angelina, similar to the copy in the Preußischer Kulturbesitz of Berlin, which has been published by Clausnitzer (1989). The star close to the second position of the asteroid is HD 106189, next to the grid intersection at RA 12h 6m and Dec 1° (1855). The grid spacings are 1m in RA and 15′ in Dec. North is at the bottom.

"… so disgusted that he had lost the will to search for new planets." (our translation). Ironically, asteroid (59) Elpis was found by Chacornac later that year (see Discovery of Minor Planet 59, 1860). However, Tempel did not abandon his own search, and on 4 March 1861 he found asteroid 64 (Tempel, 1861b), called Angelina by Valz (Peters, 1861). A few days later, on 8 March, Tempel (1861c) discovered asteroid 65 (Figure 4) and asked Steinheil to name it. Steinheil chose the name Maximiliana, in honor of the Bavarian King (Name des Planeten (65), 1861). As in the case of the naming of Victoria (Gould, 1850), the choice of a political rather than a classical name for asteroid 65 gave way to a (mostly German) campaign against it. At the end of 1861, this asteroid was renamed Cybele (Iliazd, 1964).[2] For both of these asteroid discoveries, Tempel was awarded the 1861 Lalande Prize by the French Academy of Science (*Comptes Rendus*, 1861).

After leaving the Marseille Observatory Tempel discovered three more asteroids while observing from the windows of his houses: Galatea in 1862 (Tempel, 1862), Terpsichore in 1864 (Tempel, 1865) and Klotho in 1868 (Tempel, 1868b). The 40× eyepiece was used in the search for asteroids (Tempel, 1884c). Later, Tempel (1885) claimed to have stopped hunting for asteroids because his telescope was too good for that purpose: it showed many more stars than those on the charts at his disposal (see also Tempel, 1863; 1883a), making it difficult to mark them and search for newer, ever fainter, minor planets.

3.3 Nebulae

Another famous discovery by Tempel was the Pleiades Nebula, which was made from Venice on 19 October 1859. Tempel (1861a; 1874; 1885) recounted the discovery on various occasions in the literature. He observed the Pleiades in March 1859 and made a sketch, which was later reproduced as a lithograph (Figure 5). After about six months, he observed the star cluster again and, comparing his drawing with the sky, he noted there was nebulosity around the star Merope. At first he thought it was a comet, but on the following evening the nebula's position was unchanged. The discovery was only announced to the scientific community in 1861, when Tempel showed the nebula to Valz and others (Tempel, 1861a). A drawing of the nebula was published much later (Tempel, 1874). In the years following the publication of the discovery in *Astronomische Nachrichten*, many astronomers tried to observe the nebula. Many did not succeed, and others thought it was a variable nebula (see d'Arrest, 1863; Steinicke, 2009; Tempel, 1875). In 1880, Tempel pointed out the reason for these unsuccessful observations: it is more important to have a wide-field eyepiece than a telescope of large aperture.

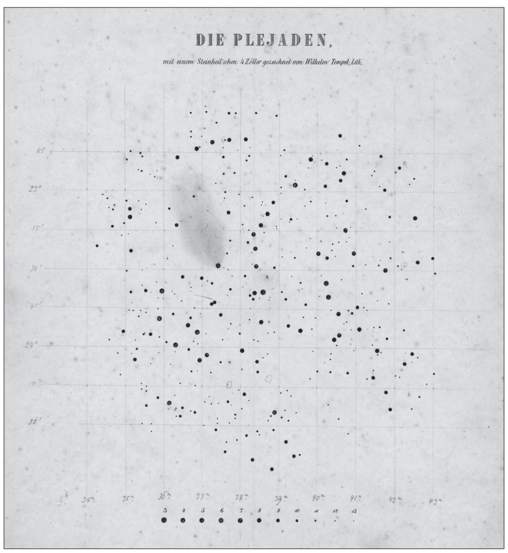

Figure 5: Lithograph of the stars in the Pleiades, from the Arcetri Archive (Series: *Wilhelm Tempel*). The Merope Nebula (and the coordinate grid) has been drawn by hand. The Archive has several versions of this diagram, some without the nebula. A diagram with the nebula drawing and dated *März 1859* is bound in a personal copy of Über Nebelflecken (Tempel, 1885) which was once in the Arcetri Library but is now housed in the Library of the Institute and Museum of the History of Science in Florence. A complete lithograph including the nebula was published later (Tempel, 1874). Tempel's last drawing of the field was done at Arcetri using the Amici I telescope in 1880. In all of these diagrams the field of view is about two degrees, which is that of the Steinheil telescope with the 24× eyepiece (Tempel, 1866). North is at the bottom.

Tempel also observed the Orion Nebula, a drawing of which was published in *Astronomische Nachrichten* (Peters, 1862). The editor of the journal, Christian Peters, praised Tempel for his skills in observing and drawing. He also described the telescope used by Tempel: a 4-inch refractor, with low magnification from 24× to 40×, i.e., the configuration used in the search for comets and asteroids. During his surveys, Tempel must have come across many nebulous objects. For example, one was seen in the stellar field where he found (74) Galathea (Tempel, 1862). Two other nebulae were discovered in Marseille in 1861, and registered on a small star chart that he used during his search for new comets (Tempel, 1882); they were the planetary nebula NGC 1360, first seen by Swift, and the galaxy NGC 1398 (Steinicke, 2009).

In reply to Chacornac's (1863) announcement of the discovery of a variable nebula, Tempel (1863) wrote a letter to the magazine *Les Mondes* in which he expressed doubt about the variability. Believing that nebulae were unresolved star clusters (Tempel was against the idea that some of them were gaseous; Dreyer, 1887), he argued that it was rather improbable to have them all variable at the same time. Instead, he claimed that the supposed variability was the result of changeable atmospheric conditions: for example, his detection of the Pleiades Nebula was due to the exceptional transparency of the sky on the night of the discovery. Then, he suggested a test to verify his claims: one should draw on a copy of the Berlin Academy star chart (Akademische Sternkarten, 1859) the nebulae of the Virgo cluster listed in John Herschel's General catalogue, as observed with a 4-inch telescope, such as his own one. If the map was then compared to those of other astronomers (he referred to d'Arrest and a map in Mädler, 1841), one could get some idea of the different appearance of the same field observed under different circumstances. As we can perceive from the text, Tempel actually made the test: in the Arcetri Archive (series: *Wilhelm Tempel*) there are two maps of the Virgo Cluster, one drawn from observations of d'Arrest, another based upon Tempel's own observations. The latter is much richer in nebulous objects, confirming the good transparency of the sky over Marseille, and most likely showing the self-esteem Tempel had of his ability as observer! In *Les Mondes*, Tempel also resolved to verify the variability of Chacornac's nebula and to give a report on his observations. On a copy of Herschel's General Catalogue,[3] Tempel wrote that he had indeed shown Valz that the object was only a false image. However, they did not publish a note on it, and the nebula ended up classified as variable in the Catalogue. Nevertheless, Tempel sent a comment to John Dreyer, who reported it in the notes of the New General Catalogue (Dreyer, 1888). Indeed, the object, NGC 1988, is just a star (Steinicke, 2009).

A trace of Tempel's first observations of nebulae can be found in his later work, *Observations and Drawings of Some Nebulae*, a collection of twenty-two plates made at the Arcetri Observatory in about 1879. The collection, which is still unpublished, is held in the Arcetri Library. From this work, we know that Tempel used his Steinheil telescope to observe the Andromeda Galaxy (M31) and Omega (M17), Lagoon (M8; Tempel, 1877), Flame (NGC 2024) and Helix (NGC 7293) Nebulae.

3.4 The Moon

The Earth's satellite was one of the first objects to which Tempel directed his observing and drawing skills. In the Arcetri Archive there are several of his drawings of craters and other lunar formations, most of which were made in Venice between July and October

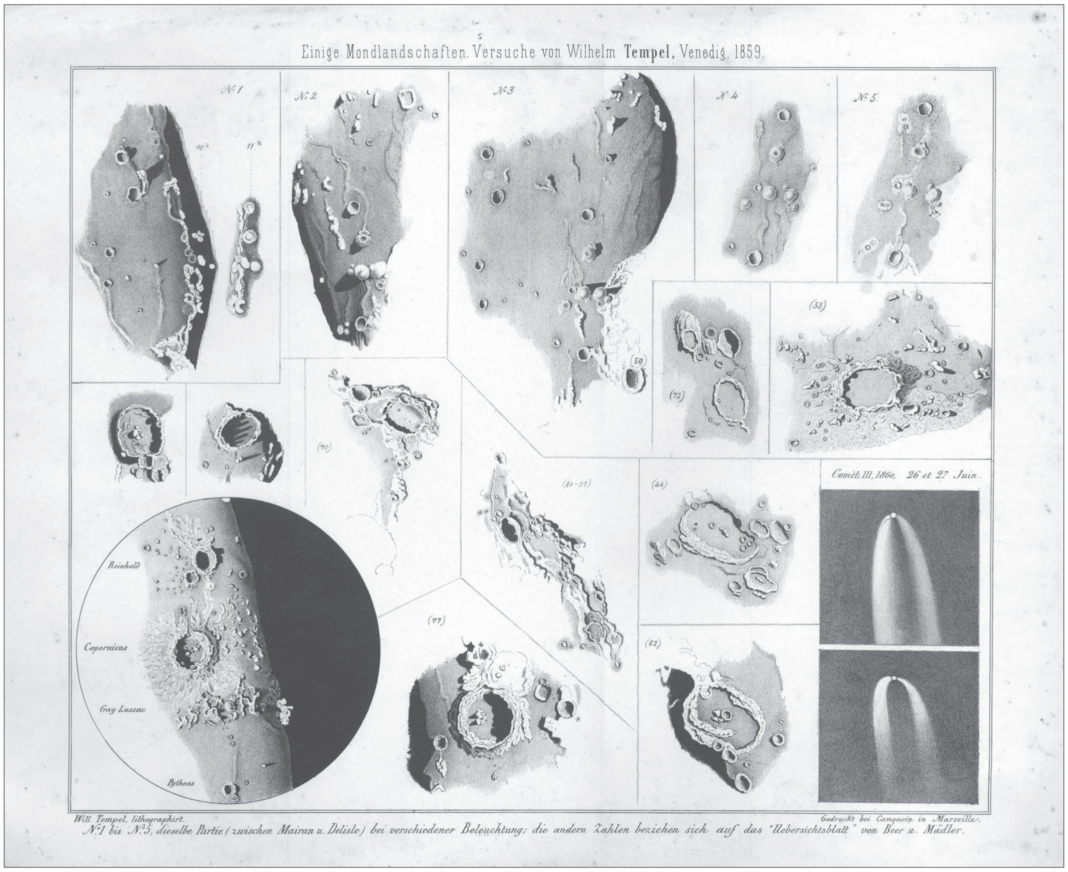

Figure 6: Unpublished lithograph with observations of the Moon, made in Venice in 1859, from the Arcetri Archive (Series: *Wilhelm Tempel*). At the top, the sequence numbered from 1 to 5 shows an area between craters Mairan and Delisle, and in particular the region around Mairan A and Gruithuisen, under different illuminations of the Moon (Tempel 1867b). Around the circular insert are shown, clockwise, the craters Gassendi, Archimedes, Mersenius, Sirsalis and Damoiseau, and Theophilus. The circular insert shows the region around Copernicus, identical to a smaller lithograph published by Clausnitzer (1989: 28); it has a diameter of about 4', probably the field of view of the Steinheil telescope's 120× eyepiece. Under panels n. 4 and 5 the craters Cook and Monge, and Plato are shown (from the left). Beside the comet drawings are the craters Cleomedes (top) and Posidonius (bottom). The Archive has the original drawings for some of the regions shown in the litograph, dating from July to October 1859. In all of Tempel's lunar drawings south is at the top. The two drawings of Comet C/1860 M1 were later published (see Tempel, 1874).

1859. Some of them were included in a lithograph made in Marseille probably in the second half of 1860 (Figure 6). Later, Tempel (1867b; 1867c) published some remarks on the appearance of the Moon's surface, following the news of the disappearance of the crater Linné (Schmidt, 1867).[4] Tempel confirmed the disappearance of the crater, and observed in its place a round white spot, similar to those observed elsewhere on the Moon. He suggested that these spots may be "… of interest for chemically warm activity." (our translation). One of these 'small bubbles' is drawn between craters Diophantus and Delisle (top-left in panel N.3 of Figure 6). In reality, the spot corresponds to a high-albedo area centered on the small craters Samir and Louise, and its appearance (together with that of Linné) may have been due to a lack of resolution and poor seeing.

However, Tempel (1867b) warned about the difficulty of identifying real changes on the Moon's surface, both because lunar atlases were incomplete and because of the differing appearance of the same area in the course of a lunation. In support of this, he described five drawings that he had made of the region between the craters Mairan and Delisle that changed so much from night to night that they looked to have been drawn by different observers, or represented different areas of the Moon's surface (most certainly these are the five numbered panels on the top of Figure 6).

Tempel also suggested that astronomers should look for possible signs of 'luminous activity' on the Earth-lit part of the Moon, not directly illuminated by the Sun. In this way he had been able to observe a light which was "… star-like, diffused, in color reddish-yellow …" (our translation) coming from the crater Aristarchus (Figure 7) during two events in 1866 and 1867. Tempel can thus be counted among the observers of the controversial Transient Lunar Phenomena (TLP), which have been reportedly seen on numerous occasions in the Aristarchus region (Crotts, 2008).

For his lunar observations, Tempel used larger magnifications, from 120× (Tempel, 1867b) to 300× (Tempel, 1867c). By contrast, he used 24× to observe the

Moon during the total eclipse of 1 June 1863. He made a realistic color drawing of this event in his notebook (Arcetri Archive, series: *Wilhelm Tempel*), and later published a lithograph of it (Tempel, 1874).

3.5 Other Observations

In July 1860, Tempel joined an Italian scientific expedition to observe a total solar eclipse, organized by Giovanni Battista Donati and Francesco Carlini, Directors of the Florence and Milan Observatories, respectively

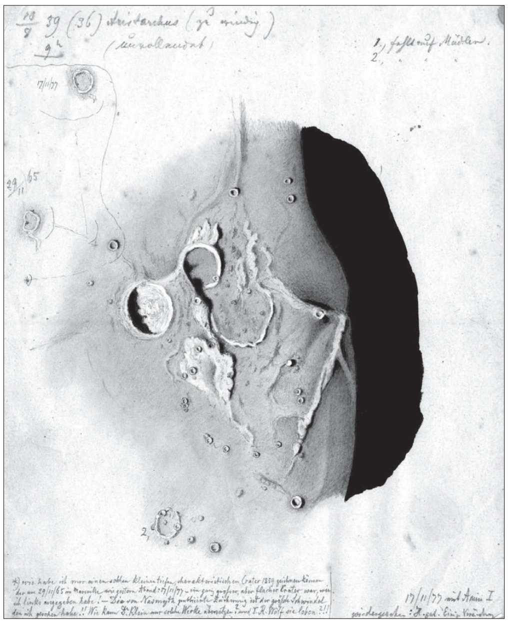

Figure 7: The lunar craters Aristarchus and Herodotus, observed on 16 August 1859 (Arcetri Archive, Series: *Wilhelm Tempel*). The floor of Aristarchus is colored in red, probably to describe the later observations of a TLP (Tempel, 1867b). The small crater to the top left (Aristarchus F) was drawn on two other occasions, on 29 November 1865 from Marseille, and on 17 November 1877 from Arcetri with the Amici I telescope. Tempel noted that this crater appeared larger and shallower in the two later drawings. The rest of the note reports criticisms on a drawing of the same region by Nasmyth, which Tempel considered to be the biggest fake he had ever seen. The same criticisms were written by Tempel on the Aristarchus and Herodotus plate in a copy of the German translation of the work by Nasmyth and Carpenter (1876). This book, once at the Arcetri Library, is now housed in the Library of the Institute and Museum of the History of Science in Florence. As a matter of fact, the plates in Nasmyth and Carpenter's book do not show drawings, but rather photographs of models of the lunar surface (Astronomical Register, 1874).

(Donati, 1866b). The expedition embarked from Marseille for Spain, the final destination being Torreblanca, a town on the Balearic Sea north of Valencia. On the day of the eclipse, 18 July, Tempel was given the task of following it with his telescope and of giving an overall description of the phenomenon, while the other astronomers determined the times of the event, measured the positions of sunspots and prominences, and took photographs. Once back in Marseille, Tempel made two lithographs for Donati (1866b): one showing the appearance of the solar disk before and after the eclipse, based upon the photographs and on sunspot drawings that he made (Donati, 1860a); the other, of the appearance of the corona during totality, again based upon his own drawings. Eddy (1974) compared the drawings made by Tempel with those of other astronomers who observed this eclipse, and claimed that a prominence in Tempel's drawing is a coronal mass ejection, a rare phenomenon to observe during an eclipse, and that the German astronomer produced a more realistic description than that given by the more experienced and well-known P. Angelo Secchi, who observed the event at the same time from a nearby location.

In the summer of 1863, Tempel went on a trip to Germany, where he visited his birthplace, gave a public lecture in Ebersbach and spent time at the Leipzig Observatory (Clausnitzer, 1989), where he probably sought employment. He also had the objective of his telescope cleaned by Steinheil in Munich, which corrected some shape imperfections (Tempel, 1864b).

Back in Marseille, Tempel tested his telescope and was very satisfied with the result: he managed to resolve double stars as close as 1.5″, even objects such as β Orionis which he had not been able to resolve prior to the cleaning. After these tests, he went on to observe Sirius. The companion, Sirius B, had been discovered by Clark in 1862 and observed many times with large telescopes in America and Europe (Holberg and Wesemael, 2007). In Paris, Goldschmidt (1863) claimed to have observed six stars around Sirius, some closer to the main star than Sirius B (the separation at the time was about 10″; Wesemael and Racine, 2008). Tempel, observing with a slightly larger telescope than Goldschmidt and from a place with better atmospheric conditions, was indeed able to see point sources with the lower magnifications (24 and 40×). However, these were fainter at 60× and disappeared with magnifications larger than 80×. Since this was at odds with his experience on the Pleiades, where fainter stars were more readily visible with larger magnifications, Tempel (1864b) concluded that the companions seen by Goldschmidt were only false images. Later, Tempel (1872b; 1874) returned to the topic of the visibility of fainter stars next to bright ones and also observed Sirius from Arcetri (Tempel, 1875-1877; 1878a).

Finally, Tempel (1874) used his Steinheil telescope to observe Jupiter and Saturn. He was particularly interested in the satellites' configuration, but did not neglect to give a realistic representation of their appearance in the telescope (e.g. see Figure 8). Later, he was committed to planetary observations and made numerous drawing using the Amici I at Arcetri; these were never published, and are now held in the Arcetri Archive (series: *Wilhelm Tempel*).

4 THE TELESCOPE AT BRERA AND ARCETRI (1871-1889)

Because of the Franco-Prussian War, at the beginning of 1871 Tempel, being German, was expelled from France. He moved to Milan, and was employed as an Assistant at the Brera Observatory, which at the time was directed by Schiaparelli; thus he again became a professional astronomer (Clausnitzer, 1989). While at Brera, Tempel discovered three more comets: C/1871 L1, C/1871 V1 and the periodic 10P/1873 N1 Tempel 2. Tempel's skills were well suited to the research interests of his employer, Schiaparelli, which related to the study of cometary orbits and tails, and the association with meteors. Schiaparelli took advantage of Tempel's drawing and engraving ability, which allowed the Italian astronomer to publish an overdue work on the shape and direction of cometary tails which had been delayed for more than ten years because of the "… difficulty of finding a way to reproduce exactly and faithfully the numerous drawings …" that he had made of comet 109P/1862 O1 Swift-Tuttle (Schiaparelli, 1873: 3; our translation). In this period, Tempel (1874) also had the opportunity to publish some of his own earlier, unknown, drawings.

While at the Brera Observatory, Tempel could use a micrometer and an equatorially-mounted telescope, the Sisson equatorial sector with the Plössl objective (which he called the Plössl telescope). With these instruments, he made accurate positional measurements that were included in his publications. However, Tempel believed that his Steinheil refractor was of better quality than the Plössl telescope, although both had the same aperture and focal length (Schiaparelli, 1871): "… the difference in visibility of nebulae and faint comets was sometimes incomprehensible … [while in the Plössl] often there was no trace of nebulae and comets, that were seen so well in the Steinheil." (Tempel, 1875: 67; our translation). In the publications of this period (most of which were translated into Italian and included in Tempel, 1874), Tempel wrote several times that he had used the Steinheil to observe comets too faint for the Plössl. Thus, it is very likely that he used the Steinheil telescope for the comet discoveries (even though the 'discovery telescope' is never mentioned). We can guess this for C/1871 L1, which was discovered when he was drawing nebulae (Tempel, 1871), and perhaps also C/1871 V1, which was found next to the open cluster (he said *nebula*) M26 (Tempel; 1872a). In one case there is no doubt: on 29 December 1871 he reported a comet (X/1871 Y1, which was never seen again—Kronk, 2003) with his instruments without an equatorial mounting (Tempel, 1872b). Furthermore, using the Steinheil refractor and the 24× eyepiece he made three plates describing the changing appearance of Coggia's Comet, C/1874 H1, along its path (Tempel, 1874).

Because of health problems and the cold Milan winters, at the beginning of 1875 Tempel moved to the Astronomical Observatory of Arcetri in Florence (Schiaparelli, 1889b),[5] where, sponsored by Schiaparelli, he was first employed as *aiuto* (helper), then Assistant Astronomer. Tempel arrived in Arcetri after the death of the founder Director, Giovanni Battista Donati in 1873, and of the *aiuto*, Domenico Cipolletti, in 1874. He was the only astronomer in service at Arcetri till the end of his life, since the astronomy chair at the Institute of Superior Studies[6]—upon which the Observatory depended—remained vacant till 1894. Being alone, and with only the tasks of preserving and maintaining the instrumentation (Parlatore, 1876), he was free to use the telescopes at will. The principal instrument in Arcetri was the 28-cm refractor, Amici I, which Tempel (1877) immediately used to observe nebulae. This became his principal activity at Arcetri. Besides drawing the plates of *Observations and Drawings of some Nebulae* (Tempel, 1879), for which he received from the Lincei Academy the Royal Prize of H.M. King Umberto I for Astronomy (*Atti della R. Accademia dei Lincei*, 1881), he discovered many new objects (about 150 entries of Dreyer's [1888] *New General Catalogue*; Steinicke, 2009) and published a more extended work on the topic, Über Nebelflecken (Tempel, 1885). From Florence he discovered yet another comet, C/1877 T1, while moving the Amici I telescope from Mars to some nebulae he had discovered earlier (Tempel, 1878b). For this and the comet discoveries in Milan, he received four other prizes from the Imperial Academy of Sciences in Vienna (Weiss 1878). As final recognition for his comet discoveries, he received the Valz Prize in 1881 (Clausnitzer, 1989).

Although only sporadically, he kept using his Steinheil telescope to observe comets (Tempel, 1878c; 1883b). Since the Amici I could not be used for targets located <20º above the horizon (Tempel, 1877), he also used the Fraunhofer equatorial telescope for positional measurements. It is interesting to note that Donati, who was a pioneer of spectroscopy, equipped the Fraunhofer refractor with a spectroscope (Cipolletti, 1872), but Tempel does not seem to have used it, and indeed he did not trust spectroscopic studies (Tempel, 1885). It should be noted, however, that following Donati's death even Schiaparelli (1875), with a supporting letter from Struve, stated he preferred classical astronomy over the yet uncertain role of astrophysics.

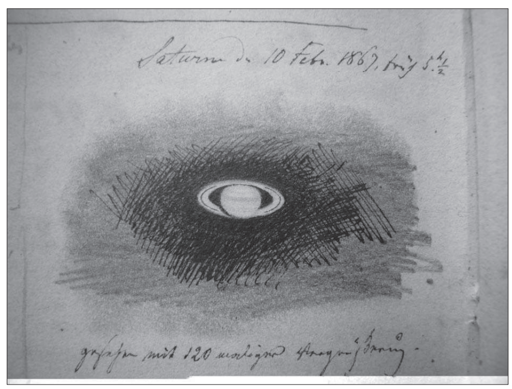

Figure 8: A drawing of Saturn made on 10 February 1867, using the 120× eyepiece. From one of Tempel's notebooks (Arcetri Archive, Series: *Wilhelm Tempel*). South is at the top.

As for the Fraunhofer telescope, it was identical to Tempel's Steinheil refractor in aperture and focal length but, like the Plössl in Brera, was not as good for the observations of comets and nebulae (Tempel, 1884d; 1885). In his declining years, Tempel (1884b; our translation) wrote to A. Steinheil about his superb telescope:

> Shouldn't you remember, the excellent work of your father – my beautiful four inch! – had a big part in my astronomical successes. I must always remember with respect and gratitude the firm: C.A. Steinheil.

A last note on the total number of discoveries made with the Steinheil refractor: Tempel told Geltrude Walker Baldelli (1881), a visitor to the Observatory, that he made 26 discoveries with his telescope, while in a letter to A. Steinheil he wrote that he found 5 asteroids with the 40× eyepiece, and made another 21 discoveries with the 24× – again 26 discoveries (Tempel, 1884c). In his list of discoveries either as first observer or independent discoverer (see Table 1) Tempel named 24 objects. To these, we can add the galaxy NGC 1398, the planetary nebula NGC 1360, and the comets X/1871 Y1 (never seen again) and C/1874 G1, the priority of which belongs to Winnecke (Tempel, 1874). We thus have a total of 28 discoveries, though there are some inconsistencies: 6 asteroids, rather than 5, are listed, including (79) Eurynome, which was found by Watson (Tempel, 1864a); three objects are not included in the 1874 list, though they had been discovered before the publication date; for a comet, probably 7P/1869 G1, two discovery dates are given because Tempel claimed to have found it before and after perihelion, independently while lacking any news or ephemerides. Unfortunately, these inconsistencies, together with the discrepancy between the current count and his later claims, do not help us in clarifying whether the comet discoveries from Milan (objects 22, 23, 24 and 28 in Table 1) were made with the Steinheil telescope. But, if this is true, Tempel used this telescope to discover a total of 11 comets (excluding X/1871 Y1), 5 asteroids, the Pleiades Nebula and the galaxy NGC1398.

5 THE TELESCOPE AFTER TEMPEL'S DEATH (1889-PRESENT)

In the last years of his life Tempel was ill and had to abandon observing (Dreyer, 1890; Schiaparelli, 1889b), but partly also because of the terrible conditions of the Observatory building, which had experienced rain-proofing problems since the early years of its existence (Baldelli, 1881; Schiaparelli, 1875). In December 1887, the Amici I was dismantled and sheltered to avoid damage from a possible collapse of the rotten wooden dome. In March 1888 the roof of the east wing of the Observatory, where Tempel lived with his wife, collapsed and they had to move to a nearby villa (Tempel, 1888). Despite illness, which often confined him to bed, we can imagine that Tempel still found time to use his telescope, for after his death (on 16 March 1889) his widow told a visitor to the Observatory that "… Tempel worked to the last … the poor sufferer observed, ill as he was, from the top of his house with a small telescope." (Sawerthal, 1889: 349).

Marianna Gambini,[7] who shared with Tempel a meager and frugal life, found herself in a state of poverty upon the death of her husband. Furthermore, she could not receive any pension from the Government, as Tempel had not worked in Italy long enough to be entitled to it (Sovrintendente, 1890). To help her, an international subscription was opened (Roberts; 1889), while Schiaparelli acted for her to open a licensed salt and tobacco shop (Hagen, 1912). In addition, Gautier (1889) reported that Tempel's widow "… hopes to realize something from the books, letters, and instruments which he possessed – among other things from the telescope with which he worked so heroically." Through the interest of the Institute of Superior Studies, the Italian Ministry of Public Education agreed to help the widow by rewarding her for the extraordinary work of her husband[8] if she "… handed over to the Observatory all of the drawings of nebulae and other celestial objects made by her husband at the Observatory." (Sovrintendente, 1890; our translation). The Steinheil telescope was added to these negotiations, and Marianna Gambini initially asked for 2000 Italian lire, "… an amount already asked by my deceased husband." (Gambini-Tempel, 1890a; our translation) in a previous negotiation (of which we could find no other trace). After talking to Pietro Tacchini, Director of the Observatory at the Collegio Romano in Rome, she settled for 1500 lire for the telescope, and 3000 lire for the nebula plates (Gambini-Tempel, 1890b). Tacchini wanted the telescope for the Museum of the Collegio Romano, but the purchase was made only in favor of the Institute of Florence (Targioni Tozzetti, 1890). The Minister delayed making the payment for the telescope until April 1891 (Ministro dell'Istruzione Pubblica, 1891), while negotiations for the plates lasted even longer, as some of them were missing and it was necessary to reassemble the collection (Ministro dell'Istruzione Pubblica, 1893).

Although the intended destination of the telescope and of the plates was the Arcetri Observatory, after the purchase they were added to the collections of the Museum of Ancient Instruments at the Florence Institute of Superior Studies (and the collections later became the core of the current Institute and Museum of the History of Science in Florence; see Miniati, 1991). In the inventory of the Museum, item 1266 is a "Steinheil telescope built in wood and brass, of length 1.6m with objective, eyepieces and other accessories, mounted on a wooden foot of height 2.06m." (*Inventario*, 1872-; our translation). The description is fully compatible with the appearance of the telescope and mounting as depicted in Figure 1, showing that the telescope had not been altered up to that date. The value of the instrument is given as 1500 lire (i.e. the payment given to Tempel's widow). In March 1895, the new Director of the Observatory, Antonio Abetti, asked for the plates and the telescope to be transferred to Arcetri. He held that

> Tempel's telescope, which provided him in many details because of his exceptional eyesight, has to come back to Arcetri, where it could still be used to view the sky in those areas explored and drawn by the very skillful astronomer and artist. (Abetti, 1895b; our translation).

In exchange for it, Abetti would give to the Museum "… some old instruments that are renowned here, but are useless, since they have been dismantled or are unsuitable for current astronomical research …" (Abetti, 1895a; our translation).[9] The Director of the Museum, A. Roiti (1895; our translation), looked favorably upon the transfer of the telescope "… if there is somebody who really uses it …", but not of the plates, because they could be damaged. Abetti insisted on the necessity of having the plates, to compare them with other drawings and notes by Tempel already at the Observatory. The aim was to publish the plates, and the name of a young astronomer, Bortolo Viaro, was suggested for the task (Abetti, 1895c). Also the telescope was necessary, since it was needed "… to make a check of the sky …" (our translation) and verify the conditions under which Tempel observed. Abetti (1895b) probably did not refer here to the plates, all of which were taken with the Amici I telescope, but rather to the other drawings made by Tempel. The transfer of the telescope (and Viaro's appointment) were authorized in the summer of the same year by the Superintendent of the Institute of Superior Studies (Nobili, 1895). However, in subsequent years Viaro was employed for astronomical observations (Abetti, 1923), and the plates, which were eventually transferred to the Arcetri Observatory Library (Abetti, 1921), were never published.

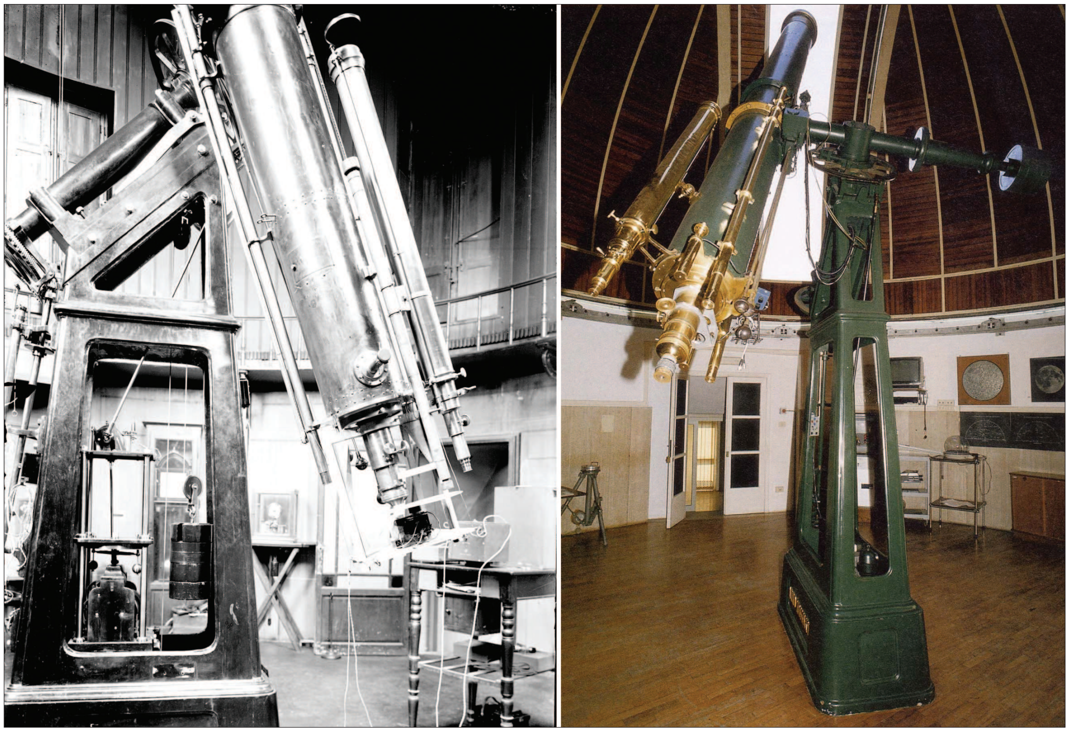

Figure 9: Tempel's telescope, used as a guide scope on the Amici telescope. In the left panel, a photograph taken in 1933 in the old central dome of the Arcetri Observatory, Tempel's telescope is the longer instrument to the right of the Amici tube. The smaller, thinner, tube next to Tempel's telescope and to its left is one of Galileo's original telescopes. The whole apparatus was used to convert lunar light, as observed through Galileo's telescope, into a radio signal to light the Chicago *Century of Progress International Exposition* during an homage to Guglielmo Marconi (Colacevich, 1933). The right-hand panel shows a modern view inside the Amici Pavilion. In this photograph, Tempel's telescope is the brass tube to the left of the Amici telescope.

Tempel's telescope, which was again in Arcetri at the end of 1895 (Cerulli, 1895), was only sporadically used. When the equatorial mounting of the Fraunhofer telescope was restored, Abetti (1901; our translation) foresaw a use also for the "… historic Steinheil telescope of 109 mm, which was property and glory of Tempel ...", but instead, the telescope was put in a room at the Observatory where old instruments were stored (Abetti, 1909). We found only one trace of its use during this period, when "… a telescope called the Tempel …" was used with a wide field eyepiece (probably the 24×) to observe Comet Gale, C/1912 R1 (Abetti, 1913; our translation).

At the beginning of the 1920s, Giorgio Abetti succeeded his father, Antonio, as Director of the Arcetri Observatory. He had the "… renowned telescope of Tempel …" mounted as a finder on the Amici equatorial telescope,[10] so that it could be used as a "… guide [scope] during photographic exposures and to observe the Sun." (Abetti, 1922; our translation). From this time, photographs of the telescope are available (e.g. see Figure 9). At an unknown date between late 1895 and early 1922, the instrument was modified, and it now has a cylindrical brass tube in place of the original wooden one shown in Figure 1. It is possible that this brass tube originally belonged to the Fraunhofer telescope, which was almost identical to the Steinheil and was the only instrument of that size at the Observatory. The Fraunhofer refractor originally had a mahogany tube, as documented in price lists (e.g. see Verzeichnifs …, 1822) and in the catalogue of instruments at the old observatory of Florence, where the Fraunhofer telescope came from (Catalogo, 1839-1854). Its tube could have been changed during the two main modifications that the telescope underwent. The first involved the making of an equatorial mounting by the workshop Officina Galileo in Florence, to prepare the telescope for a scientific expedition to Sicily in 1870 in order to observe a total solar eclipse (Chinnici, 2008; Cipolletti, 1872). The second upgrade of the mounting, which we have already mentioned, was carried out in the workshop of the Observatory of Padua by the mechanics Giuseppe Cavignato and Sante Mioni (Abetti, 1901). The Fraunhofer telescope is mentioned for the last time in the 1906 inventory of the Arcetri Observatory (Abetti, 1909), and its dome was dismantled in 1924 (Abetti, 1925), a couple of years after Tempel's telescope was mounted as a guide scope on the Amici refractor. It should be stressed, however, that the identification of the tube in Figure 9 as that of the Fraunhofer telescope is not certain, as no supporting documentation could be found in the Arcetri Archive. However, the engraving on the brass ring holding the objective leaves no doubt about its identification, as it reports the original production number of Tempel's telescope: "Steinheil in München N. 216" (Figure 10). The altazimuth mounting that Tempel had made for the telescope in Venice is lost, along with the wooden tube.

With the passing of the years, memory of the presence of Tempel's telescope at the Arcetri Observatory was almost lost, and it was only at the beginning of 2008 that the instrument was 'rediscovered', after we read some of the old publications of the Observatory. In the summer of 2008 the telescope was detached from the Amici refractor and restoration began. Once the restoration is completed, the telescope will be displayed to the public in the Amici Pavilion, together with information panels. Thus, we will finally pay homage not just to an instrument that is of some importance in the history of astronomy, but also to its owner, "… ensuring for his memory a fame that will last as long as mankind continues to honor the study of astronomy." (Schiaparelli, 1889a: 472; our translation).

Figure 10: The objective of Tempel's telescope. The engraving on the brass ring holding the objective states: "Steinheil in München N. 216". The production number is on the right side of the ring (a close-up is shown on the top right).

6 NOTES

1. The Historical Archive of the Arcetri Astrophysical Observatory contains the scientific and private documents of several astronomers, most notably Giovanni Battista Donati, Wilhelm Tempel, Antonio and Giorgio Abetti, Guglielmo Righini, Pietro Tacchini and Giuseppe Lorenzoni (Capetta and Gasperini, 2008). Tempel's documents and books were probably left in the Observatory at the time of his death or were later bought from his widow, Marianna Gambini (see Section 5, above). In a probable attempt to sell her husband's correspondence, in 1895 the widow made a detailed inventory that still existed in the 1960s (Iliazd, 1964), but is now missing. The remainder of Tempel's documents were finally sold in 1907 by Marianna Gambini to the Preußischer Kulturbesitz, for 250 marks. Only three out of a total of six boxes are now available, the others having been lost during World War II (staff at the Preußischer Kulturbesitz, private communication, 2009).
2. During the twentieth century, events surrounding the naming of Maximiliana and the disagreement between Tempel and some of the academic community inspired the German painter, Max Ernst, and the Georgian poet and editor, Iliazd (Ilia Zdanevich). A biography of Tempel's life was published by Iliazd (1964) together with the illustrated book *Maximiliana ou l'Exercice Illégal de l'Astronomie: L'Art de Voir de Guillaume Tempel* (Ernst, 1964). In 1966, Max Ernst and the German film director, Peter Schamoni, produced the short film *Die widerrechtliche Ausübung der Astronomie - Ein Film über Ernst Wilhelm Leberecht Tempel *1821 +1889*, and another book was subsequently published (Schamoni, 1974).
3. In Tempel's obituary, John Dreyer (1890: 182) wrote:

   > In the beginning of 1887, when he found himself unable to observe, Tempel began to arrange and put in order his scattered notes and sketches, many of which had as yet only been jotted down on various maps, and intended to enter them all in a copy of Herschel's General Catalogue, interleaved with two white leaves between each two pages, but we are not aware whether he succeeded in completing this task.

   A copy of the General Catalogue (Herschel, 1864) with those characteristics still exists in the Arcetri Library. Several drawings and notes by Tempel, dating from the end of 1876 to 1885, are written on the white pages. A copy of the Supplement by Dreyer (1878), which is bound in with this volume, is also annotated. The Supplement includes many objects discovered by Tempel while he was at the Arcetri Observatory (see Steinicke, 2009).
4. Schmidt's 1867 paper resulted in a long series of observations by many different astronomers. Nowadays, the event is not considered to have been real (Moore, 1977).
5. In 1921 this became the Arcetri Astrophysical Observatory (see Abetti, 1922).
6. In 1924 this became the University of Studies of Florence (see Lotti, 1986).
7. Countess Baldelli (1881) described Marianna Gambini as "… if not scientific herself, certainly a benefactor of astronomy."
8. It should be noted that Tempel was knighted by the Italian Crown in 1883 for his contribution to Italian astronomy (see Clausnitzer, 1989).
9. Among the items on Abetti's list (1895a) that were "… renowned here, but are useless …" is part of the apparatus used by Donati for his pioneering observations of the spectra of stars (Donati, 1866a) and for the first observation of a cometary spectrum, that of C/1864 N1 (Donati 1864), one of the comets discovered by Tempel. This apparatus is now on display at the Institute and Museum of the History of Science in Florence.
10. The current Amici telescope at the Arcetri Astrophysical Observatory and the Amici I used by Tempel only have in common a cast-iron pedestal. The equatorial mounting, lacking graduated setting circles and a clock-drive mechanism, was upgraded in 1894, and the original wooden tube was replaced by a metal one (Abetti, 1896). A 36-cm Zeiss objective was then substituted for the 28-cm Amici I objective (Abetti, 1926). The original tube of the Amici I is conserved at the Institute and Museum of the History of Science in Florence, while the Amici I objective is at Arcetri (Righini, 1969).

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JAMES DUNLOP'S HISTORICAL CATALOGUE OF SOUTHERN NEBULAE AND CLUSTERS

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Abstract: In 1826 James Dunlop compiled the second ever catalogue of southern star clusters, nebulae and galaxies from Parramatta (NSW, Australia) using a 23-cm reflecting telescope. Initially acclaimed, the catalogue and author were later criticised and condemned by others—including Sir John Herschel—and both the catalogue and author are now largely unknown. The criticism of the catalogue centred on the large number of fictitious or 'missing' objects, yet detailed analysis reveals the remarkable completeness of the catalogue, despite its inherent errors. We believe that James Dunlop was an important early Australian astronomer, and his catalogue should be esteemed as the southern equivalent of Messier's famous northern catalogue.

Keywords: James Dunlop, southern sky catalogue, clusters, nebulae, galaxies

1 INTRODUCTION

The first southern catalogue of clusters and nebulae was produced by the Frenchman, Nicolas Louis de Lacaille (1713–1762), from Cape Town in 1751-1752 with a tiny half-inch aperture (1.3-cm) refractor (see Lacaille, 1755). The second catalogue was compiled by James Dunlop (1828), who observed from Sydney in 1826 with a nine-inch aperture (23-cm) speculum-mirror reflector. Sir John Herschel, who observed firstly from London between 1825 and 1833, and then from Cape Town between 1834 and 1838, made the third catalogue of southern clusters and nebulae, using an 18.5-inch aperture (47-cm) speculum-mirror reflector (see Herschel, 1847).

Prior to 1654, Giovanni Battista Hodierna (1597–1660), observing from Sicily, catalogued 11 NGC objects (Hodierna, 1654). Charles Messier (1730–1817) and Pierre Méchain (1744–1804) later compiled their famous catalogue of 109 bright clusters and nebulae from Paris, between 1758 and 1782 (e.g. see Messier, 1781; Méchain, 1783). Together they found 66 new NGC objects. Messier used many telescopes, including a 7.5-inch aperture (19-cm) speculum-mirror reflector. Sir William Herschel (John's father), with his sister Caroline's help, went on to compile a very large catalogue of more than 2,500 clusters and nebulae, from London, between 1782 and 1802, using an 18.5-inch (47-cm) aperture speculum reflector (Herschel, 1786; 1789; 1802). Thus, by 1802, the sky visible from the northern hemisphere was well catalogued, while the far southern sky was still largely unknown.

As noted above, James Dunlop (Figure 1) compiled the second southern catalogue, which was titled *A Catalogue Of Nebulae And Clusters Of Stars In The Southern Hemisphere, Observed At Parramatta In New South Wales.* In 1828, after the publication of this catalogue, Dunlop was awarded the Gold Medal of the Astronomical Society of London by the President, Sir John Herschel. Upon awarding the Medal, Herschel praised Dunlop for his zealous, active, industrious and methodical work, and his recognition seemed assured. Instead, this catalogue of 629 objects was largely ignored by later observers for a number of reasons, but primarily because the positions given for the objects were not accurate (with average offsets of 9′) and because about half of the listed objects were supposedly 'missing'.

Furthermore, six years later, when Herschel began observing the southern skies from Cape Town, South Africa, he became frustrated by the inaccuracy of Dunlop's positions, and only succeeded in identifying 211 (34%) of the objects in the catalogue. In the introduction to his own catalogue of southern nebulae and clusters, included in his monumental *Results of Astronomical Observations Made During the Years 1834, 5, 6, 7, 8, at the Cape of Good Hope,* Herschel (1847) dismisses Dunlop's catalogue:

> I cannot help concluding that, at least in the majority of those cases, a want of sufficient light or defining power in the instrument used by Mr. Dunlop, has been the cause of his setting down objects as nebulae where none really exist.[1]

Figure 1: James Dunlop, 1793–1848 (courtesy: http://en.Wikipedia.ord/wiki/James_Dunlop).

Criticism of Dunlop continued during the following years. Herschel's friend, James David Forbes (1849), published a damning article in *The Quarterly Review* that was critical of Dunlop:

> If men like [John] Herschel are to spend the best years of their lives in recording for the benefit of a remote posterity the actual state of the heavens … what a galling discovery to find amongst their own contemporaries men who … from carelessness and culpable apathy hand down to posterity a mass of errors … [so] that four hundred objects out of six hundred could not be identified in any manner … with a telescope seven times more powerful than that stated to have been used.

In this paper we provide brief biographical data about James Dunlop and discuss his reflecting telescope before critically examining his catalogue.

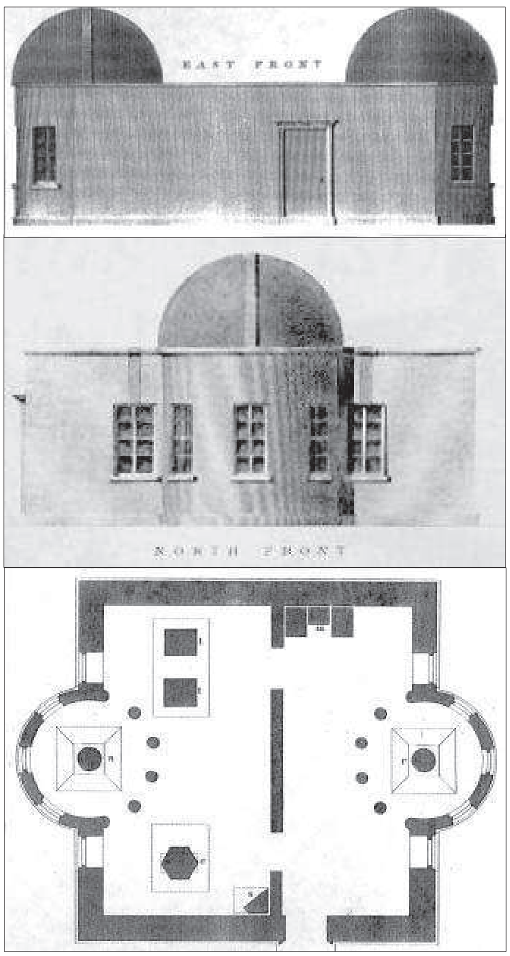


Figure 2: Side elevations and plan view of the Parramatta Observatory (after Richardson, 1835).

2 JAMES DUNLOP

In his biography of James Dunlop, John Service (1890) notes that Dunlop was born in Dalry, Scotland, in 1793. He came from a working-class family and was poorly educated. At age 14 he began work in a thread factory in the neighbouring town of Beith, and it was there that

> ... his natural aptitude for mechanics was … developed. During his intervals of leisure he constructed turning lathes, telescopes, and reflectors from such materials as his limited means afforded. The ingenuity he displayed attracted the attention of his employers and fellow workmen, who discerned in him the dawning of a distinguished scientist. (Service, 1890: 69).

While Service can be forgiven for seeing the makings of a 'distinguished scientist' in his illustrious ancestor, what specifically interests us is the reference to the manufacture of telescopes and especially 'reflectors'. In her biography of Dunlop, Salmon (1911: 627) provides further details:

> When he was only seventeen years of age, he was constructing lathes and telescopes, and casting reflectors for himself; and in a dark closet of a cellar under one of the factory stairs, he made a telescope four feet long and six or nine inches in aperture. His brother John, a boy of fourteen, helped him to the extent of holding the candle whilst Jamie did the work. When the instrument was completed they took it up to an attic and had a look at "Cock-my-lane" on the Dalrig Hills. His employer, Mr. Faulds, came up to have a look, and was astonished at the wonderful "skyglass."

What this reveals is that as a teenager Dunlop was making successful reflecting telescopes with speculum mirrors, and it was this aptitude and his mechanical skills and training that brought him to the attention of fellow Scot, Sir Thomas Brisbane (1773–1869), who was a dedicated amateur astronomer and maintained a well-equipped private observatory at Largs (Allison-Mow, 2004).

Brisbane was subsequently appointed Governor of New South Wales, and he decided to set up a private observatory in Australia so that he could explore the southern skies (see Saunders, 1990). He also decided to employ Christian Carl Rümker (1788–1862), a German astronomer (Bergman, 1960), to carry out astronomical observations, and James Dunlop to maintain the astronomical instruments

In November 1821 Brisbane, Dunlop and Rümker arrived in Sydney, and they soon began erecting an observatory near Government House. 'Parramatta Observatory', as it was known (Figure 2), was completed in May 1822, and Rümker then began compiling a southern star catalogue while Dunlop assisted him and attended to the instruments.[2]

Friction soon developed between Brisbane and Rümker, and the untrained Dunlop took over observations for Brisbane's catalogue of southern stars when Rümker left in June 1823. Bergman (1960) notes that tension had also developed between Rümker and Dunlop because Rümker thought that Brisbane favoured Dunlop. Brisbane was also having problems as Governor, and at the end of 1825 he returned to Scotland, leaving Dunlop to continue working on the star catalogue, which he completed in February 1826. In April of that year Dunlop left the Parramatta Observatory, and Rümker resumed working there.

Dunlop moved to a nearby house in Parramatta, where he began observing southern clusters and nebulae. No doubt he had noticed many of these objects while working on the Parramatta star catalogue with a 3.75-inch (9.5-cm) aperture transit instrument, many more than the mere 42 entries in Lacaille's 1755 catalogue of southern clusters and nebulae.

This inspired Dunlop to compile a larger catalogue to supersede Lacaille's catalogue, and for this he used a 9-inch (23-cm) aperture, 9-foot (274-cm) long reflecting telescope with a speculum mirror which he had made. The current whereabouts of this telescope is not known. The clock which Dunlop used to record the times of his observations may have been one of the four clocks brought to Australia by Brisbane (though there is no documentation on this).

Apparently Dunlop had no financial support and no assistant during the seven months he spent on his catalogue. He worked constantly and determinedly, in the end observing and recording a total of 629 clusters and nebulae (Dunlop, 1828; some of these objects are also discussed in Dunlop 1829b). At the same time he also produced a catalogue of 253 double stars (Dunlop, 1829a), observing these on the nights when the Moon was too bright for him to search for clusters and nebulae.

Early in 1827 Dunlop returned to Scotland, where he once again worked for Brisbane, serving as astronomer in his Makerstoun Observatory near Kelso (see Morrison-Low, 2004). His catalogue of clusters and nebulae was reduced during this time, and was published by the Royal Society (of London) in 1828.

Almost ten years to the day after Dunlop first arrived in Australia, he returned to Sydney as "...superintendent of the Government Observatory at Parramatta, with a salary of £300." (Salmon, 1911: 627).[3] Dunlop remained in this post from 1831 until 1847, when a review of the run-down facility led by Captain Phillip Parker King (see Orchiston, 1988) resulted in its closure. Dunlop then retired to his farm near Gosford, N.S.W., and just one year later he was dead. He was buried at the Kincumber Anglican Church.

3 DUNLOP'S TELESCOPE

In compiling his catalogue of southern nebulae and clusters James Dunlop used a telescope he built while maintaining the instruments at the Parramatta Observatory. This telescope had a speculum mirror of 23-cm aperture (d_s), and we can convert this to the equivalent of a modern aluminium-coated mirror (d_m) in a Newtonian reflector by using the formula

$$d_m = \sqrt{(pr_s \times sr_s \times d_s)/(pr_m \times sr_m)} \qquad (1)$$

where pr_s and pr_m are the primary reflectivity of a speculum mirror and a modern mirror, respectively, and sr_s and sr_m are the secondary reflectivity of a speculum mirror and a modern mirror, respectively. Speculum was made with different percentages of copper and tin, and in calculating the equivalent modern telescope a 45% tin speculum was assumed. The composition of the speculum mirror in Dunlop's telescope is not known, but 45% tin speculum tarnished more slowly than other mixes. The calculation also assumes that after six months in a damp atmosphere, speculum has a reflectivity of ~63% (Tolansky and Donaldson, 1947)[4] and aluminium a reflectivity of 87%. Upon feeding these figures into Equation 1, we obtain the results listed in Table 1. As a general statement, we can say that Dunlop's mirror was equivalent to a modern mirror of about 16.6-cm aperture.

Determining the equivalent modern telescope to Dunlop's telescope is useful because it allows the limiting magnitude of the telescope to be determined, as this information is available for modern telescopes. The limiting apparent visual magnitude for stars for a modern 16.6-cm Newtonian (and for Dunlop's 23-cm telescope) is conservatively 13. Knowing the limiting magnitude of Dunlop's telescope, we can determine the completeness of his catalogue.

In his printed catalogue, Dunlop mentions using powers of 170× in his descriptions of D250 and D290 and he mentions a power of 260× for D389. These eyepieces would be approximately 16 mm and 10.5 mm focal length respectively since his telescope's focal length was 274 cm. In his handwritten notes there is evidence that his 'sweeping' eyepiece had a field of 45′. By comparison, Herschel used a 39 mm focal length eyepiece with a power of 157× and a field of view of 15′.

Dunlop was about 1.73m tall (Service, 1890: 207), so he must have used a ladder to climb up to the eyepiece when viewing objects located more than 35º or 40º above the horizon. He used candle light to record the time, the south polar distance and a description of each object seen as he swept back and forth across the southern sky.

Table 1: Reflectivity and magnitude limits for a 45% tin speculum mirror telescope.*

λ (nm)	d_s (cm)	pr_s (%)	pr_m (%)	d_m (cm)	m_v limit
450	23	61	86	16.3	13.1
650	23	65	88	16.8	13.2

* After 6 months

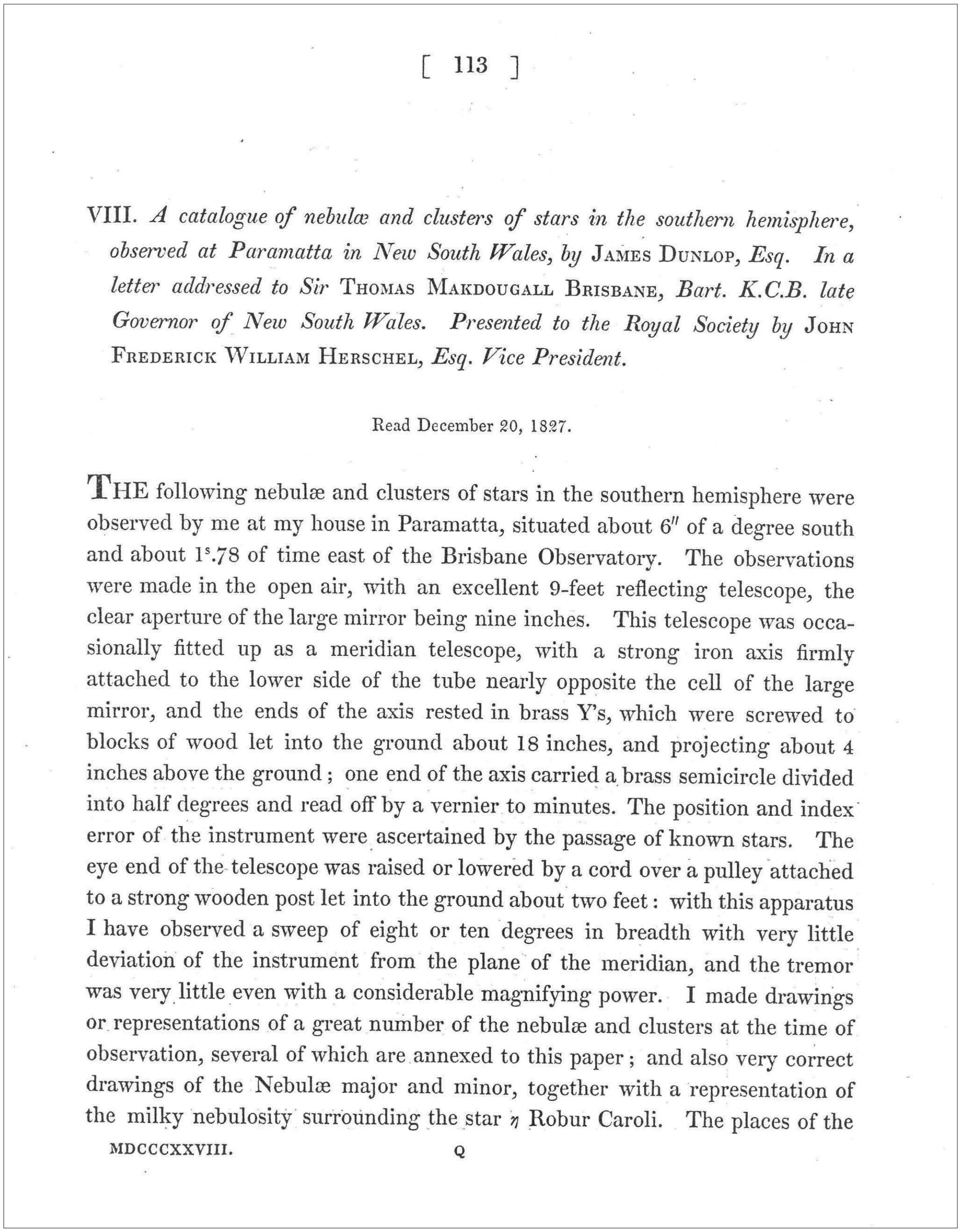
4 THE DUNLOP CATALOGUE

Dunlop's catalogue lists most of the bright non-stellar objects in the far southern sky, including the following distinctive types of objects:

Globular Clusters: NGC 104 (47 Tuc), 2808, 5139 (ω Cen), 6397, 6541 and 6752;
Nebulae: NGC 2070 (Tarantula), 3199, 3324, 3372 (η Car);
Open Clusters: NGC 2547, 3114, 3293, 3532, 4755 (κ Cru) and 6231;
Planetary Nebulae: NGC 2818A (in an open cluster), 5189, 6563; and
Galaxies: NGC 55, 300, 1291, 1313, 1316, 1553, 4945, 5128 (Cen A), 6744 and 7793.

Images and Dunlop's descriptions of globular clusters, galactic nebulae and galaxies can be seen on picasaweb (Cozens, 2009). The images are 28 × 28′ in size (except where the caption says 'wide'), with north at the top.

Two pages from the printed catalogue are shown in Figures 3 and 4. The objects in it were arranged by south polar distance (SPD) from declination –77° to –28°. Many entries in Dunlop's catalogue have not been positively identified, but it seems that no one has systematically worked through the whole catalogue to ascertain if more objects could be identified since Herschel identified 211 of these objects back in the 1830s. Using modern digital star atlases with accurate positions, and using Dunlop's original hand-written notes (available on microfilm) and other images, the first author has identified many new objects.



[113]

VIII. *A catalogue of nebulæ and clusters of stars in the southern hemisphere, observed at Paramatta in New South Wales, by* JAMES DUNLOP, *Esq. In a letter addressed to Sir* THOMAS MAKDOUGALL BRISBANE, *Bart. K.C.B. late Governor of New South Wales. Presented to the Royal Society by* JOHN FREDERICK WILLIAM HERSCHEL, *Esq. Vice President.*

Read December 20, 1827.

THE following nebulæ and clusters of stars in the southern hemisphere were observed by me at my house in Paramatta, situated about 6″ of a degree south and about $1^s.78$ of time east of the Brisbane Observatory. The observations were made in the open air, with an excellent 9-feet reflecting telescope, the clear aperture of the large mirror being nine inches. This telescope was occasionally fitted up as a meridian telescope, with a strong iron axis firmly attached to the lower side of the tube nearly opposite the cell of the large mirror, and the ends of the axis rested in brass Y's, which were screwed to blocks of wood let into the ground about 18 inches, and projecting about 4 inches above the ground; one end of the axis carried a brass semicircle divided into half degrees and read off by a vernier to minutes. The position and index error of the instrument were ascertained by the passage of known stars. The eye end of the telescope was raised or lowered by a cord over a pulley attached to a strong wooden post let into the ground about two feet: with this apparatus I have observed a sweep of eight or ten degrees in breadth with very little deviation of the instrument from the plane of the meridian, and the tremor was very little even with a considerable magnifying power. I made drawings or representations of a great number of the nebulæ and clusters at the time of observation, several of which are annexed to this paper; and also very correct drawings of the Nebulæ major and minor, together with a representation of the milky nebulosity surrounding the star η Robur Caroli. The places of the

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Figure 3: The Second page from Dunlop's catalogue of southern nebulae and clusters of stars.

These include 187 objects outside the Magellanic Clouds (78 open clusters, 34 globular clusters, 50 galaxies, 4 planetary nebulae, 3 nebulae, 12 asterisms and 4 other objects) and about 150 objects in the Large and Small Magellanic Clouds, giving a grand total of 335 objects. A further 37 objects in the catalogue were entered more than once, with two different coordinate positions. Table 2 lists the 187 objects; some objects are uncertain, and these are marked with an asterisk. The remaining objects seem to be faint double stars. Apparently Dunlop was unable to distinguish between small nebulae and faint (magnitude 11-13) double stars with his poor quality eyepieces. It is not possible to identify most of the double stars because in each instance there are generally several within 20′ of the Dunlop position.

114 MR. DUNLOP'S CATALOGUE OF NEBULÆ AND

small stars in the Nebulæ major and minor, and also those accompanying the η Robur Caroli, I ascertained by the mural circle in the year 1825, at which time I was preparing to commence a general survey of the southern hemisphere. These stars being laid down upon the chart, enabled me to delineate the nebulosity very accurately.

The nebulæ are arranged in the order of their south polar distances to the nearest minute for 1827, and in zones for each degree in the order of their right ascension. The column on the right hand shows the number of times the object has been observed.

The reductions and arrangement have been principally made since my return to Europe; and I trust this catalogue of the nebulæ will be found an acceptable addition to that knowledge which the Brisbane observatory has been the means of putting the world in possession of, respecting that important and hitherto but little known portion of the heavens.

No.	Æ h m s	S.P.D. ° '	Description of the Nebulæ and Stars.	No. of Obs.
1	4 13 0	12 14	A very small faint round nebula, about 12″ diameter, with a very minute star south following dist. 1′	1
2	0 33 6	15 41	A faint nebula, about 1½′ long, irregular figure, rather branched. This is involved in the margin of the Nebula minor	1
3	0 41 8	15 59	A small round nebula, about 12″ diameter	1
4	0 42 19	15 56	A faint round nebula, about 30″ diameter	1
5	0 47 12	15 46	A small faint nebula, about 10″ or 12″ diameter	1
6	0 47 39	15 36	A faint nebula, about 20″ diameter	1
7	1 9 32	15 46	A faint round nebula, 35″ diameter, with a small star near the south margin, but not involved	1
8	1 10 23	15 48	A small oval nebula, about 10″ diameter	1
9	1 12 37	15 44	A faint nebula, about 1½′ diameter, of an irregular round figure	2
10	1 13 43	15 51	An elliptical nebula, about 1′ long and 40″ broad, with three minute stars in it	1

Figure 4: The third page from Dunlop's catalogue of southern nebulae and clusters of stars.

The catalogue contains other problems, principally positional inaccuracies of 10-20′. Dunlop took just seven months to compile this catalogue, and he did not allow enough time to check it properly. By comparison, Messier took 24 years to make his catalogue of just 109 objects. Nonetheless, Dunlop's catalogue is very significant as it is the first catalogue of southern galaxies and of objects in the two Magellanic Clouds.

John Herschel failed to rediscover many of the objects in the Dunlop catalogue, including more than 20 open clusters, 2 globular clusters and 4 galaxies. This wealthy English amateur (see Chapman, 1993) spent 46 months assembling his catalogue, using a much larger and better-quality telescope. Although Herschel (1847) states that he searched diligently for objects in Dunlop's catalogue, these omissions suggest otherwise. Some Dunlop objects missed by Herschel are listed in Table 3.

The following are descriptions from the Dunlop catalogue of a sample of objects.

D16 in the SMC is now known as Lindsay 104. Dunlop wrote "A very faint nebula of a round figure, about 2′ diameter, with a small star in the north margin." Herschel missed this object.

D175 in the LMC is now identified as NGC 1929, 34, 35, 36 and 37. Dunlop wrote "A pretty large rather faint nebula, about 5′ diameter, irregular figure, partly resolvable into stars of mixt magnitudes. The nebulous matter has several seats of attraction, or rather it is a cluster of small nebulae with strong nebulosity common to all." Herschel listed five objects here; Dunlop saw several of them.

D271 is the open cluster Melotte 105. Dunlop wrote: "A rather bright nebula, about 2.5′ or 3′ long and 1′ broad, in the form of a crescent, the convex side preceding; no condensation of the nebulous matter towards any point. This is easily resolvable into many stars of some considerable magnitude, arranged in pretty regular lines, with the nebula remaining, which is also resolvable into extremely minute stars. This is probably two clusters in the same line, Figure 10." Herschel missed this open cluster. Figure 5 shows Dunlop's drawings, including Melotte 105 in Dunlop's Figure 10.

D332 is the nebula NGC 3199. Dunlop wrote "A very faint ray of nebula, about 2′ broad, and 6′ or 7′ long, joining two small stars at the south following extremity, which are very slightly involved, but their lustre is not diminished from that of similar small stars in the field. The north extremity also joins a group of small stars, but they are not involved. Figure 15." Figure 5 includes Dunlop's Figure 15. Dunlop's position was 1º north of the nebula but his description and diagram match. It would not have been easy for Dunlop to read the south polar distance scale with a candle while trying to maintain his night vision.

Table 3: Some Dunlop objects not catalogued by Herschel.

Dunlop	Current ID	Notes
D330	IC2488	Open cluster also in Lacaille's catalogue
D437	IC 1633	Galaxy
D281	IC 2714	Open cluster
D402	IC 4651	Open cluster
D255	IC 5250	Galaxy
D546	IC 5332	Galaxy probably seen by Dunlop
D611	NGC 5824	Globular cluster
D417	NGC 6352	Globular cluster
D608	NGC 7793	Galaxy
D391	Cr307	Open cluster
D224	Har 6	Open cluster
D244	Har 8	Open cluster
D258	Mel 101	Open cluster
D271	Mel 105	Open cluster
D430	Mrk 18	Open cluster
D372	Ru 78	Open cluster
D299	Ru 164	Open cluster
D308	Tr 13	Open cluster
D310	Tr 17	Open cluster
D358	Tr 23	Open cluster
D537	Tr 25	Open cluster

D417 is the globular cluster NGC 6352. Dunlop wrote "A rather faint nebula, of an irregular round figure, 4′ diameter, slightly branched; easily resolvable into stars, with slight compression of the stars to the centre." Herschel missed this object.

D480 is the magnitude 11.9 galaxy NGC 1487. Dunlop wrote "A very faint ill-defined nebula, with two or three very small stars in it, and a small star following." This is probably the faintest galaxy in Dunlop's catalogue, and the two nearby stars would have helped him see it.

D564 is the open cluster and planetary nebula NGC 2818/2818A. Dunlop wrote "A pretty large faint nebula of a round figure, 6′ or 8′ diameter; the nebulosity is faintly diffused to a considerable extent. There is a small nebula in the north preceding side, which is probably a condensation of the faint diffused nebulous matter; the large nebula is resolvable into stars with nebula remaining."

Table 2: Identified Dunlop objects, outside of the Magellanic Clouds.

Abbreviations used in this Table:

Dun #	Dunlop number
Name	The NGC number is generally given, unless otherwise indicated
IC	Index Catalogue
Lac, H, D	Lacaille, William Herschel, Dunlop repeat object
Type	The type of object
GC	Globular Cluster
OC	Open Cluster
PN	Planetary Nebula
Gxy	Galaxy
MW	Milky Way star cloud
Em Neb	Emission Nebula
m_v	Visual magnitude (where known)
Size	In ′ except PN which are in ″
RA and Dec	J2000 position from the ESO(B) catalogue and other sources, given in fractions of an hour or a degree
Offset	Distance from the correct position to Dunlop's position ′

Dun	Name (NGC/IC)	Notes	Type	Const	m_v	Size	RA 2000	Dec 2000	Offset (′)
1		GSC9368335, copy error	D*	Men	12.5	0.9	4.411	-77.33	60.1
18	104	47 Tuc	GC	Tuc	4.0	50.0	0.401	-72.07	1.1
62	362		GC	Tuc	6.8	12.9	1.054	-70.83	1.6
67	4372		GC	Mus	7.2	18.6	12.436	-72.70	25.4
68	6101		GC	Aps	9.2	10.7	16.430	-72.20	4.4

69	6777	Lac I.13	Ast	Pav	8.0	2.0	19.447	-71.50	2.1
164	4833		GC	Mus	6.9	13.5	12.993	-70.88	4.7
206	1313	D 205, D 207	Gxy	Ret	9.2	9.1	3.304	-66.48	3.9
224		Harvard 6	OC	Mus	10.7	5.0	12.633	-68.42	10.0
225	6362		GC	Ara	8.1	10.7	17.532	-67.03	11.0
244		Harvard 8	OC	Mus	9.5	4.0	13.300	-67.12	8.2
252	5189		PN	Mus	9.5	140"	13.559	-65.97	14.6
255	IC 5250		Gxy	Tuc	11.1	3.1	22.788	-65.05	3.5
258		Melotte 101	OC	Car	8.2	15.0	10.703	-65.10	27.1
262	6744		Gxy	Pav	8.8	20.0	19.163	-63.85	11.2
263	7083		Gxy	Ind	11.4	3.9	21.596	-63.90	18.7
264	1559		Gxy	Ret	10.7	3.5	4.294	-62.78	17.8
265	2808		GC	Car	6.2	13.8	9.201	-64.85	20.5
271		Melotte 105	OC	Car	9.0	5.0	11.328	-63.48	4.6
272	4609		OC	Cru	6.9	5.0	12.705	-62.98	8.7
273	5281		OC	Cen	5.9	8.0	13.777	-62.90	2.1
281	IC 2714		OC	Car	8.2	15.0	11.289	-62.72	6.3
282	5316		OC	Cen	6.0	13.0	13.899	-61.87	3.1
289	3766		OC	Cen	5.3	12.0	11.602	-61.62	10.2
290*		Rup 95	OC	Cen		5.0	9.727	-61.13	8.6
291	4103		OC	Cru	7.4	6.0	12.111	-61.25	11.6
292	4349		OC	Cru	7.4	15.0	12.403	-61.87	4.8
295	6752		GC	Pav	5.3	20.4	19.181	-59.98	10.3
296	1672		Gxy	Dor	10.2	6.6	4.762	-59.23	14.4
297	3114		OC	Car	4.2	35.0	10.042	-60.12	9.6
299		Rup 164	OC	Cen		2.0	11.514	-60.73	2.2
300	4439		OC	Cru	8.4	4.0	12.475	-60.10	7.5
301	4755	kappa Cru	OC	Cru	4.2	10.0	12.893	-60.33	4.6
302	5617		OC	Cen	6.3	10.0	14.496	-60.70	2.5
304	6025		OC	TrA	5.1	12.0	16.062	-60.50	5.9
306	1543		Gxy	Ret	10.3	4.9	4.212	-57.73	11.7
308*		Trump 13	OC	Car	11.3	5.0	10.397	-60.13	29.3
309	3372	eta Car	Em Neb	Car	3.5	120.0	10.730	-56.98	11.0
310		Trump 17	OC	Car	8.9	5.0	10.940	-59.20	18.6
311	4852		OC	Cen	8.9	11.0	13.004	-59.62	7.3
312	5138	copy error	OC	Cen	7.6	7.0	13.455	-59.02	15.7
313	5606		OC	Cen	7.7	3.0	14.463	-59.62	10.6
314		Lac III.9	Ast	Cir	8.1	2.3	15.377	-59.20	1.3
315		5 stars	Ast	Nor		1.6	15.550	-58.67	18.4
316		arc of stars	Ast	Ara		4.0	16.733	-58.60	0.8
319		kite shaped asterism	Ast	Tuc		2.0	22.321	-57.13	2.9
321	3293		OC	Car	4.7	6.0	10.597	-58.23	16.7
322	3324		Em Neb	Car		5.0	10.623	-58.62	5.1
323	3532		OC	Car	3.0	55.0	11.107	-64.40	7.2
324		Lac II.11, line of 7 stars	OC	Car		55.0	11.383	-58.32	15.0
326	6087	D 335	OC	Nor	5.4	12.0	16.314	-57.93	7.3
329		Lac III.14	Ast	Ind	8.4	4.4	21.518	-56.92	5.1
330	IC 2488		OC	Vel	7.4	18.0	9.460	-56.98	2.1
331	1553	Copy error	Gxy	Dor	9.4	4.5	4.270	-55.78	503.0
332	3199	1 deg error in dec	Em Neb	Car		22.0	10.290	-57.92	60.6
333	5715		OC	Cir	9.8	5.0	14.725	-57.57	9.4
334	6005		OC	Nor	10.7	3.0	15.930	-57.43	15.6

337	1261		GC	Hor	8.3	6.9	3.204	-55.20	4.6
338	1566		Gxy	Dor	9.8	7.0	4.333	-54.93	10.9
339	1617		Gxy	Dor	10.7	4.3	4.528	-54.60	11.4
342	5662		OC	Cen	5.5	30.0	14.587	-56.55	9.0
343	5999		OC	Nor	9.0	3.0	15.869	-56.47	8.8
347*	7689		Gxy	Phe	11.7	2.9	23.554	-54.08	17.9
348	1515		Gxy	Dor	11.4	5.2	4.068	-54.10	11.6
349	3960		OC	Cen	8.3	6.0	11.843	-55.67	5.4
350		curve of stars	Ast	Lup		2.7	14.550	-55.10	10.7
351	5823		OC	Cir	7.9	12.0	15.092	-55.60	7.9
355	3330		OC	Vel	7.4	6.0	10.646	-54.12	6.2
356	5749		OC	Lup	8.8	7.0	14.815	-54.48	7.7
357	5593	copy error	OC	Lup		7.0	14.428	-54.78	20.1
358		Trump 23	OC	Nor	11.2	9.0	16.013	-53.53	3.6
359	6031		OC	Nor	8.5	2.0	16.126	-54.00	6.2
360	6067	D 361	OC	Nor	5.6	12.0	16.220	-54.22	1.8
362*		Norma star cloud	MW	Nor		180.0	16.350	-53.12	45.8
364	6208		OC	Ara	7.2	15.0	16.824	-53.72	8.2
366	6397		GC	Ara	5.3	25.7	17.678	-53.67	5.7
367		bunch of stars	Ast	Tel		2.2	18.994	-53.68	7.4
374	6253		OC	Ara	10.2	5.0	16.985	-52.70	8.7
376	6584		GC	Tel	7.9	7.9	18.311	-52.22	5.9
379	6115		OC	Nor	9.8	3.4	16.407	-51.93	4.8
380		Rup 119	OC	Nor	8.8	8.0	16.471	-51.50	10.9
381*	6326		PN	Ara	11.1	15"	17.346	-51.75	27.7
386	3228		OC	Vel	6.0	5.0	10.363	-51.72	7.0
388	5286		GC	Cen	7.4	9.1	13.774	-51.37	4.9
389	5927		GC	Lup	8.0	6.0	15.467	-50.67	10.5
391		D 392, Cr 307	OC	Ara	9.7	5.0	16.589	-51.00	5.5
397	2972	NGC 2999	OC	Vel	9.9	4.0	9.671	-50.32	6.9
400	6167	D 401	OC	Nor	6.7	7.0	16.576	-49.77	13.9
402	IC 4651		OC	Ara	6.9	10.0	17.414	-49.93	4.6
406	7049		Gxy	Ind	10.6	4.2	21.317	-48.55	4.8
409	1527	D 429*	Gxy	Hor	11.0	3.7	4.140	-47.88	10.1
410	2547		OC	Vel	4.7	20.0	8.178	-49.27	12.0
411	4945		Gxy	Cen	8.9	20.0	13.091	-49.47	3.4
412	6134		OC	Nor	7.2	6.0	16.463	-49.15	6.1
413	6193	also saw NGC 6200	OC	Ara	5.2	14.0	16.689	-48.75	6.6
417	6352		GC	Ara	7.8	7.1	17.425	-48.42	17.3
425*	6861	1 deg dec copy error	Gxy	Tel	11.2	2.8	20.122	-48.37	63.4
426	1433		Gxy	Hor	10.1	6.5	3.700	-47.22	18.2
430		Mrk 18, Cr 205	OC	Vel	7.8	2.0	9.009	-48.98	21.7
431	5460		OC	Cen	5.6	35.0	14.124	-48.33	6.2
437	IC 1633		Gxy	Phe	11.4	2.6	1.165	-45.92	6.3
438	1493		Gxy	Hor	11.4	3.5	3.958	-46.20	1.1
440	5139	omega Cen	GC	Cen	3.7	36.3	13.447	-47.48	4.3
442	6204		OC	Ara	8.2	5.0	16.769	-47.02	16.1
445	3201		GC	Vel	6.9	18.0	10.294	-46.40	12.6
454	6216	NGC 6222	OC	Sco	10.1	4.0	16.824	-44.72	6.0
455*		Ly 14 or NGC 6249	OC	Sco	9.7	3.0	16.918	-45.23	22.4
456	6259		OC	Sco	8.0	10.0	17.013	-44.65	10.9
457	6388		GC	Sco	6.8	8.7	17.605	-44.73	1.5

458		line of stars	Ast	Sco		15.0	17.726	-44.10	9.5
460	6496		GC	Sco	8.6	6.9	17.984	-44.27	12.7
466	1512		Gxy	Hor	10.6	8.9	4.065	-43.35	11.0
468	2982	Ru 80	OC	Vel		12.0	9.700	-44.02	8.4
469	5643		Gxy	Lup	10.5	4.6	14.545	-44.17	7.8
473	6541		GC	CrA	6.3	13.0	18.134	-43.70	5.0
475	7552	Grus-Quartet	Gxy	Gru	10.7	3.4	23.270	-42.58	6.9
476	7582	Grus-Quartet	Gxy	Gru	10.6	5.0	23.306	-42.37	24.7
477	7590	Grus-Quartet	Gxy	Gru	11.6	2.7	23.315	-42.23	37.0
477	7599	Grus-Quartet	Gxy	Gru	11.4	4.4	23.323	-42.26	37.0
480	1487	Faintest galaxy	Gxy	Eri	11.9	2.0	3.930	-42.37	15.4
481	3680		OC	Cen	7.6	12.0	11.428	-43.23	10.4
482	5128		Gxy	Cen	6.8	25.7	13.425	-43.02	10.8
483	6192	D 470	OC	Sco	8.5	7.0	16.673	-43.37	3.8
487	1291	NGC 1269	Gxy	Eri	8.6	9.8	3.288	-41.11	4.5
489	2671		OC	Vel	11.6	4.0	8.770	-41.87	3.0
490		Tr 10, copy error	OC	Vel	4.6	15.0	8.777	-42.57	20.7
499	6231		OC	Sco	2.6	15.0	16.900	-41.80	3.7
507	55		Gxy	Scl	8.3	32.4	0.252	-39.22	5.4
508	1851		GC	Col	7.1	11.0	5.235	-40.03	15.8
509		stars in an F shape	Ast	Cen		29.0	12.400	-41.22	13.3
510	4696	D511 = NGC 4709?	Gxy	Cen	10.5	4.5	12.814	-41.30	13.7
514	6124		OC	Sco	5.8	40.0	16.427	-40.67	1.4
518	7410		Gxy	Gru	10.6	5.5	22.917	-39.65	11.7
519	986		Gxy	For	11.0	3.9	2.559	-39.03	9.8
520	6242		OC	Sco	6.4	9.0	16.927	-39.50	4.2
521	6268		OC	Sco	9.5	6.0	17.036	-39.72	2.5
522	6318		OC	Sco	11.8	5.0	17.270	-39.42	18.6
530	300		Gxy	Scl	8.3	21.9	0.915	-37.67	8.7
531	1792		Gxy	Col	10.2	5.2	5.088	-37.97	14.9
535	2477		OC	Pup	5.8	27.0	7.872	-38.55	11.5
536	6139		GC	Sco	9.1	5.5	16.461	-38.85	23.6
537		Tr 25	OC	Sco	11.7	8.0	17.408	-39.02	12.8
545		stars in a T shape	Ast	Gru		12.0	22.700	-38.10	116.4
546*	IC 5332	1 deg error in dec	Gxy	Scl	10.4	8.9	23.574	-36.10	71.3
547	1317		Gxy	For	11.2	2.8	3.379	-37.10	15.7
548	1316		Gxy	For	8.5	12.0	3.378	-37.20	20.1
549	1808	D 532	Gxy	Col	10.0	6.5	5.129	-37.50	9.0
552	5986		GC	Lup	7.6	9.8	15.768	-37.78	5.2
556	6281	D555 is 32' in pa252	OC	Sco	5.4	8.0	17.078	-37.98	5.6
557	6441		GC	Sco	7.2	7.8	17.837	-37.05	2.7
559		Bernes 157	Dark neb	CrA		80.0	19.050	-37.15	40.6
562	1365	copy error	Gxy	For	9.6	11.2	3.560	-36.13	128.9
563	2546		OC	Pup	6.3	41.0	8.207	-37.63	16.1
564	2818	Data is for PN	OC & PN	Pyx	11.6	35"	9.269	-36.62	17.2
568	6400		OC	Sco	8.8	12.0	17.670	-36.93	4.6
573	6723		GC	Sgr	6.8	11.0	18.993	-36.62	17.2
574	1380		Gxy	For	10.2	4.8	3.608	-34.97	19.6
578	2298		GC	Pup	9.3	6.8	6.816	-36.00	5.7
590	134	D 599	Gxy	Scl	10.5	8.5	0.506	-33.23	18.3
591	1350		Gxy	For	10.7	5.2	3.519	-33.62	15.0
594	2090		Gxy	Col	11.3	4.9	5.784	-34.25	3.3

597*	6444		OC	Sco		12.0	17.826	-34.82	26.1
600	1532		Gxy	Eri	10.6	11.1	4.201	-32.87	7.5
604		5 stars	Ast	Sco		2.5	16.883	-33.65	16.6
605		Star cloud and Dark nebula B283	MW & Dark nebula	Sco		85.0	17.817	-33.87	95.9
606*	6563		PN	Sgr	10.8	54"	18.201	-33.87	36.5
607	6652		GC	Sgr	8.5	3.5	18.596	-32.98	34.0
608	7793		Gxy	Scl	9.2	9.3	23.964	-32.58	14.5
609	2658		OC	Pyx	9.2	12.0	8.724	-32.65	3.3
611	5824		GC	Lup	9.1	6.2	15.066	-33.07	27.9
612*	6405	M6 or NGC 6416	OC	Sco	4.2	25.0	17.668	-32.22	13.6
613	6637	M 69, not Lac I.11	GC	Sgr	7.6	7.1	18.523	-32.33	27.2
614	6681	M70	GC	Sgr	7.8	7.8	18.720	-32.28	19.6
616	2243		OC	CMa	9.4	5.0	6.493	-31.28	33.4
617	3621	H I 241, D 610	Gxy	Hya	9.2	12.3	11.305	-32.80	9.4
619	6569	H II 201	GC	Sgr	8.4	5.8	18.227	-31.82	14.8
620	6809	M55	GC	Sgr	6.3	19.0	19.667	-30.95	25.7
621	613	H I 281	Gxy	Scl	10.1	5.5	1.572	-29.42	37.0
622	2997	H V 50	Gxy	Ant	9.6	8.9	9.761	-31.18	14.7
623	5253	H II 638	Gxy	Cen	10.7	5.0	13.666	-31.63	2.5
624	6715	M54	GC	Sgr	7.7	9.1	18.918	-30.47	28.9
626	2489	H VII 23	OC	Pup	7.9	8.0	7.938	-30.05	30.3
627	6266	M62	GC	Oph	6.4	14.0	17.020	-30.10	11.1
628	5236	M83, copy error	Gxy	Hya	7.6	11.0	13.617	-29.87	159.8
629	6316	H I 45	GC	Oph	8.1	4.9	17.277	-28.13	37.1

5 ASTROMETRY

The first consideration in analysing the Dunlop catalogue was the discrepancies in the positions given for the identified objects. In the printed catalogue the Right Ascension and Declination of each object was given in 1827 coordinates. Before analysis these coordinates were converted to J2000. Analysis was carried out at equinox J2000 after precession to that date using the Starlink precession program COCO. No allowance for proper motion was made. The J2000 positions were then compared to accurate coordinates obtained from the ESO (B) catalogue (Lauberts, 1982), where coordinates are given for both B1950 and J2000. The offsets between the Dunlop position and the position given in the ESO (B) catalogue were calculated, in the sense ESO (B) minus Dunlop.

General trends become obvious when all objects are considered. Figure 6 plots the difference in Right Ascension against the difference in Declination. It shows that Dunlop's offsets in Right Ascension (0-30′) are generally worse than his offsets in Declination (0-20′) and that his positions are more likely to be negative in Right Ascension and positive in Declination.

Table 4: Some copy errors in Dunlop's published catalogue.

Dunlop Number	Position in Notes	Published Catalogue	Object ID
1	RA 04h 30m 00s	04h 13m 00s	60' offset
44	RA 01h 06m 02s	01h 06m 22s	N419
45	RA 01h 07m 15s	01h 07m 50s	
275	RA 14h 48m 10s	14h 18m 10s	
312	SPD 31° 58′	31° 38′	N5138
331	RA 04h 12m 30s	05h 12m 30s	N1553
357	RA 14h 50m	14h 15m	N5593
425	SPD 41° 12′	42° 12′	N6861
491	RA 09h 27m 16s	09h 07m 16s	
525	RA 18h 50m 30s	17h 50m 30s	
562	RA 03h 27m 39s	03h 37m 39s	N1365
628	RA 13h 28m 03s	13h 15m 03s	M 83

There are a number of explanations for such large positional offsets including: misidentification of a reference star during one sweep of the Large Magellanic Cloud; copying errors from his hand-written notes to the printed catalogue; and in a few cases errors of 1° in reading or recording the South Polar Distance. Some examples of copying errors are given in Table 4.

6 MAGNITUDE LIMITS

Like all early catalogues, Dunlop's catalogue does not include all objects that were bright enough to be visible to him. Nebulae and clusters are more difficult to see than stars of the same magnitude because they are larger and more diffuse. This means that the theoretical limiting magnitude calculated in Table 1 as 13.1 for stars does not apply for other types of objects.

Instead, to determine which objects he missed, a working magnitude limit was ascertained and a list of bright objects which were missed was compiled. To estimate the working magnitude limit, the magnitudes of identified objects were obtained from a modern catalogue specific to a particular type of object. Open clusters, globular clusters, nebulae and planetary nebulae were found to be unsuitable for finding the working magnitude limit of Dunlop's telescope. This is because open clusters vary greatly in size and detachment; there is a lack of globular clusters faint enough to test his magnitude limit; only a few diffuse nebulae have known magnitudes; and planetary nebulae are often very small and easily missed. Galaxies,

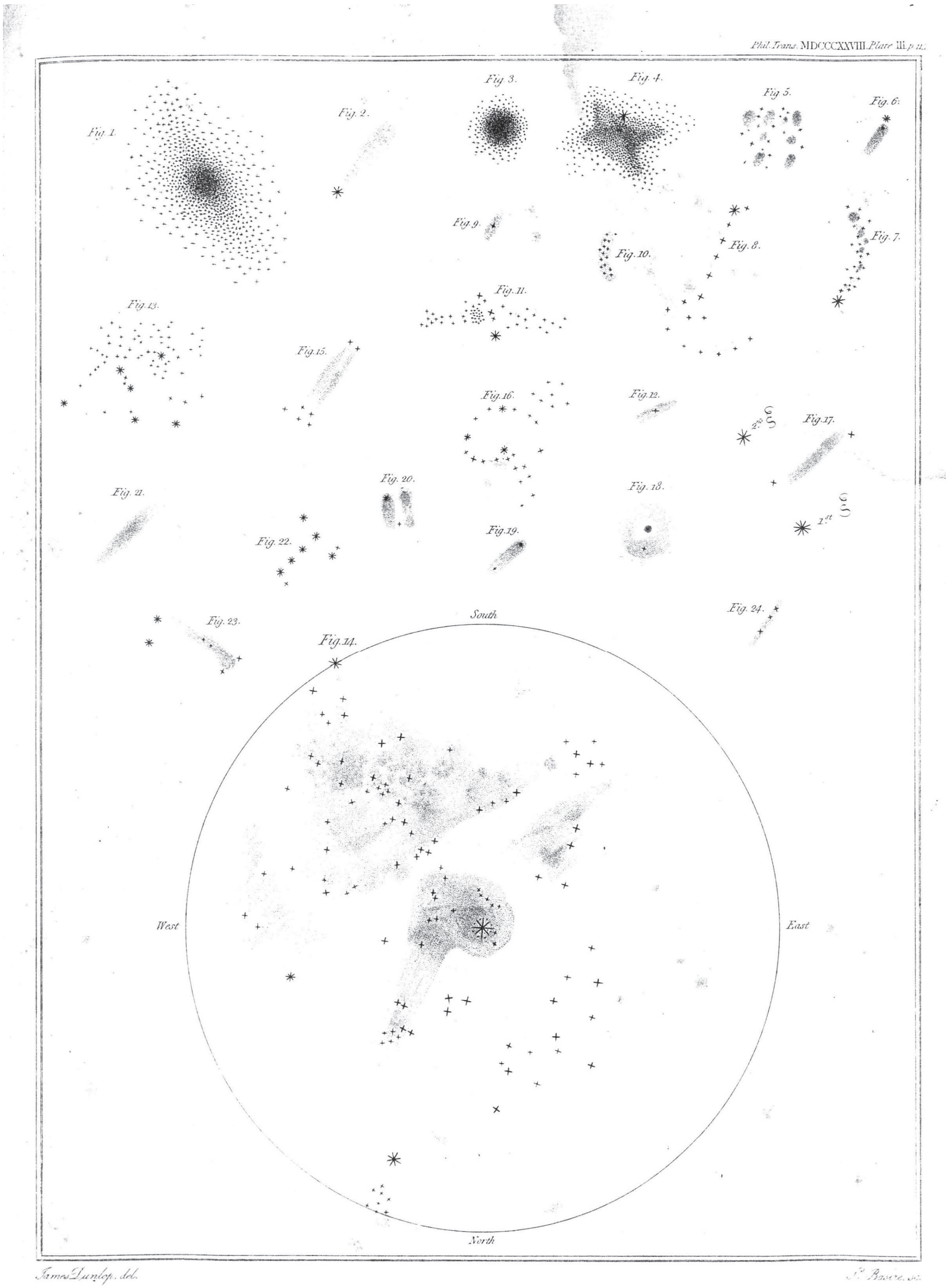

Figure 5: Dunlop's drawings of some of the objects he found.

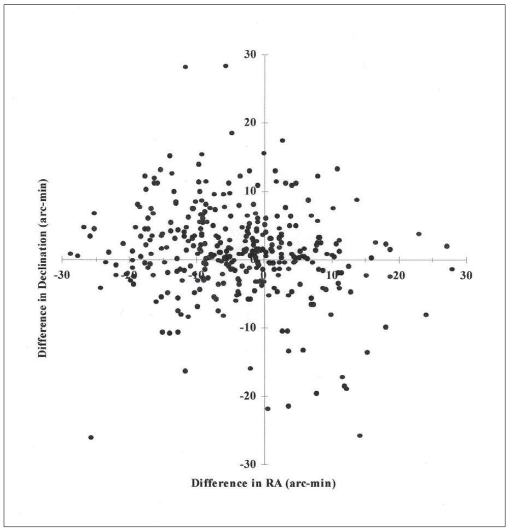

Figure 6: The difference in right ascension versus the difference in declination for identified objects in the Dunlop Catalogue (in the sense ESO – Dunlop).

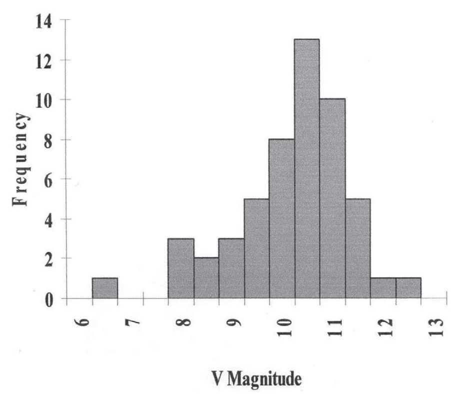

Figure 7: Histogram of the number of galaxies by half magnitude in the Dunlop catalogue.

however, do not have these limitations. Instead, the number of galaxies increases exponentially at fainter magnitudes. Dunlop's galaxies were compared with those in the LEDA galaxy catalogue (Paturel et al., 2003). Visual magnitudes were calculated using the total B magnitude (bt) minus the effective B–V colour (bve) or minus the total B–V colour (bvt), depending upon which values were given in the LEDA catalogue.

A number of different indicators were then used to determine Dunlop's working magnitude limit. These included comparisons using the following:

Table 5: Number of Dunlop objects brighter and fainter than magnitude 10.9 by type.

		Globular Clusters	Planetary Nebulae	Galaxies
Dunlop	Bright Objects Missed	5 (12%)	10 (71%)	46 (46%)
	Faint Objects Seen	0	2	14

- histograms of the number of Dunlop galaxies and LEDA galaxies, at half-magnitude increments (Figure 7)
- the log of the cumulative frequency of Dunlop galaxies with upper and lower Poisson limits
- the log of the cumulative frequency of Dunlop galaxies and LEDA galaxies (Figure 8)
- the log of the cumulative frequency of Dunlop galaxies and a line of 0.6 gradient (Figure 8), representing the increase in density that would occur in a homogeneous Universe with a homogenous mixture of galaxy types, and
- the magnitude at which Dunlop catalogued 50% and missed 50% of the LEDA galaxies.

Using the mean obtained from each method it was found that the working magnitude limit for the Dunlop catalogue was $m_v = 10.9$.

7 COMPLETENESS

With the working magnitude limit determined at 10.9, a list of bright objects missed by Dunlop was compiled. These objects could have been seen by Dunlop and included in his catalogue. A list of objects fainter than the working magnitude limit which were seen and catalogued by Dunlop was also compiled. The result of this analysis is summarised in Table 5.

Dunlop found most of the southern globular clusters, cataloguing 88% of those brighter than magnitude 10.9. None fainter than this was seen by him. Dunlop also catalogued 4 out of 14 (29%) planetary nebulae brighter than magnitude 10.9, and larger than 12″ according to the Strasbourg-ESO catalogue (Acker, et al., 1992).

Fifty-four percent of the galaxies brighter than 10.9 were seen by Dunlop and 46% were missed. The faintest galaxy in Dunlop's catalogue is NGC 1483, at magnitude 12.3, but it is unlikely that he actually saw this. Herschel (1847) wrote the following about this object:

> … very faint; pretty large; round; very gradually a little brighter in the middle; 80″ across. I feel convinced that this nebula is too faint to have been seen by Mr Dunlop. Put on the 9 inch aperture, could not discern the least trace of it. Mirror polished yesterday and in high beauty. Sky superb.

The second-faintest object in the Dunlop catalogue is the magnitude 11.4 galaxy IC 1633. His description for this (D437) is: "An extremely faint small nebula; round, with a very minute bright point in the centre." His position offset is only 5.5′ to the south-west. This galaxy has a bright core and Dunlop probably saw it.

Table 6 lists the four brightest globular clusters, planetary nebulae and galaxies missed by Dunlop. Suggested reasons for their omission are: NGC 1097 at declination +30°) was near his northern declination limit; NGC 5102 is near a bright star (magnitude 2.7); and it is just possible that the elliptical galaxies NGC 1399 and NGC 1549 were mistaken for stars because of dew on the optics of Dunlop's telescope.

The open cluster NGC 2516 is included in Dunlop's notes but does not appear in the printed catalogue. The galaxy NGC 253 is not in his catalogue because it is north of his declination limit. The planetary nebula NGC 5882 does not match Dunlop's description of D447. D567 is an asterism (see Table 7), not the

Table 6: The four brightest globular clusters, planetary nebulae and galaxies missed by Dunlop.

Globular Cluster		Planetary Nebula		Galaxy	
Name	Magnitude	Name	Magnitude	Name	Magnitude
NGC 6558	9.3	NGC 6302	9.7	NGC 1097	9.5
NGC 6528	9.6	IC 4406	10.2	NGC 1399	9.6
IC 4499	9.8	NGC 6153	10.6	NGC 5102	9.7
NGC 6453	10.1	NGC 3211	10.7	NGC 1549	9.8

planetary nebula NGC 6302, as suggested by Hartung (see Malin and Frew, 1995). The planetary nebulae NGC 3132 and NGC 3918 are in the Brisbane star catalogue (Richardson, 1835) but are not in Dunlop's catalogue of nebulae and clusters.

Analysis of Dunlop's catalogue shows that he produced a remarkably-complete catalogue in a very short time.

8 CONCLUDING REMARKS

Dunlop's catalogue contains most of the bright star clusters, nebulae and galaxies south of declination –30°, and therefore is the southern equivalent of Messier's famous northern catalogue, as suggested by Cozens and White in the June 2001 edition of *Sky and Telescope*. It unfortunately also contains a large number of entries which are probably faint double stars or asterisms, because Dunlop was unable to resolve them.

Omitting the double stars and asterisms gives rise to an impressive catalogue. We therefore believe that the Dunlop catalogue should be a useful resource for southern amateur astronomers viewing galaxies, nebulae and clusters. Table 2 lists 187 identified objects outside of the Magellanic Clouds. Objects in the Magellanic Clouds are not included as they require more detailed descriptions, which goes beyond the scope of this paper.

John Herschel failed to recover many of Dunlop's objects, but his criticisms did not take into account the limitations imposed by Dunlop's home-made equipment. Neither was the continued criticism of Dunlop by Forbes and others completely justified. James Dunlop was not a careless astronomer. He did his best with the resources he had at his disposal, and ended up producing a valuable catalogue. Yet he is virtually unknown today, a forgotten pioneer of the southern sky.

9 NOTES

1. As Saunders (2004: 208, Note 115) has pointed out, J. Service, who was one of Dunlop's biographers, was far from amused by these scurrilous attacks on his illustrious relative, quoting Henry Chamberlain Russell's views that:

   > There are a good many very stupid mistakes in Herschel's own Catalogue, he need not have been so hard on others. The effort in those days seems to have been to get through a fearful lot of work without too much regard for quality, but times have changed since then. (Service, 1890: 177).

   Russell could speak with some authority, for at that time he was Director of the Sydney Observatory and one of Australia's foremost astronomers (e.g. see Bhathal, 1991; Orchiston, 2002).
2. For details of the various instruments at the Parramatta Observatory see Lomb (2004).
3. In his biography of Dunlop, Jervis (1926: 44) incorrectly states that at this time Dunlop "... was officially appointed Astronomer Royal of New South Wales."
4. By way of comparison, Riekher (1957) gives the reflectivity of speculum at 555 nm as 60%, which produces a modern equivalent aperture of 15.8-cm for Dunlop's telescope. This is consistent with the values listed in Table 1

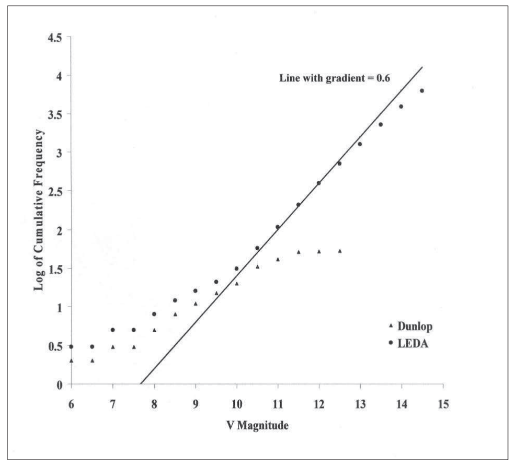

Figure 8: Distribution of log of the cumulative frequency as a function of V magnitude for the Dunlop and LEDA galaxies.

10 ACKNOWLEDGEMENTS

We are grateful to Dr David Frew (Macquarie University, Sydney) for reading and commenting on the manuscript, while the first author also wishes to thank his wife, Julie, for her secretarial help, and Dr Graeme White, who initially supervised this thesis project .

Table 7: A sample of asterisms found by Dunlop.

Dunlop Number	Description	Constellation	Size (')	RA 2000	Dec 2000
509	stars in an F shape	Cen	29.0	12.400	-41.22
350	curve of stars	Lup	2.7	14.550	-55.10
315	5 stars	Nor	1.6	15.550	-58.67
316	arc of stars	Ara	4.0	16.733	-58.60
604	5 stars	Sco	2.5	16.883	-33.65
458	line of stars	Sco	8.0	17.726	-44.10
367	bunch of stars	Tel	2.2	18.994	-53.68
319	kite-shaped asterism	Tuc	2.0	22.321	-57.13
545	stars in a T shape	Gru	12.0	22.700	-38.10

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THE ASTRONOMICAL SIGNIFICANCE OF MEGALITHIC STONE ALIGNMENTS AT VIBHUTHIHALLI IN NORTHERN KARNATAKA

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Abstract: A megalithic site at Vibhuthihalli in Karnataka, India, contains alignments of stones that are arranged in a square pattern with rows and columns showing a diagonal arrangement. Such structures are non-sepulchral, and although their purpose is not clear it has been suggested that they have astronomical significance. We investigated this possibility and our observations showed that the rows of stones point to the direction of equinoctial sunrise and sunset. It is likely that calendrical events were monitored at this site.

Keywords: Megalithic astronomy, stone alignments, equinoxes, solstices

1 INTRODUCTION

Observing and recording the positions of the Sun, the Moon and the stars as objects of wonder and realizing that their movements are repetitive was a major step in the intellectual growth of ancient man. In tracing the history of observational astronomy in India, it is of interest to see how prehistoric people became aware of the passage of time, such as the seasons, the year, the month, etc. Knowledge of the changing seasons was crucial for pastoral societies.

What kind of 'tools' did ancient people use in tracing the movements of celestial objects? In this context it is appropriate to study megaliths, which are the earliest existing structures erected by the prehistoric Indians, with a view to establishing whether they may have been used for astronomical (or calendrical) purposes. However, many megaliths were associated with rituals relating to human burials, where the astronomical requirements may have been compromised or combined with religious rites. It therefore would be preferable to seek out non-sepulchral megalithic structures that seem to exhibit astronomical characteristics.[1]

In 1956 F. Raymond Allchin published an important paper in which he identified forty non-sepulchral megalithic alignments that according to him were oriented to cardinal directions. These sites, and a few additional sites added later by K. Paddayya and others, are all restricted to a limited geographical region within the districts of Raichur, Gulburga in Karnataka and Mahabubnagar and Nalgonda in Andhra Pradesh, in what used to be known as southern Hyderabad (see Figure 1).

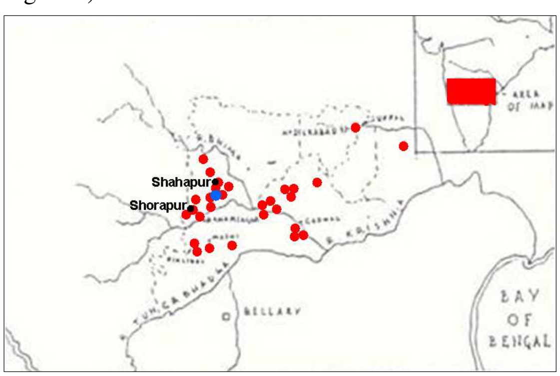

Figure 1: The geographical distribution of non-sepulchral stone alignments in Southern India (adapted from Allchin, 1956). The Vibhuthihalli site is marked by the blue dot.

These alignments consist of parallel lines of standing stones which are spaced at regular intervals. Most of the stones are between 0.91m (3ft) and 1.83m (6ft) in height, although in one case (at Mudumala, in the Mahbubnagar district of Andhra Pradesh), the stones are 4.3-4.9m (14-16ft) high. The diameters of the individual stones were found to vary between 0.61m (2ft) and 1.23m (4ft). The stones are generally of granite, gneiss or dolerite. In Kannada these structures were known as *Salgal* (rows of stones), and *Niluvurallu* (standing stones) or *Enugurallu* (elephant stones) in Telugu. None of the stones shows evidence of having been quarried or dressed.

Allchin (1956) identified two different types of stone arrangements, which he termed 'square' and 'diagonal'. In the square alignments the stones are laid out like a checker board (Figure 2). Mostly the smaller alignments are of this type, with 3 × 3 rows of stones, 4 × 4, 5 × 5, and so on. Meanwhile, the diagonal alignments consist of one more stone in the centre of the squares formed from a sets of four rows of stones (from odd numbered rows), as shown by the example in Figure 2. The effect is to stress the diagonal lines. Diagonal alignments always contain larger numbers of stones than square alignments.

Our limited survey of the sites mentioned by Allchin revealed that many of the smaller alignments have disappeared, and some of the larger alignments have also been affected or are in the process of disruption (such as those at Hanamsagar and Karnataka).

The purpose of these non-sepulchral megalithic alignments is unknown,[2] but Allchin (ibid.) suggests that "It may well be that sunrise was employed as it is in some Buddhist countries to orient religious structures … [and] the problem merits further study." This prompted us to take up the challenge, and in this paper we report on our investigation of the stone alignments in Vibhuthihalli, which are in a better state of preservation than many of the other extant sites of this kind.

2 THE VIBHUTHIHALLI STONE ALIGNMENTS

2.1 Location and Archaeological Setting

The Vibhuthihalli stone alignments are located at latitude 16° 39′ 53″ N and longitude 76° 51′ 29″ E, and lie 4km south of Shahapur at the foot of the Shahapur hill range in Yadgir district of Karnataka (see Figure 1). They begin ~20m north of Vibhuthihalli village, and lie on the east side of the Shorapur-Shahapur main road. This locality is part of Shorapur Doab, in the semi-arid Deccan zone. About 20km east of Shahapur is the Bhima River.

Several Neolithic and megalithic sites and monuments exist within a 10km radius of the Vibhuthihalli alignments (Sundara, 1975). The Benkanahalli ash-mound discovered by Mukherjee (1941) is about half a kilometer away to the north, and Paddayya (1973) found a small number of potsherds and artifacts of the blade industry in the surrounding fields. Neolithic habitation sites at Kannekolur are about 4.5km away. An ashmound with a disrupted stone alignment on top of it was discovered by Paddayya at Shakapur, and is about 10km to the north.

The stone alignments are not the only signs of prehistoric occupation at Vibhuthihalli, for Sundara (1975) has reported the existence of a megalithic habitation site on the other side of the Shorapur-Shahapur main road opposite the alignments "… and within a distance of about 500m." Thus, the Vibhuthihalli alignment site is situated in an environment where Neolithic communities practised pastoralism and possibly some agriculture as well, and we suggest that it was constructed some time between 1800 and 1400 BC (see Section 5.3 below). The name 'Vibhuthi' refers to ash from cow dung—so 'Vibhuthihalli' literally means 'village of ash'. The association of stone-cists or stone circles in the vicinity of the alignments has been pointed out by Allchin (1956).

2.2 The Discovery and Later Descriptions of the Stone Alignments

The first published account of the Vibhuthihalli stone alignments was by Colonel Meadows Taylor (1852), and was followed by descriptions by Walhouse (1878) and Mukherjee (1941). In a colorful paper titled "Notices of cromlechs, cairns and other ancient Scytho-Druidical remains in the principality of Shorapur", Taylor gives the following detailed description of the site.

> I presume it to have been ground regularly marked out for a cemetery of cairns, and the labour bestowed upon it has been enormous. The ground has been marked out in parallel or diagonal lines, leaving a square of from eighteen [5.5m] to twenty-four feet [7.3m] between each four points, which would be enough for an ordinary cairn; the points of squares and the lines being formed of large granite rocks, which have evidently been rolled down the neighboring hills, and placed in the situation they now occupy - but at what expense of labour, and with what patience!

Taylor found that the

> … sides of the square, as it very nearly is, gave twenty rocks west, by twenty south, if the whole were complete ... but a portion of the north east corner and north side has not been completed … [On average, the rocks are] … not less than six [1.85m] to seven feet [2.1m] long by three [0.91m] to four [1.22m] thick or high, and very many are at least half as large again.

Taylor's paper (ibid.) also included a 'scaled' plan, which we reproduce here as Figure 3. He gives the dimensions of the site as 360ft (109.7m) from east to west and 340ft (103.6mm) from north to south.

The Annual Report of Hyderabad Archaeological Department for 1940-1941 (Ahmad, 1941) includes a 1940 photograph of the site which we reproduce on page 76 as Figure 4. The report (ibid.) also states that:

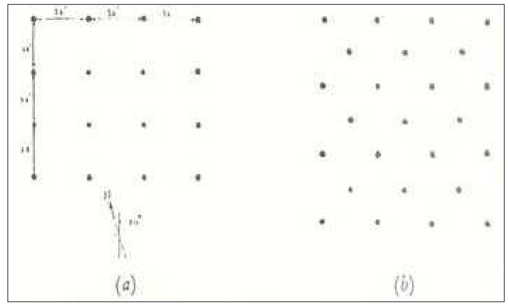

Figure 2: Idealized plans of the (a) square and (b) diagonal types of stone alignments (after Allchin, 1956).

> … steps have been taken to mark the boundaries of this site. Obelisk shaped pillars have been now set up, one at each corner of the field and a permanent notice board has been put up to mark the field [which] has been protected under the Ancient Monuments Act.

At about the same time Mukherjee (1941) published an interesting but rather inaccurate account of the site:

> … a group of stone alignments ... on a plot of land about 300 yards square ... are found to occur in parallel rows, lying at about 10 yards [9.1m] apart from each other. Some boulders lie singly and others in groups arranged in ellipses or circles ... Many stone circles are seen lying along these rows of single boulders. From the large number of boulders crowded in one place, it is suggested that the group would mark the site of a prehistoric grave yard and each of these boulders, the grave of a prehistoric man.

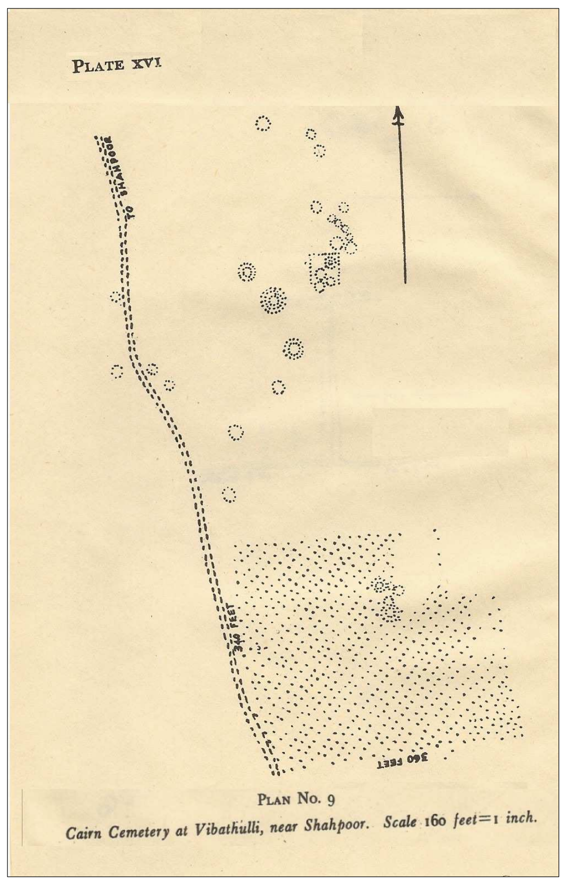

Figure 3: The layout of the Vibhuthihalli stone alignments according to Taylor (1852).

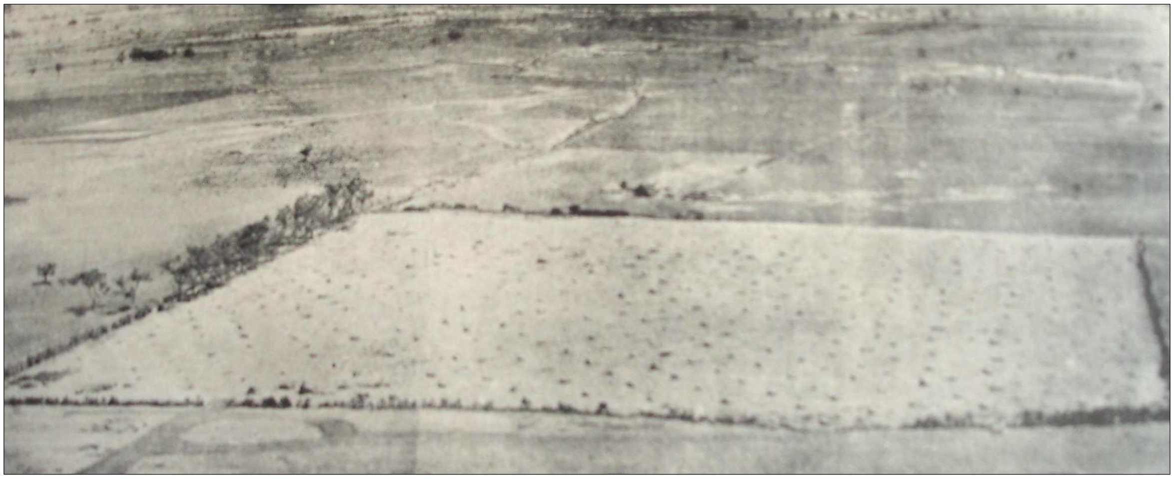

Figure 4: Panoramic photograph of the Vibhuthihalli stone alignments in 1940 showing a diagonal arrangement (Ahmad, 1941: Plate XIVb).

The 1940 photograph (Figure 4) shows otherwise. Meanwhile, Alchin (1956) used this photograph to estimate that there were about 36 alternating rows of 15 or 14 stones at the site.

Finally, Sundara published a detailed account of the site in 1975, where he gives overall dimensions of 200m × 225m, which differ markedly from Taylor's values. Sundara reported that the site contained approximately equidistant and parallel rows of stone boulders, 34 on the north-south side and 37 on the east-west side, that presented a diagonal effect. The distance between any two stones in each row on average was from 8m to 11m (again differing from Taylor's account). The boulders were undressed, medium sized, and on average measured 1.60m in girth. Most of the boulders were not driven into the ground but were simply placed on the surface. Taylor's plan (Figure 3) clearly shows five stone circles within the alignment and some more to the north of the site, but Sundara could not find any of these.

Figure 5 shows the site as photographed by Sundara in 1970. This photograph and the 1940 photograph clearly show that the stone alignments are on barren land devoid of trees with well marked rows of stones and clear horizons.

Figure 5: Photograph of the Vibhuthihalli stone alignments in 1970 showing clearly the parallel rows of stones (after Sundara (1975).

2.3 Our Investigation of the Site

Sometime between 1970 and 2008, the administration of the area was taken over by the State Forest Department, which fenced the site, planted trees (including tamarind and teak), dug bore wells and began using it as a nursery. In the process some stones were uprooted and the horizons were blocked increasingly by trees and bushes. The photograph in Figure 6 was taken in March 2009 from a similar perspective to the 1940 image, and it shows that the site is now full of trees.

Figure 7 shows some of the stone rows as seen from the west, looking east, and not a single row can now be seen fully from end to end. The inset shows a typical stone (granite?) in one of these rows. These boulders are very similar in size and shape to ones seen on the nearest hill to the west of the stone alignment, and it is very likely that they were simply rolled down the hill and arranged in rows.

When we came to measure the dimensions of the site we found that the pillars installed in 1940 still existed,[3] which allowed us to clearly identify the boundaries. Our re-measurement of the site agreed with the dimensions given by Sundara (200m E-W with 19 rows, and 220m N-S with 19 rows). We sampled the separations of the stones at various randomly-selected places in the alignment and found that the average distance (both east-west and north-south) was 11.4 ± 0.91m (37.5 ± 3ft). The separation from one of the corner stones of a mini-square formed from four stones, two each; from two adjacent parallel rows to a diagonal stone in between the mini-square was on average 7.9 ± 0.76m (26.0 ± 2.5ft). If 11.4m is one side of the mini-square, then the expected diagonal is 16.16m (53ft) and the half of it is 8.08m (i.e. the expected separation between a corner stone of the mini-square and a stone at the middle of the diagonal), whereas the measured value was 7.9m—very close to our estimate. Thus, the site is made up of a succession of mini-squares.

In arriving at the number of rows, Sundara (1975) seems to have counted the main row and the diagonal stone row together i.e. 19 main rows and 18 diagonal stone rows, which combine to provide 37 rows in the east-west direction amounting to 225m. Similarly, 18 main rows and 17 diagonal stone rows add up to 35 stones (but one stone row would be common for both N-S and E-W).

There seems to be a very gentle slope downwards from west to east. In some places close to the centre of the western boarder the stones appear to be much larger (adjacent to the present entrance to the site). We also looked for the stone circles mentioned by Taylor (1853) inside the alignment, but were unable to clearly identify any stone arrangement that looked like a circle; only one small group of six stones slightly north east to the middle of the site gave an impression of circular arrangement.

3 THE HORIZONS

The view of the horizons is very important in any assessment of the suitability of a site for observing sunrises and sunsets. Currently, the Vibhuthihalli site is bordered by a fence and several trees planted in recent years, but the horizon is still clearly visible through gaps between the trees and bushes.

A hill to the west dominates the view from the eastern edge of the site. There is a significant dip in the hill contour and the skyline drops low and rises again along the more distant hill contour. This dip is important, as will be shown later.

The southern horizon has a hillock with two prominent naturally-occurring stone pillars, as shown in Figure 8. These pillars seem to act as markers, the taller one being in line with the north-south rows of stones

4 THE CALENDRICAL EVENTS

From September 2008 we tried to observe sunrises and sunsets from the site during the equinoxes and solstices. Since the megalithic astronomers only made visual observations, we likewise made visual observations (i.e. no instruments were used, other than a camera). We defined sunrise as when the lower limb of the Sun grazed the horizon (i.e. allowing for refraction, the zenith distance was 90° 20′).

4.1 Equinox Sunrise

The September 2008 equinox was to occur on 22 September at 21:14 (IST), however both 22 and 23 September were cloudy and we could only observe the sunrise on 24 September at 6:18 a.m. (IST). The computed azimuth (A) and zenith distance (Z) were A = 90° 45′ and Z = 89° 20′, being about one and half solar diameters south of the expected equinox sunrise. The observation was made from a spot ~45.7m (150ft) from the eastern end of the site. A 1.22m (4ft) diameter stone would subtend an angle of 18′ from a distance of 220m (720 feet; i.e. at the western end of the alignment). Thus the accuracy of the estimation of direction would be within half a solar diameter.

On 24 September we noted that the row of stones which we took the observations from was in line with the sunrise (within the uncertainty of a semi-diameter of Sun's disk). We chose this particular row for one main reason: it was in the middle of the site (i.e. 110m from the southern edge). Coincidently, it was also one of the few areas of the site that currently offers a clear unobstructed view of the eastern horizon.

Figure 6: A similar view to the 1940 photograph but taken by the authors on 20 March 2009. The site is now fully covered by trees.

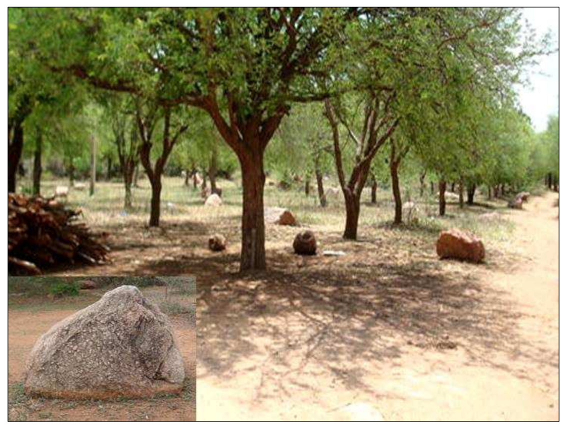

Figure 7: The rows of stones as they exist now in between rows of trees. The inset (bottom left) shows a typical stone.

Since the rows of stones are parallel, the same alignment was also seen from the neighboring rows during the equinox sunrise. The equinox was to occur on 20 March 2009 at 17:30 (IST), and Figure 9 shows a series of images of the Sun's disk that morning. The sequence was extrapolated to see the location of the Sun's disk on the horizon, which showed that this row of stones was in line with the sunrise. Similar observations were made on 21 September 2009, close to the 23 September equinox.

Figure 8: The southern horizon from the Vibhuthihalli stone alignments. Note the two stone pillars on the hillock marked by the two black arrows. The taller one, in particular, might have had a role in defining the rows (see the text).

Figure 9: A composite photograph of the sunrise on 20 March 2009. The stone rows point to the equinoctial sunrise. By extrapolating the track to the horizon one can pinpoint the location of the sunrise on the horizon.

4.2 Equinox Sunset

The equinox sunset seems to be more dramatic and significant and occurs in the dip shown in the western horizon (although trees presently block this view). Moving a little further to the east one can see the western skyline and the sunset. The equinox occurred on 23 September 2009 at 02:49 (IST) and the closest sunset to the equinox was on 22 September, but clouds prevented us from making any observations. However, what could be expected on that day can be extrapolated from observations made on 19 and 21 September, when we used a series of photographs to chart the progress of the sunset. On the 19th, the setting Sun was still slightly north of the dip in the western horizon when viewed with the last stone of an east-west row in the foreground (as seen in Figure 10). We calculated that the Sun was 54′ north of the expected equinoctial sunset position, which would occur right in the middle of the U-shaped depression in the skyline. Using these sorts of observations and horizon markers, the ancient megalithic astronomers at Vibhuthihalli would have been able to pinpoint the date of the equinox with an accuracy of a day.

4.3 Summer Solstice

Monitoring the other calendrically-important events—solstices—is presently hampered by trees, so we could not observe sunrises from the western edge of the site overlooking the stone rows. We wanted to see whether solstice sunrises were aligned with any sets of stones (including diagonally-aligned ones), that is, if one chooses a position in between the stone alignments, is it possible then to observe both the solstice and the equinox sunrises from the existing stones?

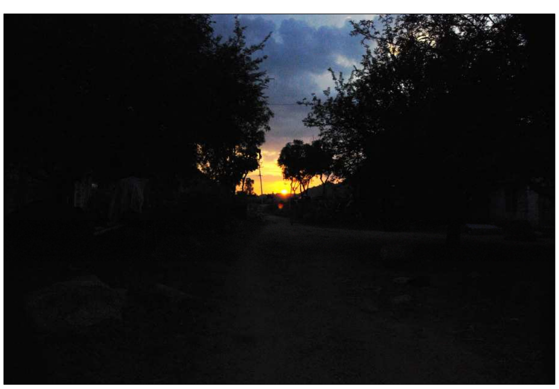

Figure 10: A photograph of the sunset on 19 September 2009 from the Vibhuthihalli stone alignment. This was three days before the equinox.

Figure 11: Three diagonal stones point to the sunrise on 22 June 2009. The lower stone and the one on the right point to the equinox sunrise.

4.3.1 Sunrise

In order to observe the solstice sunrise we chose the same row of stones mentioned earlier in the middle of the alignment on the eastern side of the site. Figure 9 also shows the position adopted from which both the equinoctial sunrise as well as summer solstice sunrise can be viewed. The solstice was expected to occur on 21 June at 11:16 (IST), and on the 22nd three (or possibly more) diagonal stones pointed to the solstice sunrise.

Another set of stone rows which is oriented towards the summer solstice sunrise as well as equinox sunrise is shown in Figure 11. A set of three stones points to the sunrise on 22 June a few hours after the expected solstice.

4.3.2 Sunset

The position of the summer solstice sunset seems to be marked by one of the hills on the western horizon, as viewed by us from the eastern side of the site less than one day prior to the solstice (which occurred on 21 June at 11:16 IST).

4.4 Winter Solstice

4.4.1 Sunrise:

Figure 12 illustrates the direction of the winter solstice sunrise from the chosen position. Three stones mark this position. The expected winter solstice was to occur on 21 December 2008 at 17:34 (IST), and the image was obtained just 13 hours later.

It is clear that solstice directions can be marked from the existing stones at the site once a fixed position is chosen.

4.4.2 Sunset

Winter solstice sunset was observed to occur on the peaks to the south west of the site, as viewed from the same location as the summer solstice and equinox sunset. The most southerly sunset occurs at a distinctive position on the horizon that is easily recognizable.

5 THE ANATOMY OF THE STONE ALIGNMENT

It is clear that calendrically-important events, particularly during the equinoxes, are well marked by the rows of stones (sunrises on the eastern side) or distinctive features on the horizon (sunsets on the western side). Heggie (1981) has pointed out the many issues that need to be addressed if such alignments are to be seriously considered as having astronomical significance. One of these is: how can one distinguish between intentional astronomically-motivated alignments and those that are coincidental? And why did the constructors of a particular monument decide to use a certain geometrical design?

There are two things that are distinctive about these Indian alignment sites: their restricted geographical distribution and their distinctive design. This suggests there is nothing coincidental or accidental about them: they were built for a common purpose.

5.1 The Plan

All the sites discussed by Allchin (1956) are located between latitude 16° and 17° N, and the total azimuthal range of the Sun's position on the horizon from summer to winter solstice was 49° 03′ 14″ in about 1500 BC. The Sun's diameter is ~30′, with horizontal refraction adding a further 15-20′ to the size, so the total extent of the Sun's traverse along the horizon would have been ~26° on either side of the equinoctual point.

From any location, if the Sun's position on the horizon was of interest, then it was likely that both sunrises and sunsets were monitored. A direction could be accurately specified if viewed from a corner (a point defined by the intersection of two lines). Thus for a square plan, a diagonal line drawn from the centre of a side to the opposite corners would subtend an angle of 26° 30′, very similar to the angle expected for the Sun's position on the horizon at the solstices. A square plan would therefore seem very appropriate for a stone alignment site at this latitude.[4]

In the particular case of Vibhuthihalli, the dimensions of the site and the total number of stones are uncertain. The present dimensions and those measured by Sundara (1975) are double those given by Taylor in 1853. Clearly Taylor's figures are wrong, but it is hard to know why he was out by a factor of two. Moreover, it is likely that part of the E-W arrays were reduced at the time the present boundaries were established in 1941 (as we could only account for about 17 stones in a row in the E-W direction and 19 in the N-S direction). If we double the dimensions given by Taylor, the E-W side would be 220m (720ft) long and N-S side 207m (680ft) long, and the angle between the E-W line at the centre of the most westerly line to the two corners of the most easterly row is 25° 18′ (which is very close to the angle expected for the solstice direction to the equinox east at the mid-point of the most westerly row). This is shown graphically in Figure 13.

Figure 12: A photograph of the sunrise on 22 December 2008. Three diagonal stones from the stone at the lower right point to the winter solstice sunrise, while the former stone and the one to its left point to the equinox sunrise.

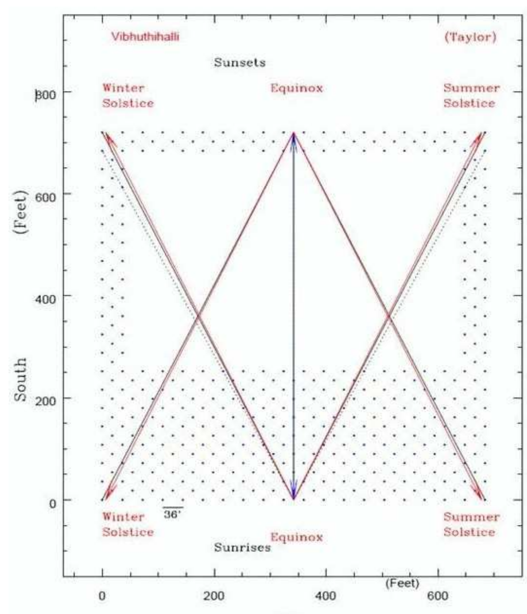

Figure 13: A schematic view of the Vibhuthihalli site as described by Taylor but doubling the size to 20 rows, (20+19) N-S and (21+20) E-W. The solstice sunrises and sunsets are shown in red as viewed from the middle of the extreme western and eastern rows. The black lines join the corners of the site to the middle of the extreme eastern and western rows. Note that the red and black lines coincide. The dashed lines show a similar view if the alignment is a square.

5.1.1 The Degree of Precision

Sundara (1975) states that "In the arrangement of stones there is a mathematical precision." Allchin (1956) also remarks that "… the alignments consist of parallel lines of standing stones set out with mathematical precision." We randomly measured how much the stones in an alignment deviated from a straight line and found that three or four stones tended to follow a straight line, then the fourth or fifth stone would deviate by as much as a stone length ~0.91m (3ft), then the next stone would be back in line ±0.3m (1ft), as though the lines are constructed by sighting a distant land mark (on the horizon) and positioning the stones in line with it.

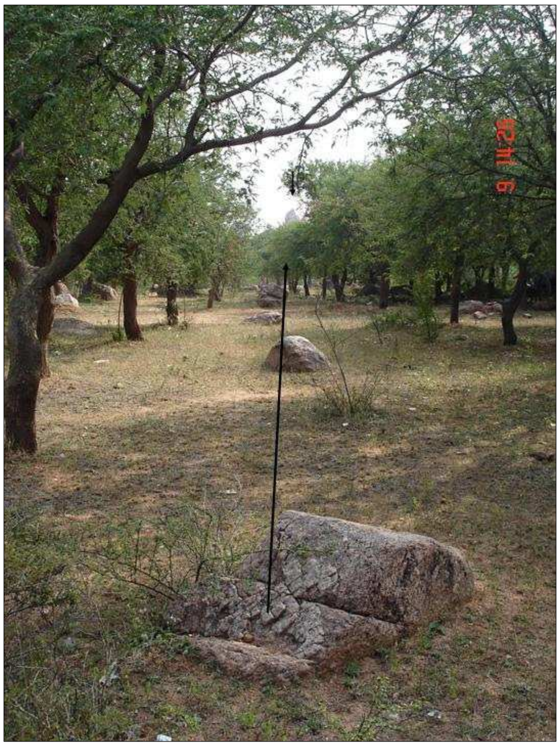

Figure 14: A photograph of a N-S stone row at Vibhuthihalli that points to one of the two stone pillars on the horizon shown in Figure 8.

For example, Figure 14 shows a N-S row of stones in line with the taller stone pillar on the southern horizon and this pillar probably was used as a land mark when setting up the row of stones. We arrived at the N-S direction very simply by using a stick as a gnomon to measure the shadow. The meridian direction was established by marking the direction of the shortest shadow (when the Sun was on the meridian), and the N-S direction was thus marked on the ground. This was repeated over several days.

The E-W lines might have been established from equinox sunrises and sunsets. The equinox sunset could be marked to better than a half a solar diameter, and in constructing the alignment this line of sight must have been used as a primary marker, since all the E-W rows are parallel to the primary row.

Since there is a mild downward slope of the ground from west to east, a view from the middle of the western end row would presumably provide a clear view of the eastern corners (the solstice directions). Viewing to the west was done from the eastern end, to record the Sun's horizon movement among the various notches and dips on the hills there.

It might be asked why so many stone rows were needed to monitor the major calendrical events. This is not an easy question to answer, but the Sun's movement on the horizon was not uniform, as it was more rapid near the equinoxes and slower near the solstices. The same uniform spacing of ~11.6m (38ft) at the eastern end of the site, as viewed from the mid-point of the western end row, would correspond to 3° 00′ near the equinoxes and 2° 42′ near the solstices. Maybe there was a need to measure smaller increments near the solstices, and this could be achieved with the approximately uniform spacing of the rows.

5.2 Is the Vibhuthihalli Site Unique?

Allchin (1956) lists a few sites that have stone alignments that are similar to the configuration seen at Vibhuthihalli. Moreover, its diagonal arrangement is not unique as a similar kind of alignment, but on a much larger scale can be found at Hanamsagar, on the banks of the Krishna River ~75km from Vibhuthihalli.

5.2.1 The Hanamsagar Site

Detailed accounts of this site, including photographs, have been presented by Allchin (1956), Paddayya (1995) and Rao (2005). Many parts of this large site have already been disturbed, and other sections could soon disappear as the land is under cultivation and is owned privately.

We measured the separations of stones in a few randomly-selected rows that seemed undisturbed. The average spacing between successive stones was 11.3 ± 1.9m (37.2 ± 6.3ft) and the diagonal stone was at 7.9m (26ft). Note that these figures are about the same as those obtained at Vibhuthihalli. Meanwhile, Allchin (1956) measuring a spacing of 11m (36ft) at a much smaller square alignment of 4 × 4 stones at Jamshed I. Maybe this measurement is a kind of basic standard. In any case, these results suggest that the sites are connected, were established with the same basic plan, for the same purpose, and at around the same time.

5.3 The Age of these Stone Alignment Sites

When were these sites established? No absolute dates have been obtained from any of the sites, but as mentioned earlier, the Vibhuthihalli site is located close to Neolithic habitation sites and ashmounds, and Sundara (1975) also discovered a nearby megalithic habitation site. In addition, Ahmad (1941) seems to have discovered 'flakes' (of probable Neolithic antiquity) at the Vibhuthihalli alignment site.

Paddayya (1995) also noted similar associations with neighbouring Neolithic sites and ashmounds at Hanamsagar. The Kodekal ashmound is only 2.4km to the west. Although the ashmound at Benkanhalli has not been dated, the Kodekal ashmound has a date of ~2893 BC (Johansen, 2004). Boivin et al. (2007) and assert that

> … by the mid-third millennium BC, Southern Neolithic sites had a mixed economy of pastoralism and indigenous crop cultivation, although which came first (the domesticated plants or animals) and where precisely

> this happened (e.g. Western Andhra or Shorapur Doab, etc.) remains to be resolved. (cf. Boivin et al, 2005).

The ashmound tradition in early Southern (Indian) Neolithic society seems to have changed from a food foraging economy to one dependent upon agricultural production by late Neolithic times and during the transition to the Megalithic period. Around 1900-1800 BC, introduction of wheat and barley occurred at some southern Neolithic sites (Boivin et al., 2007). Seasonality and scheduling of such crops have been discussed by Fuller et al. (2001). Such scheduling required awareness of the seasons and their repeatability. Thus there was a demand for individuals with astronomical knowledge, and there was a need to predict calendrical events. According to Boivin et al. (2005: 83), "The replacement of ashmounds with megaliths as the primary monuments in the landscape at the tail end of the Neolithic signals wider ritual and cosmological changes."

Fuller, Boivin and Korisettar (2007: Table 9) provide a revised chronological framework for the Southern Neolithic based on radiocarbon dating and major trends in archaeological evidence. The Neolithic III and Megalithic (pre-Iron Megalithic) periods ranged between 1800 and 1400 BC. The fact that the Vibhuthihalli stone alignment site is immersed in a Neolithic environment and lacks any suggestion that iron was in use, would seem to indicate that it was constructed between 1800 and 1400 BC.

5.3.1 Society

The construction of a site like Vibhuthihalli involved a lot of planning, and employment of large numbers of people, which indicates the seriousness of its purpose. If it was astronomical, as we suggest, foreseeing the coming seasons and monitoring the movements of the Sun god would provide a deep sense of purpose. We also suggest that the construction of the Vibhuthihalli site was not a one-off venture, but evolved after a few smaller alignments were constructed and successful observations were carried out.

Was Neolithic Indian society then mature enough to undertake such a venture? According to Boivin et al. (2007)

> …it seems likely that the emergence of Megalithic societies had much to do with the external contacts and complexity engendered by the ongoing expansion of Neolithic exchange networks. There are clear signs of such expansion, particularly, as our recent researches indicate, in the archaeo-botanical record.

Thus, it was not only indigenous local knowledge but also information obtained through exchanges with other communities to the north that may have provided the impetus for this ambitious project.

5.3.2 Earlier Evidence of Astronomical Activity and Interest

Is there any evidence in southern India to suggest an earlier awareness of astronomical phenomenon which possibly led at a later time to astronomical constructions like the stone alignment sites? Studies of the South Indian ashmounds, their surroundings and the environment seem to suggest deliberate attempts were made to orient (or to locate) the ashmounds with respect to each other in certain directions which highlighted special solar events. The ashmounds are now viewed as the result of repeated ritualistic cycles of cow dung accumulation followed by fires that sometimes involved enormous conflagrations (Allchin and Allchin, 1968; Foote, 1887; 1916; Korisettar et al., 2002) performed by Neolithic pastoralists. Boivin (2004) has studied two extremely large ashmounds at Kudatini and Toranagallu, in Bellary district (about 180km south of Vibhuthihalli), and he suggests that (1) their locations were deliberately selected so that they not only lay on an E-W axis but (2) the view from Kudatini was chosen such that the Sun on two special occasions (23 April and 24 August) would set on top of Toranagallu Hill, thereby providing for spectacular ritualistic events. Thus, an awareness of the movement of the Sun was already present in southern India almost a millennium before the stone alignments were constructed. This would seem to indicate the emergence of a local astronomical tradition that was restricted to this particular area of India.

6 CONCLUDING REMARKS

The stone rows at the Vibhuthihalli site point towards equinoctial east-west. The directions of the corners of the site when viewed from the middle of the rows on the extreme east and west might also point to sunrises and sunsets during the solstices. Thus, this site could have been used for calendrical astronomy. The period during which the site was erected is not certain but the accumulated evidence suggests the late Southern Neolithic to the early Megalithic (i.e. between 1800 and 1400 BC). At that time, the socio-cultural needs of a pastoral and agricultural society relied upon the predictability of the seasons and a knowledge of the passage of the year. Archaeobotanical evidence and the presence of some domesticated animals suggest possible contacts with societies in the northern part of the country. Thus, astronomical knowledge that accumulated locally and through interaction with outside communities allowed the construction of elaborate sites like Vibhuthihalli.

The existence of other large and small stone alignment sites of similar basic design in this area of India suggests the need for calendrical monitoring at this time. The larger alignment sites might have evolved from smaller ones as the need emerged to monitor closely the rate of motion of the Sun (and maybe other celestial objects, such as the Moon) on the horizon.

These stone alignments are either on private land or on Government land that has been distributed to people for cultivation, and in most instances the land-users are totally unaware of their historical and scientific importance. Consequently, many of the stones have been relocated and used for other purposes; some sites have disappeared altogether; and other sites are in the process of disappearing. Clearly, there is an urgent need for their preservation, but unfortunately, even those Government agencies which are supposed to protect these sites sometimes make inappropriate decisions (such as the planting of trees, the digging of wells and the use of the area for a nursery in the case of the Vibhuthihalli site).

It is to be hoped that a less disturbed stone alignment site can be found which can be subjected to more systematic and thorough investigation. More precise dating of these sites is also urgently required.

7 NOTES

1. Thom and Thom (1971) have suggested that similar stone alignments in Europe at sites such as Le Ménec have astronomical significance.
2. Allchin (1956) quoted local fables that they are either cattle petrified by curses or king's camping places where the horses and elephants were tethered to the stones (Taylor 1852). The locals at Hanamsagar (a similar site to the Vibhuthihalli alignments) told us that the stones were cursed thieves who stole jewels from heaven.
3. The notice board had disappeared long ago, but at some date after April 2009 the Archeological Survey of India installed a new board.
4. It is of interest to note that a similar arrangement is seen in some medieval Sun temples (e.g. Modhera and Marthanda), where the corners of the rectangular tank (*Kund*) define the directions of the solstice sunrises as seen from the centre of the *Gudha Mandapa* (see Kameswara Rao 1995; 1998).

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of ELODIE, the échelle spectrograph at Haute–Provence that provided the first successful detection of a perturbing mass of planetary dimension orbiting another star. Here Hearnshaw identifies a high blaze angle grating as an innovation. Another innovation is the use of both crown and flint glass prisms for the cross-disperser. These are fine and worthy design issues, but they seem to me to be refinements or extensions, not innovations. I raise this point because there is a rich historical literature that explores the many processes that can be classified as instrument innovation that would have allowed the author to provide deeper and more helpful perspective on the nature of instrument innovation in astronomy. One more helpful definition is available in the work of Tom Gieryn and Richard Hirsh (1983) in their study of X-ray astronomers. Elaborating on the standard definition issued by the U.S. National Science Board in 1978, they identified innovation as "… contributions that challenge dominant theoretical, empirical or technical assumptions, and which result in palpable changes in problems chosen for research, theories adopted and techniques exploited." (page 93).

Given this definition, I would have given more weight to the fact that the spectrograph was fed by fibre optics, allowing it to be stationary and thus avoiding all sorts of nasty instrumental errors associated with motion on the telescope. In his top ten chapter Hearnshaw does cover fibre-fed designs, especially his own 2001 Hercules instrument, recognizing it as "… one of the first of the vacuum fibre-fed high resolution échelle spectrographs …" (page 210). ELODIE was in service as early as 1993, and fibre-fed designs date back to the 1980s, as he well points out in an earlier chapter.

Hearnshaw's insights on innovation throughout the book can be gleaned by the deliberate knowledgeable reader. At one level one can presume that if a particular instrument or technique is discussed, it represents innovation of some sort. To access deeper levels, however, one needs to dig through the copious references and engage the secondary historical literature, which unfortunately is absent from this book.

The book is well documented by references to the primary scientific literature in abbreviated bibliographical style, but unfortunately there is no comprehensive bibliography for the book, or any discussion of the nature of his sources. That made it difficult to determine if there was any significant engagement with views of the field by earlier reviewers, such as Ira S. Bowen. I did find that the watershed series *Stars and Stellar Systems* from the 1960s was queried by references to Bowen's chapter on spectrographs in the *Astronomical Techniques* volume (1962). But I found no commentary on how Hearnshaw's perspective, from 2009, contrasted with Bowen's from the 1960s. Nor were there any references to the important review articles in the 1930s on astronomical spectroscopy in the *Handbuch der Astrophysik*. Since those works represent received scientific opinion in their times, it would have been very useful to engage them as historical signposts to see how opinion, inclusiveness, and emphasis has changed over time. I also found it curious that the historical introduction chapter, to 1900, had some 236 references, but only one was to an explicit historical paper, by Don Osterbrock in the *JHA*.

The emphasis throughout the book is on the instruments and their designs, not on the people. There is some information on what these instruments were used for, and this is also welcome. Although there is frequent mention of the types of detector systems employed—photography, electronography, solid state detectors—these are merely mentioned in passing without substantial discussion of the impact new detectors had on instrument design, or even if there was impact. Thus, there is a welcome richness of detail, but here and there I was left wishing for a broader perspective, such as that provided in the latest issue of the *JAH²*; the paper by Lamy and Davoust on "General-Purpose and Dedicated Regimes in the Use of Telescopes" provides just such a refreshing and fruitful conceptual framework that I wished to find in this otherwise important work.

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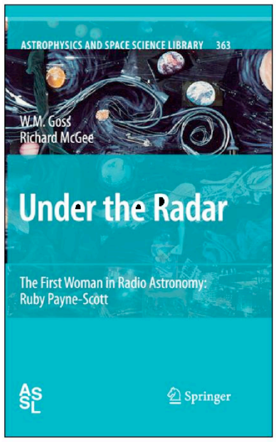
Under the Radar. The First Woman in Radio Astronomy: Ruby Payne-Scott, **by W.M. Goss and Richard X. McGee (Heidelberg, Springer, 2009), pp. xxii + 354, ISBN 978-3-642-03141-0 (hardcover), €59.00, 242 x 160 mm.**



By all accounts Ruby Payne-Scott (1912–1981) was an amazing person. Back in the late 1920s and early 30s she studied physics at the University of Sydney when few women did, then after brief diversions she joined the CSIR's secret Radiophysics Laboratory in Sydney and worked on radar developments during WWII. It was at this time that she carried out her first explorations in radio astronomy, a field in which she would quickly build a fine international reputation. While all this was occurring she was a member of the Communist Party of Australia when such affiliations were frowned on (to say the very least), but, more importantly, she was a wife. Her marriage only became common knowledge at CSIRO headquarters in 1950, and the following year she felt impelled to resign from the Division of Radiophysics (RP) given the imminent arrival of her first child. Maternity leave was not available in those days, and legislation prevented married women from holding permanent research posts in the Commonwealth public service. Those surely were draconian times!

The skeletal account presented above is fleshed out with admirable tenderness by Miller Goss and Dick McGee, two well-known radio astronomers. Miller's time at Radiophysics came long after Ruby had left, but she was still spoken of by long-standing staff members, whereas Dick joined RP soon after Ruby's departure, when her image was still very much part of the 'corporate culture'.

After providing an introductory chapter, Goss and McGee launch into a series of chronologically-ordered chapters where they deal with Payne-Scott's education; her early career with the Cancer Research Committee of the University of Sydney while she carried out part-time studies for an M.Sc.; her short stay as Science Mistress at Woodlands Church of England Girls' Grammar School in Adelaide after obtaining teacher training qualifications at her *alma mater*, the University of Sydney; and her two years at Amalgamated Wireless Australasia.

For those of us with a passion for radio astronomical history, this book takes a new turn on page 37, with the start of Chapter 4. Titled "Personnel File from CSIR/CSIRO", this recounts Payne-Scott's appointment to the Radiophysics Laboratory in August 1941 and events leading up to her departure in July 1951. During this decade of service she made an important contribution to the war effort and then to international science, and this is surveyed in the following five chapters. Apart from her wartime contributions to radar development, the pioneering solar research she carried out at Collaroy, Dover Heights, Hornsby Valley and Potts Hill is well-known to those familiar with early Australian radio astronomy, and has been covered by various authors in a series of papers and at least two books, but Goss and McGee succeed in expanding this story by incorporating material drawn from archival sources and personal reminiscences from some of Payne-Scott's contemporaries. Complementing the main thread of their account throughout is a plethora of interesting footnotes. These five chapters collectively span 134 pages, and I found them entertaining and illuminating. This applies equally to the following chapter about the 1952 URSI meeting, which was held in Sydney, but involved field visits to the Division of Radiophysics' field stations at Dapto, Hornsby Valley and Potts Hill. This major international meeting was to be Payne-Scott's last serious involvement in radio astronomy, although she did not end up presenting a paper at any of the sessions.

After almost 200 pages, one would expect Ruby Payne-Scott's story to be nearing an end, but in fact we are little more than half way through the book! Successive chapters then focus on: "Reminiscences and Anecdotes of Ruby Payne-Scott as Told by Friends and Colleagues"; "A Remarkable Family: Bill and Ruby Hall" (this was her married name), including biographical sketches of her two remarkable children, Peter Hall (an eminent Professor of Mathematics) and Fiona Hall (artist extraordinaire). Then there is a fascinating chapter about Payne-Scott's communist sympathies and Party affiliation—apparently she was known to some at RP as "Red Ruby"! The final two short biographical chapters review her time as a part-time science and mathematics teacher at a private girls' school in Sydney from 1963 to 1974, and discuss "The End of Payne-Scott's Life: A Retrospective". By the time she retired from Danebank School the early stages of Alzheimer's disease were apparent, and as the disease took hold she aged rapidly, dying on 25 May 1981, just 3 days short of her 69th birthday. Thus ended the life of one of Australia's most remarkable female scientists.

In the final two and a half page chapter in this book Miller Goss and Dick McGee tell us why they wrote this book and how the journey was to take them more than a decade. Rounding out the book are 14 illuminating appendices, spanning almost 70 pages, a ten-page Bibliography; and an Index.

This is a beautifully-researched, copiously-illustrated and well-written book that tells us much more than the life of one amazing female radio astronomer. It also provides a profile on radar developments during WWII and on Australia's pre-eminent place in solar radio astronomy in the years following WWII. *Under the Radar* is compelling reading, and if you have taken the time to read right through this review then it certainly belongs on your bookshelf!

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Geschichte der Geodäsie in Deutschland, by Wolfgang Torge (Berlin, Walter de Gruyter, 2007), pp. 379, ISBN 978-3-11-019056-4, €118.00, 244 x 176 mm.

The history of geodesy in Germany, written by the retired professor Wolfgang Torge from the Institute of Geodesy at the Technical University of Hanover, is much more than the title implies. It describes the development of geodesy in Germany (although during most of the time, this meant a patchwork of small states) and central Europe. After some preliminaries about the concept of geodesy and ordnance surveys, the second chapter deals with the history of surveying in Babylonia, Egypt, Greece and in the Roman Empire. Following a survey of the tradition in the Middle Ages, the fourth chapter starts with the Copernican revolution, triangulation and plane-table methods, and early surveys in Bavaria, Saxonia and Württemberg. The fifth chapter introduces the new geodesy, i.e. the proof of the Earth's oblateness by Cassini I and his collaborators, the rise of state observatories, and the introduction of the meter. The *Carte Géométrique de la France* (1747-1793) by Cassini III (and IV) was completed at the end of the monarchy in France. Along the same lines, the military surveys of the Napoleonic era were carried out in central Europe, especially in the south of Germany and in Austria, as well as in the German southwest, then under French administration, a task completed by Prussian surveyors only after Napoleon's defeat.

Important contributors to geodesy in this period were Christian Mayer in Mannheim, Johann Georg von Soldner in Bavaria, and Carl Friedrich Gauss in Göttingen for the establishment of a geodetic network, as well as Franz X. Zach, who initiated work on a geodetic arc. The seventh chapter describes the Hanoverian and Prussian ordnance survey and similar enterprises in other German states, as well as educational efforts for surveyors and the establishment of mechanico-optical workshops. Chapter 8 describes the central European collaboration as well as international ones, and the role of the Geodetic Institute in Potsdam under Friedrich Robert Helmert. The closing three chapters deal with standardisations in Prussia and other states, the homogenization of German surveying offices, and modern trends in surveying in the second half of the twentieth century.

Readers will find the names of many astronomers of the sixteenth to nineteenth centuries in this informative book, and will learn about the work they carried out beyond astronomy: to provide tools, methods and often a major part of their working time for the progress of surveying and geodesy.

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CONTENTS

Papers

Letter to the Editor

Book Reviews

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