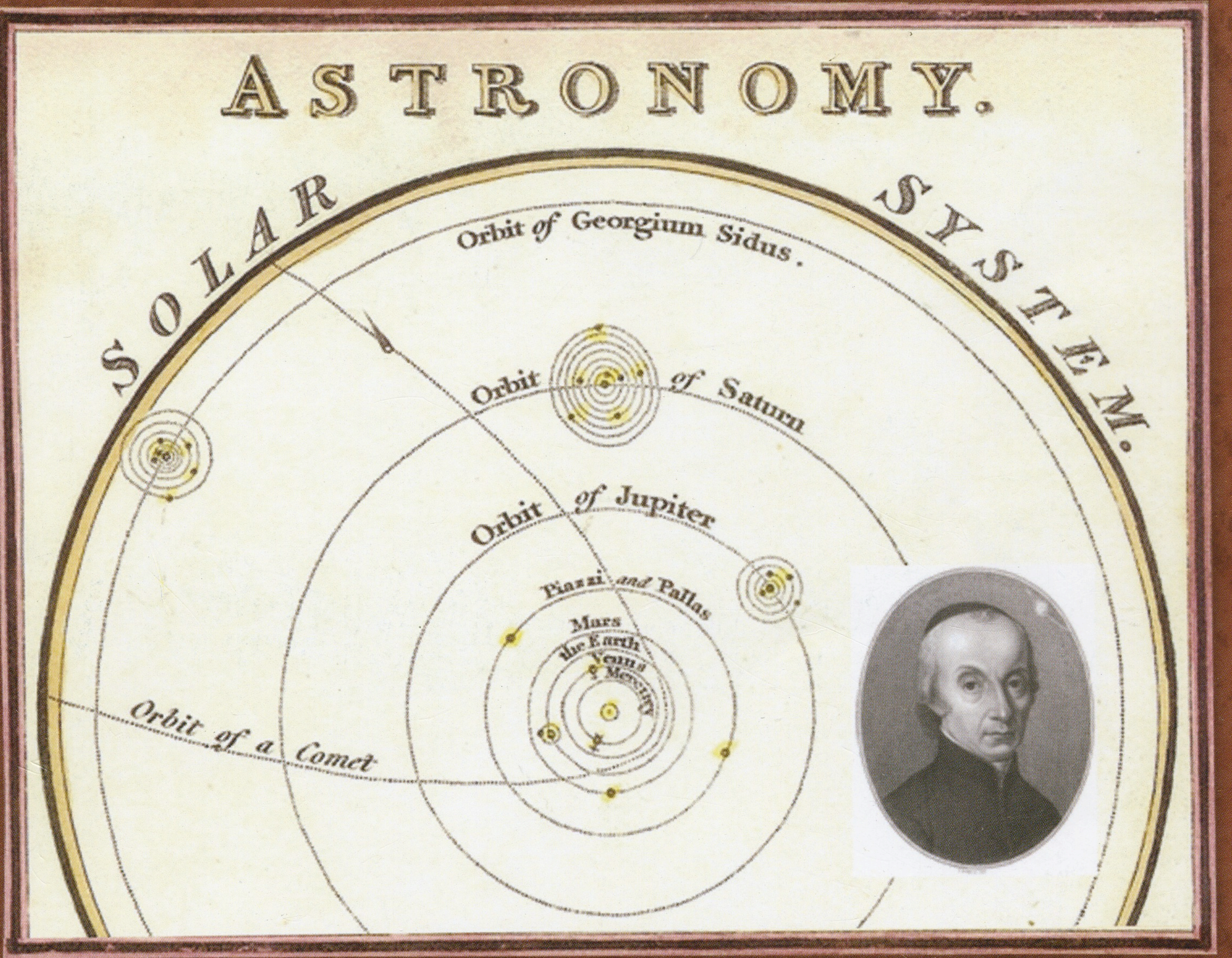
JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE



Vol. 12 No. 3

November 2009

JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807

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The annual subscription rates for Volume 13 (2010) are:

AU$200:00 for institutions
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COVER PHOTOGRAPH

The late eighteenth century and beginning of the nineteenth century was a fabulous period for Solar System astronomy, with Herschel's discovery of Uranus on 13 March 1781 and Piazzi's detection of the first asteroid, Ceres, on 1 January 1801. Other asteroid discoveries quickly followed. The naming of Uranus and Ceres involved the astronomers of Europe in considerable debate and controversy, as evidenced by the map shown on the cover of this issue of the *Journal*. This map was printed in 1802 or 1803, and Uranus is listed as 'Georgium Sidus' and Ceres as 'Piazzi'. Meanwhile, the insert shows what the astronomer, Piazzi, looked like at about this time. For an account of the controversy surrounding the naming of Ceres see the paper by Clifford J. Cunningham, Brian G. Marsden and Wayne Orchiston on pages 240-248 in this issue of the *Journal*.

JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
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VOLUME 12 NUMBER 3 NOVEMBER 2009

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

Journal of Astronomical History and Heritage, 12(3), 175-188 (2009).

HIGHLIGHTING THE HISTORY OF FRENCH RADIO ASTRONOMY. 4: EARLY SOLAR RESEARCH AT THE ÉCOLE NORMALE SUPÉRIEURE, MARCOUSSIS AND NANÇAY

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Abstract: The first tentative steps in solar radio astronomy took place during the 1940s and early 1950s as physicists and engineers in a number of countries used recycled World War II equipment to investigate the flux levels and polarisation of solar bursts and emission from the quiet Sun, and sought to understand the connection between this emission and optical features in the solar photosphere and chromosphere. There was also an abiding interest in the terrestrial effects of this solar radio emission. Among these solar pioneers were French radio astronomers from the École Normale Supérieure in Paris. In this paper we review the early solar observations made by them from Paris, Marcoussis and Nançay prior to the construction of a number of innovative multi-element solar interferometers at the Nançay field station in the mid-1950s.

Keywords: French radio astronomy, solar radio emission, École Normale Supérieure, Marcoussis, Nançay, J.-F. Denisse, J.-L. Steinberg, solar eclipse observations, the Arsac Interferometer.

1 INTRODUCTION

Solar radio astronomy was born during World War II, when Alexander (Orchiston, 2005), Hey (1946), Reber (1946), Schott (1947), Slee (Orchiston and Slee, 2002) and Southworth (1945) all independently detected solar radio emission. Military secrecy meant that most of these discoveries remained 'top secret' during the War, and only entered the public domain following the end of hostilities in Europe and the Pacific.

Hey's detection in England and follow-up observations by Appleton (1945) spawned a solar research program at Cambridge immediately after the War (for localities mentioned in the text see Figure 1), while news of Hey's, Alexander's and Southworth's wartime work led to the launch of an ambitious solar research program in Sydney, Australia, under the auspices of the C.S.I.R.O.'s Division of Radiophysics (Christiansen, 1984). For a short time during the late 1940s, smaller Australian solar radio astronomy groups also existed at Mt. Stromlo Observatory and at the University of Western Australia in Perth (see Orchiston, Slee and Burman, 2006). Canada was also quick to assemble a solar radio astronomy group under Covington immediately after the War (see Covington, 1984). Britain, Australia and Canada all were involved in radar research during the War, and this was a valued catalyst in the post-War development of radio astronomy in all three nations, providing a pool of suitable equipment and talented personnel that could be directed to this new field of science (Edge and Mulkay, 1976; Hey, 1973).

Countries like France and Holland that missed out on these radar developments were not so lucky, yet both nations initiated radio astronomy programs soon after the end of the War (see Denisse, 1984; Strom, 2005; van Woerden and Strom, 2006). This paper investigates the solar radio astronomy program that was carried out by staff at the École Normale Supérieure from 1946, and is the fourth in a series that aims to document significant developments in early French radio astronomy.[1]

2 EARLY SOLAR RESEARCH AT THE ÉCOLE NORMALE SUPÉRIEURE

2.1 Introduction

By the time he was appointed Director of the Physics Laboratory at the École Normale Supérieure (henceforth ENS) in Paris in late 1945, Yves Rocard already knew about Hey's wartime detection of solar radio emission, and saw this as a potential post-War research field. During the following year a radio astronomy group was formed at the Physics Laboratory under the leadership of J.-F. Denisse and J.-L. Steinberg. Others who soon joined the group were J. Arsac, E.-J. Blum, A. Boischot, E. Le Roux and P. Simon. It is important to note that few of these individuals had a background in electronics or radio engineering—unlike many of their counterparts in England and Australia (see Lovell, 1977; Sullivan, 2005)—and none had a background in astronomy (Steinberg, 2001: 513).

2.2 The Solar Observing Program

As in other countries at this time, the fledgling French solar radio astronomy group began by recycling and cannibalising surplus World War II radar antennas and receivers. Initially they erected a U.S. Air Force 1.5m equatorially-mounted searchlight mirror and a 6-element equatorially-mounted Yagi antenna on the roof of the Physics Laboratory (Arsac et al., 1953). The third radio telescope on the roof of the Physics Laboratory was one of the German ex-WWII 3m Würzburg radar dishes that the ENS team adapted for radio astronomy.

The 'searchlight antenna' is shown in Figure 2, and was initially installed so that the radio astronomy group could gain experience in designing and constructing equipment, but its research potential was quickly recognised and it was then used to study variations in solar emission at 9,350 MHz (Steinberg, 2004).

Denisse, Steinberg and Zisler were particularly interested in the terrestrial effects of solar radio emission, and in 1951 they reported on their regular monitoring program at 158 MHz since 1948 and confirmed that some areas with faculae, plages and sunspots were associated with bursts of solar noise (as reported previously by other radio astronomers). They noted (Denisse et al., 1951: 2291; our translation) that

> This emission is characterised by an average level of intensity in the course of a day and by its degree of agitation. Since the importance of these two features is still unknown we have defined the level of radio emission by the mixed index S, representing the sum of its average level and its degree of agitation as outlined in the following table.
>
> | Intensity | Agitation | Indices |
> |---|---|---|
> | $p < 10$ | Nil or very weak | 0 |
> | $10 < p < 20$ | Average | 1 |
> | $20 < p < 50$ | Strong | 2 |
> | $p > 50$ | Very strong | 3 |
>
> where p = average flux received in 10^{-23} W . m^{-2} $(c/s)^{-1}$

Using these criteria, 74 centres of solar activity were identified during 1948-1950 (inclusive), and these were designated *Type A*, in contradistinction to 65 relatively inactive centres (termed *Type B*). Denisse et al. (1951: 2292) then plotted these centres against the terrestial magnetic index, C, revealing a pronounced maximum in geomagnetic activity 1 or 2 days after the central meridian passage of a radio-active centre of *Type A*, and a distinct minimum in geomagnetic activity 2 or 3 days after the central meridian passage of a centre of *Type B*. They concluded: "The regularity of curves A and B [in their plot] and the persistence of these principal phenomena in the course of each year when considered individually adds considerable weight to the statistical value of these results." (Denisse et al., 1951: 2292; our translation).

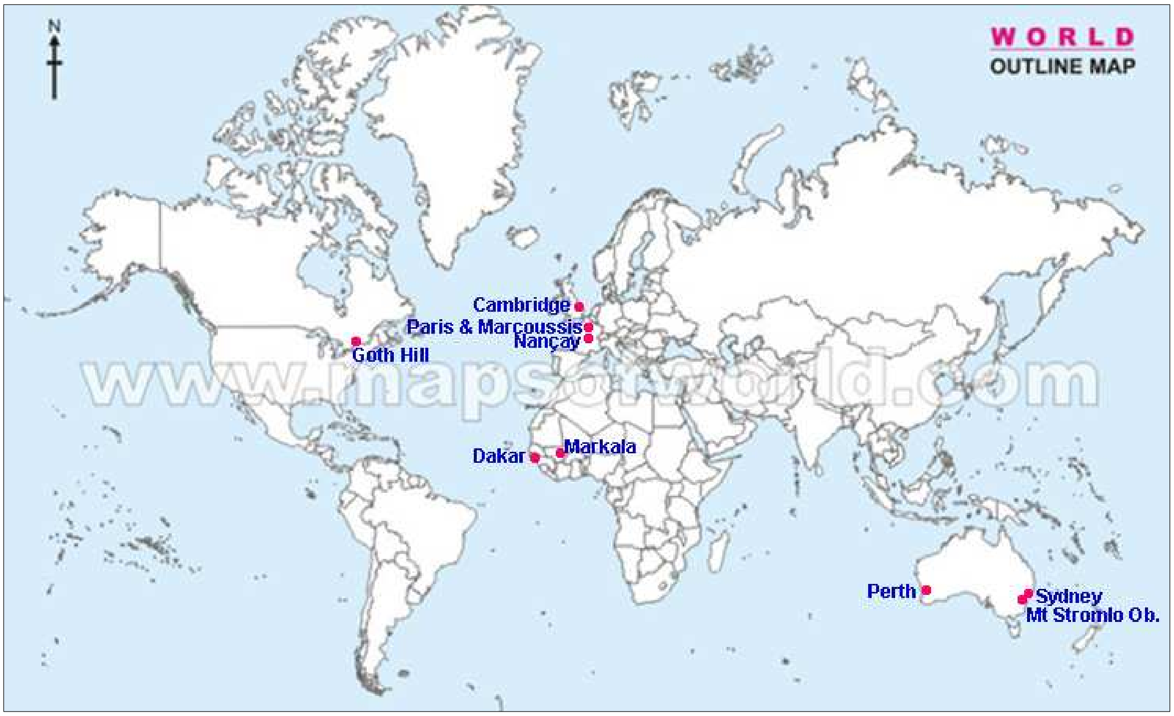

Figure 1: Localities mentioned in the text (outline map courtesy of www.theodora.com/maps, used with permission).

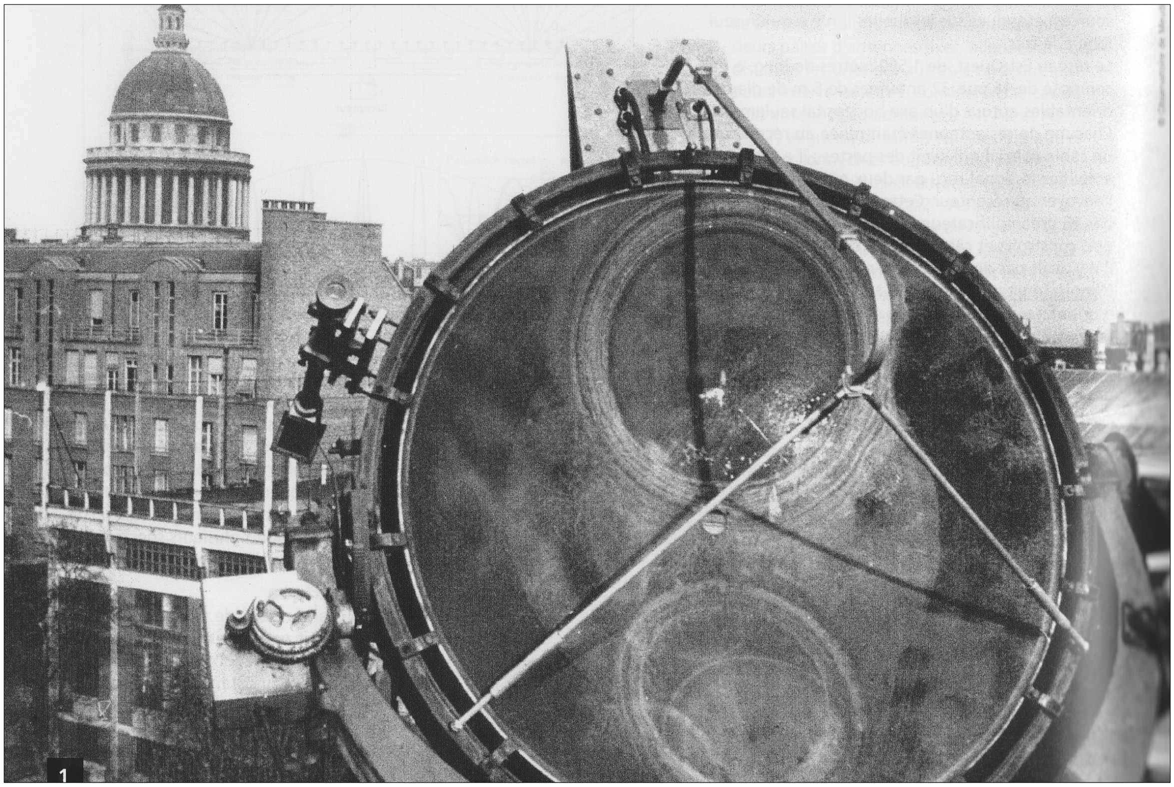

Figure 2: The 1.5m diameter ‘searchlight antenna’ mounted on the roof of the Physics Laboratory at the ENS in Paris. In the background is the dome of the Panthéon (after Steinberg, 2004: 626).

From June 1954 daily automated monitoring of the Sun at 9,350 MHz was carried out from the roof of the Physics Laboratory in Paris using the 1.5m searchlight antenna shown in Figure 2. In 1955, Kazès and Steinberg published a short paper in which they discussed atmospheric refraction associated with solar observations carried out near sunrise and sunset and how the level of solar emission dropped off rapidly as the Sun approached the horizon towards sunset.

2.3 Solar Eclipse Observations

During the 1940s and 1950s solar eclipses offered a particularly elegant way for radio astronomers to investigate the locations of solar-emitting regions, and those at the ENS observed three different eclipses (for a review see Orchiston and Steinberg, 2007).

The first of these events was a partial eclipse which occurred on 28 April 1949 when at mid-eclipse the Moon masked just 26% of the solar disk as seen from Paris. This eclipse was observed by radio astronomers from both the ENS and the Institut d’Astrophysique de Paris (see Laffineur et al., 1949, 1950; Steinberg, 1953). Steinberg and Zisler from the ENS used the 3m Würzburg dish on the roof of the Physics Laboratory and a 7.5m Würzburg antenna at Marcoussis near Paris, which operated at 1,200 MHz and 158 MHz, respectively, while Marius Laffineur carried out independent observations at 555 MHz with another 7.5m Würzburg located at Meudon. Successful observations were made with all three radio telescopes, but only results obtained with the 3m Würzburg dish and the Meudon Würzburg antenna were used to generate the eclipse curve shown in Figure 3. On the basis of this curve, Laffineur et al. (op. cit.) concluded that:

1) At frequencies of 555 MHz and 1,200 MHz the radio Sun did not appear to be significantly larger than the optical Sun (a conclusion that was subsequently shown to be incorrect); and

2) “It is necessary to suppose that at least a part of the solar radio emission derived from non-uniform sources distributed over the solar disk.” (Laffineur et al, 1950: 339; our translation). These “non-uniform sources” were thought to be associated with chromospheric plages.

The second solar eclipse involving the ENS team occurred on 1 September 1951 but was viewed solely from Africa (see Orchiston and Steinberg, 2007), so it was only on 25 February 1952 that another eclipse was observed from near Paris (Blum et al., 1952). This partial event was monitored at 169 MHz with a ‘searchlight antenna’ set up at Marcoussis, and the resulting eclipse curve from this site and Dakar—

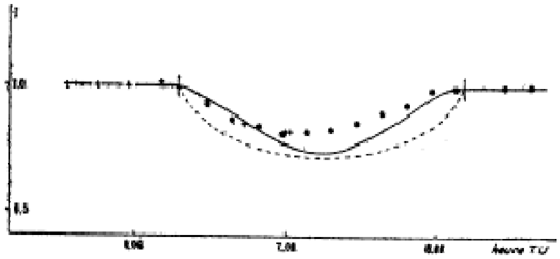

Figure 3: The 28 April 1949 eclipse curve. Dots represent measurements at 555 MHz and crosses at 1,200 MHz. The solid curve indicates the profile expected from a disk of uniform brightness, while the dashed line shows the expected profile if the radio emission derived from an annular ring (after Laffineur et al., 1950: 338).

where the eclipse was total (Figure 4)—confirmed the conclusion following the 1951 eclipse: that at 169 MHz the Sun was non-circular but took the form of an asymmetrical flattened ellipsoid.

2.4 Contributions to Instrumentation and Theory

In addition to observationally-based papers, some of the ENS staff also contributed papers which were solely about radio astronomical instrumentation (e.g. see Arsac et al, 1954; Mosnier and Steinberg, 1950; Steinberg, 1949, 1950, 1952a, 1952b). As Steinberg (2001: 511) notes:

> [Soon after joining the ENS] … I started developing radio receivers. After 4 years of occupation France was very backward in electronics while Great-Britain, Canada, Australia and the United States had many physicists and engineers who had learnt a lot when developing radars during WW II and had many surplus military radars. Fortunately I brought back from Great-Britain the books "Microwave Receivers" and "Vacuum tube amplifiers" from the MIT Radiation Laboratory Series which became our Bible. E.J. Blum joined me within a few months. He knew much more about electronics than I did. I specialized in microwave receivers and he developed the technology of meter wave receivers. We wanted to cover as much as possible of the frequency spectrum. But the frequency bands actually studied were mostly controlled by the availability of the corresponding components.

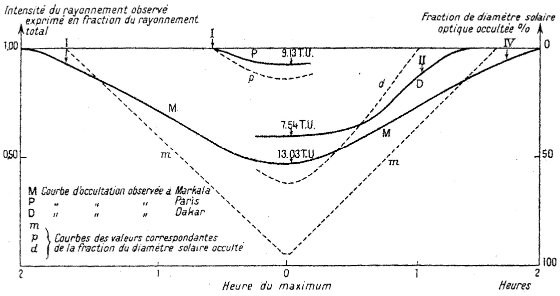

Figure 4: The 25 February 1952 169 MHz Paris (P) and Dakar (D) eclipse curves, plus the 169 MHz Markala curve (M) obtained in 1951 (after Blum et al., 1952: 1597).

A number of the ENS staff members also carried out research on radio astronomical theory. Denisse was the principal contributor, with papers on the role of a magnetic field in the production of solar radio emission (1946; 1947a; 1947b), the relation between solar radio emission and cosmic rays (1949a); the influence of refraction on the emission of radio waves in an ionised medium (1949b); the relation between solar radio emission and sunspots (1949c); the origin of thermal radio emission in an ionised medium (1950b); and the relation between solar radio emission and geomagnetic activity (1952; 1953a; 1953b). In 1956, Denisse also produced a 10-page review paper in which he combined some of his earlier results with those obtained by his Australian counterparts—including a useful account of the various spectral types of solar bursts, as identified by Paul Wild (for a review of this topic see Stewart, 2009). Finally, in 1954 Denisse and Simon published a paper on optical coronal emission and geomagnetic activity.

Meanwhile, in following up their Marcoussis observational papers, Blum, Denisse and Steinberg (1951b) examined the emission mechanisms associated with the small bursts that they believed combined to form noise storms. Their boss, Yves Rocard (1951), took this study further in one of his few escapades into radio astronomy when he published a paper titled "On a coronal radio emission mechanism." (our translation). Having said that, Denisse also teamed with Rocard in 1951, and they published a long mathematical paper where they examined the properties of a shock wave as it traversed an ionised medium. They finish by suggesting that plasma oscillations in the solar corona give rise to intense bursts of solar emission.

In an important paper, Michel Jorand (1955) examined the mechanism of solar radio emission in the corona, and identified the various altitudes at which emission at different frequencies was triggered. His work nicely complemented similar research that was undertaken at this time by the Australian radio astronomers in Paul Wild's 'Solar Group' (see Stewart, 2009).

In a long paper published in 1956 Paul Simon developed Denisse's (1952) earlier work and examined the relationships between solar radio emission and the magnetic properties of sunspots.

Finally, quite apart from research papers based upon their own French observations, Denisse (1950a) also published a 22-page review paper utilising 2,800 MHz Goth Hill data made available by Covington. In this paper, Denisse examines the relationship between sunspots and solar radio emission, and he reviews the theories proposed to account for emission at centimetre, decimetre and metre wavelengths.

3 SOLAR RADIO ASTRONOMY AT MARCOUSSIS

3.1 Introduction

In 1948 (Steinberg, 2001) the ENS established a radio astronomy field station at Marcoussis, ~20 km south of Paris, primarily to serve as a site for two World War II Würzburg antennas acquired by the Physics Laboratory that were to be used for both solar and non-solar radio astronomy (see Orchiston et al., 2007 for details). This radio-quiet environment attracted the radio astronomers at the ENS, and Marcoussis became a base for some solar radio astronomy projects—although solar monitoring continued all the while from the roof of the Physics Laboratory in Paris.

3.2 Solar Observations with one of the Würzburg Radio Telescopes

The first recorded solar research program conducted at Marcoussis was undertaken by Denisse (1952), who studied 167 MHz solar radio emission observed between 1948 and 1950 (inclusive), and related this to sunspot activity. He was able to distinguish two different sorts of sunspots, R-type spots which were connected with radio emission and Q-type spots which were not.

In a further solar study at Marcoussis, Jorand (1953) examined 160 MHz solar emission recorded between 1 September 1948 and 31 March 1951. This was a period of low solar activity, and all Jorand recorded were noise storms, bursts and occasionally outbursts. The noise storms appeared to be associated with sunspots, and accounted for the majority of the emission received during the monitoring period. Jorand proceeded to study the relationship between sunspots and the solar radio emission, and was able to demonstrate that the emission was more likely to occur when spots were within the narrow window of four days preceding and three days following central meridian passage. This led him to investigate—on theoretical grounds—the height at which the radio emission occurred in the solar corona.

In 1950, during the solar minumum, Blum and Denisse (1950) set out to investigate weak solar emission at two adjacent frequencies, 156 MHz and 164 MHz, using one of the Würzburg antennas. Simultaneous observations were carried out at the two frequencies between 10 October and 10 November 1950, and the incoming signals were recorded on two chart recorders. Comparison of the two chart records revealed the following:

1) Long periods of solar inactivity persisted for many days at both frequencies, but when interrupted by isolated bursts these occurred simultaneously at the two frequencies. However "… the detailed structure of these bursts varies from one frequency to the other and is not identical when considered only 1 or 2 seconds apart. Their durations are variable by as much as several tens of seconds." (Blum and Denisse, 1950: 1215; our translation). Very occasionally pairs of bursts occurred which had similar structures. But these were separated in time by 5-6 seconds, and always appearing first at 164 MHz.
2) In the course of several days, weak solar noise storms were recorded simultaneously at both frequencies, and they occurred when sunspots were present. Superimposed on the noise storm activity were occasional bursts which were indistinguishable from the isolated bursts mentioned above. It was significant that when bursts occurred during noise storms they almost never showed any correlation at the two frequencies (e.g. see Figure 5a).
3) On several occasions during noise storms, bursts were present at 164 MHz but totally absent at 156 MHz (Figure 5b), confirming the earlier impression (gained from evidence presented in 2), above) that the frequency range of bursts which accompanied noise storms was very restricted.

Blum, Denisse and Steinberg (1951a) subsequently carried out a further analysis of the observations at 164 MHz. They found that on days of very weak solar activity isolated bursts were generally widely separated in time, so that it was easy to determine the amplitude and duration of each individual burst. The strongest bursts had fluxes of between 2×10^4 and 2.5×10^4 Jy and lasted from 0.1 to 0.4 seconds. Having said that, sometimes groups of bursts occurred in the course of 2 or 3 seconds. In contrast, during periods of greater solar activity, the level of emission could fluctuate for several hours, and

> … one is led to believe that this type of [noise] storm is produced by the superimposition of bursts similar to those that are observed on days of relative non-activity. (Blum et al., 1951a: 389; our translation).

3.3 The 2-Element Interferometer

The first new dedicated solar radio telescope at Marcoussis was erected towards the end of 1952 and operated at 9,350 MHz. It consisted of

> … two cylindrical-parabolic antennas with a half-power beamwidth of 2° in the vertical plane, 20° in the horizontal plane. These were positioned along an East-West baseline and the distance between the antennas could be rapidly changed. The incoming radio emission was transferred via a wave-guide to the receiver … (Alon et al., 1953: 301-302; our translation).

Solar monitoring was carried out during the first six months of 1953 with a view to establishing the precise nature of limb brightening at 9,350 MHz. Earlier French solar eclipse observations offered two different models, one where at totality a uniform annulus located at 1.07 $R_\odot$ contributed 16% of the solar emission (curve A in Figure 6) and the other where the annulus was positioned at 1.04 $R_\odot$ and contributed 12% of the solar radiation (curve B in Figure 6). However, the Marcoussis observations proved ambiguous in that they could be used to support either model.

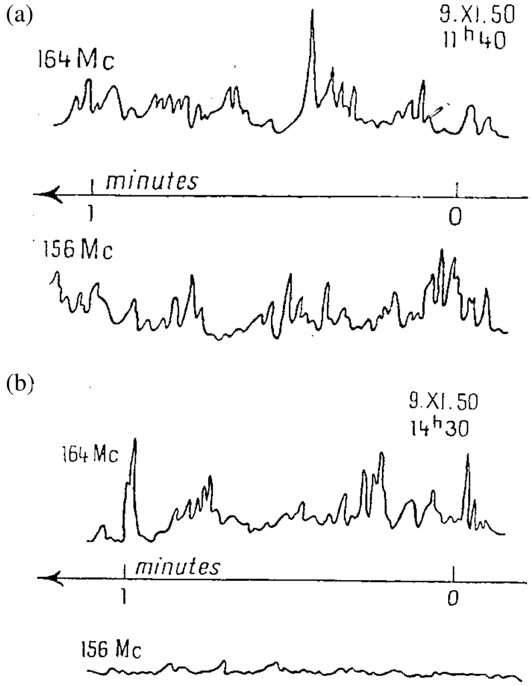

Figure 5: (a) Solar bursts recorded at 156 MHz and 164 MHz on 9 September 1950; (b) An absence of solar bursts at 156 MHz later the same day (after Blum and Denisse, 1950: 1215).

In the last three months of 1954 this radio telescope was used for another solar research program when Alon et al. (1955) investigated the one-dimensional distribution of radio brightness across the solar disk. First they derived a visibility curve for the Sun and then by making a Fourier transform of this curve they were able to calculate the integrated brightness of emission across the solar disk, perpendicular to the celestial equator (cf. Machin, 1951; Stanier, 1950). This is shown in Figure 7, where emission associated with a secondary lobe of the interferometer is apparent to the right of +1. On the basis of this Figure, Alon et al. (1955: 597; our translation) concluded that the diameter of the radio Sun, at 9,350 MHz, clearly exceeded that of the optical Sun, and that "The central part of this curve and the adjacent sloping edges are compatible with the existence of limb-brightening." Both of these conclusions confirmed earlier results obtained from French solar eclipse observations.

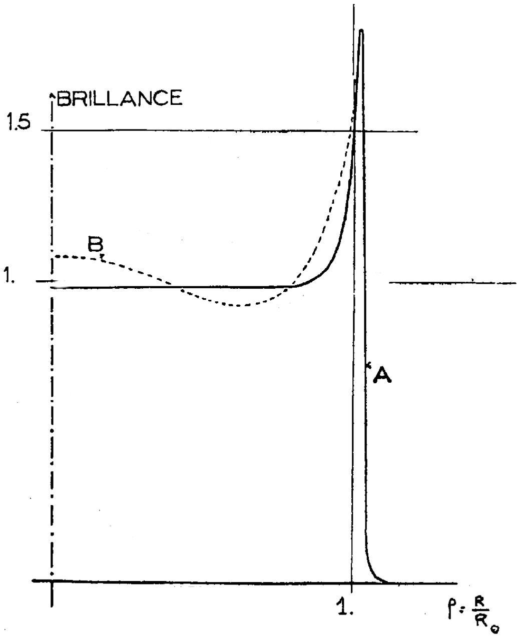

Figure 6: Alternative models (A and B) for limb-brightening at 9,350 MHz, developed from French solar eclipse observations (after Alon, Arsac and Steinberg, 1953: 301).

Finally, we should note that this 2-element interferometer has one further 'claim to fame' in that it inspired Jacques Arsac—one of the authors of the above studies—to develop a more elaborate interferometer (as discussed in Section 3.4 below).

3.4 Arsac's Non-Redundancy Array

Jacques Arsac (1955) pioneered the use of multi-element interferometers in French radio astronomy. Although he was well aware of Christiansen's East-West solar grating array at Potts Hill (Sydney), Arsac decided to take an independent approach, one which involved incomplete arrays:

> We stud[ied] incomplete arrays built with identic[al] antennae placed at abscissae equal to integer multiples of a same length, and deduced [i.e. reduced] from an uniform array by suppression of some of the antennae. With 4 antennae, 6 harmonics of same amplitude may be transmitted. It is impossible to get a constant spatial band pass with more than 4 antennae. Absence of one harmonic in the spatial band pass may introduce errors impossible to correct. (Arsac, 1956: 67; English abstract).

Arsac's primary inspiration came from French optical developments in interferometry, and in a long paper that was published in three installments he discussed the concept of interferometry in a radio astronomical context (Arsac, 1956). His ultimate objective was to construct an array that would provide information on the one-dimensional distribution of emission across the solar disk.

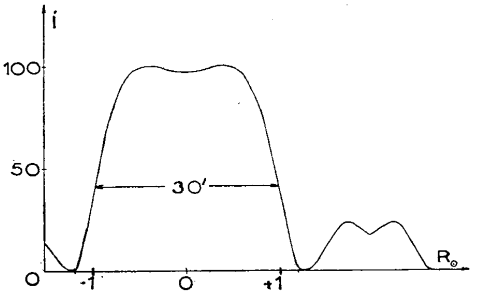

Figure 7: The integrated brightness of 9,350 MHz emission across the solar disk, based on interferometer observations (after Alon, Arsac and Steinberg, 1955: 597).

Arsac's final result was the 'Arsac Interferometer', which was installed at Marcoussis in 1955 (Figure 8). This novel array comprised four solid metal antennas 1.1m in diameter and of 60cm focal length "… placed in positions 0, 1, 4, and 6, in a manner to supply six spatial frequencies of equal amplitude without redundancy." (Denisse, 1984: 304). The array operated at 9,350 MHz, and each antenna had a beamwidth of 2° in the plane of the meridian and 7° in the horizontal plane.

In addition to operating the non-redundancy array as an interferometer, because the grating lobes of the interferometer were separated from each other by 1°, it was possible to obtain six traverses of the Sun during each day's observations and obtain a chart record of the distribution of radio emission across the solar disk. Figure 9a shows the record obtained on 3 February 1955, while in Figure 9b the same scans obtained on three successive days have been superimposed. These two figures show that radio plages were absent at this time (the Sun was at sunspot minimum), thereby allowing an accurate determination of the mean base level of emission from the quiet Sun at 9,350 MHz. Similar determinations of this base level of emission at 1,420 MHz and 500 MHz, derived from observations carried out in Australia at about this time, were published by Christiansen and Warburton (1953) and Swarup and Parthasarthy (1955).

Soon after it was operational the Arsac Interferometer was transferred to Nançay, but although the promise was there—as clearly evidenced by Figures 9a and 9b—it was never used to produce any useful scientific results. Denisse (1984: 307) explains why:

> … the ingenious concept of the "Arsac network [= array]" could not be used then: the small dimensions of the antennas limited sensitivity and the technology did not permit, at that time, the accurate phase adjustments which the system required.

Monique Pick (personal communication, 2007) recalls that when she joined the Paris Observatory radio astronomy team at Nançay she and Arsac spent some time trying to rectify the phase problems, but in the end they had to admit defeat.

4 EARLY SOLAR RADIO ASTRONOMY AT NANÇAY

4.1 Introduction

Through its growing international reputation in ionospheric research and in radio astronomy Australia made a successful bid for the 1952 URSI Congress, which was held in Sydney (Bolton, 1953; Robinson, 2002). Laffineur from the Institut d'Astrophysique de Paris and Steinberg from the ENS were the sole radio astronomers in the French delegation, and they were particularly impressed by the radio telescopes they saw during visits to the CSIRO's Division of Radiophysics field stations at Dapto, Hornsby Valley and Potts Hill in or near Sydney.[2] Of special interest were the solar spectrographs that Paul Wild and his colleagues had erected at Dapto (Stewart, 2009) and the 1,420 MHz solar grating array constructed by Christiansen's group at Potts Hill (Wendt, Orchiston and Slee, 2008).

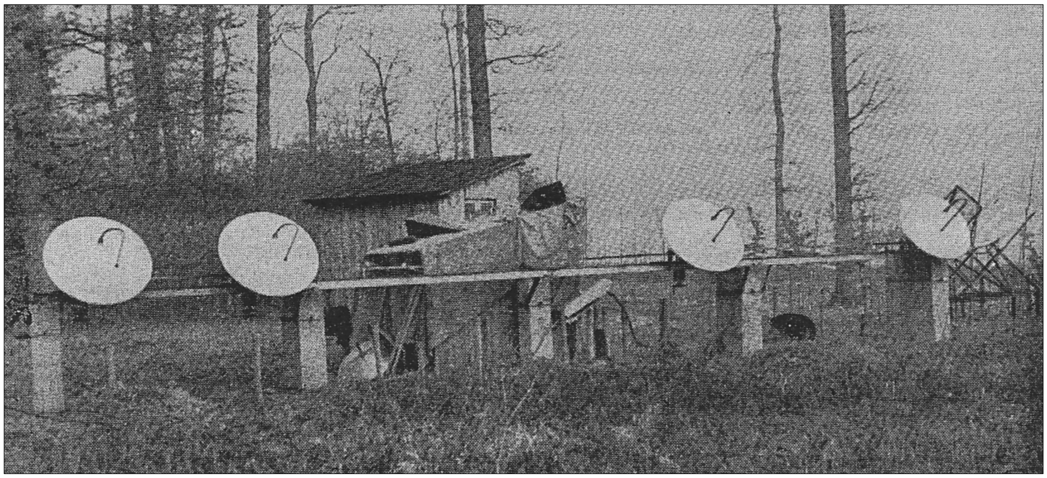

Figure 8: The Arsac Interferometer at Marcoussis (after Arsac, 1956: 406).

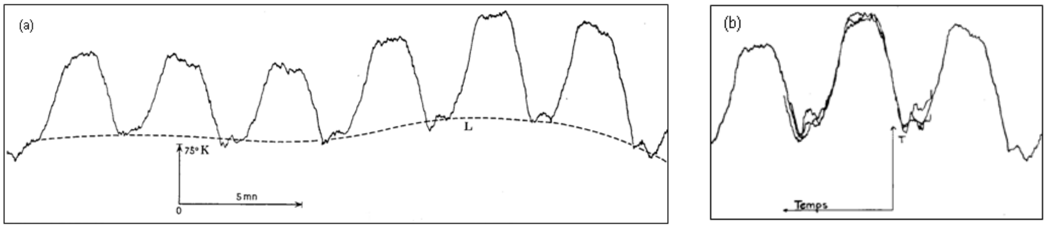

Figure 9(a): Six scans of the Sun taken with the Arsac Interferometer on 3 February 1955; Figure 9(b): Superimposed solar scans taken on three successive days (after Arsac, 1956: 409).

Laffineur and Steinberg returned to France convinced that similar instruments were required for French radio astronomy. Steinberg's first action was to approach ENS Director Yves Rocard about the establishment of a dedicated radio astronomy field station at a radio-quiet site, and this led to the founding of Nançay in 1953. One year later the radio astronomy group was transferred from the ENS to the Paris Observatory (see Bourgois et al., 1989).[3]

4.2 The Two 'Searchlight Antenna' Radio Telescopes

One of the simplest radio telescopes at Nancay comprised two 'searchlight antennas', one of which was fixed (see Figure 10) while the other was moveable and mounted on a railway track. Each was attached to its own 9,350 MHz receiver. Simultaneous observations were carried out with both antennas and were compared, but the two antennas were never configured so that they could be used as an interferometer. Steinberg and Ilya Kazès used this system to investigate solar scintillations (see Kazès and Steinberg, 1957), and were able to show that these originated in the Earth's atmosphere (Kazès, 1957).

4.3 Kundu's 2-Element Interferometer

In 1956 Mukul Kundu began research for a D.Sc. at Nançay, setting up an interferometer comprising two 2m diameter equatorially-mounted dishes located on an east-west baseline (see Figure 11). The spacing between the two dishes was 60 metres. Figure 12 shows a schematic diagram of the receiving system. Kundu used this interferometer to study the size, brightness distribution, polarization and evolution of localised sources of solar radio emission at 9,350 MHz (i.e. a wavelength of 3.2 cm).

In order to measure the brightness distribution of localized solar sources, Kundu devised an interferometric system where the distance between the two antennas would change continually in the course of a day. This was the first two-element interferometer that used Earth rotation synthesis in one dimension. The reception pattern of such a system is a series of fringes, where the angular separation, *dH*, measured in the equatorial plane varies as a function of hour angle, *H*, is given by

$$dH \propto \lambda / D \cos H \qquad (1)$$

where λ is the wavelength (3.2 cm) and D is the distance between the two antennas (60m). By using two antennas which remain pointed on the Sun all day, observations could be made at different values of *H*, thereby exploring different regions of the Fourier spectrum of the angular brightness distribution of the source without altering the separation of the antennas.

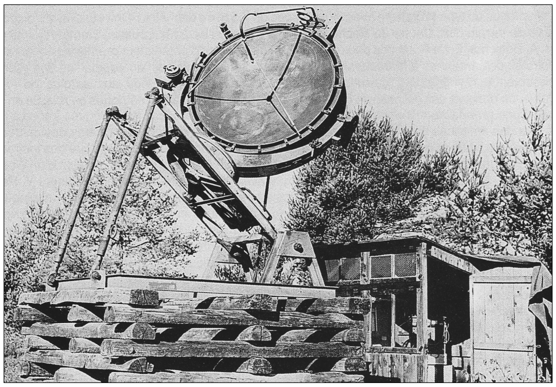

Figure 10: One of the two 'searchlight antenna' radio telescopes at Nançay (after Bourgois et al., 1989: 6).

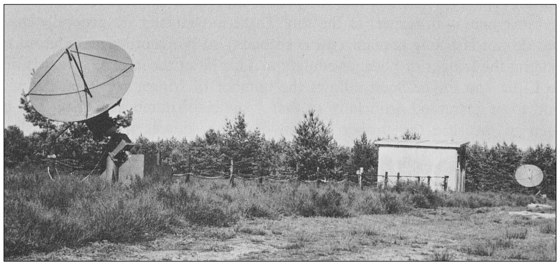

Figure 11: An image of the two antennas constituting the 'Kundu Interferometer' (after Steinberg and Lequeux, 1963: 66).

The resolving power varied continually from sunrise to noon and symmetrically during the afternoon. Therefore, it was possible to measure several Fourier components provided the orientation of the source relative to the fringes did not vary in the course of the day. The resolving power varied between 1.9′ and 6′ at the solstices and 1.8′ and 20′ arc at the equinoxes. When it was decided to carry out polarisation measurements, crossed feed horns were installed at the foci of the two antennas (Figure 13).

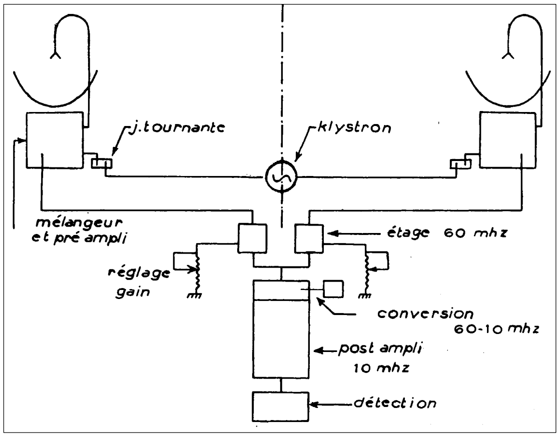

Figure 12: Schematic diagram of the interferometer/receiver system (after Kundu 1959b: 13).

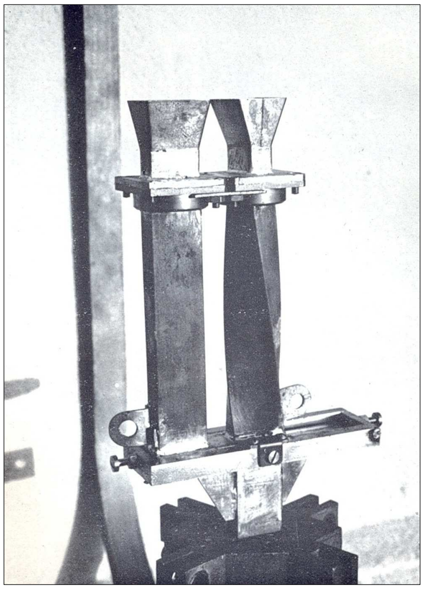

Figure 13: Two crossed feed horns whose E-vectors are perpendicular to each other (after Kundu, 1959b: facing 94).

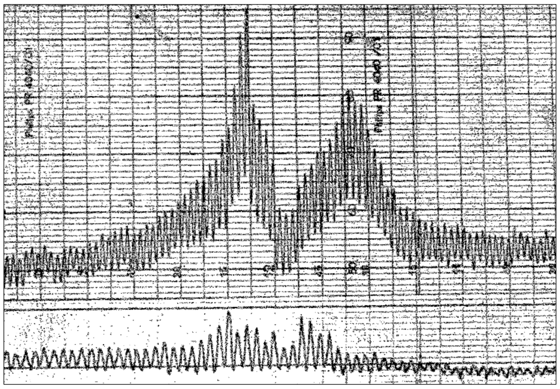

Figure 14: Chart records of the 25 January 1957 (top) and 17 January 1957 (bottom) outbursts (after Alon et al., 1957: 1728).

Alon, Kundu and Steinberg (1957) used the 2-element interferometer to study the diameters of radio plages. By measuring variations in the amplitudes of the observed interference fringes obtained near sunrise and sunset they were able to calculate the diameters of the radio-emitting regions, on the assumption that these were circular and did not vary appreciably in diameter in the course of one day's observation. They found that "… at least 75% of the energy from persistent sources was emitted from regions with diameters of 5′. Neverthless, active regions were sometimes observed with diameters that were much smaller." (Alon et al., 1957: 1728; our translation). The authors also report observations of two outbursts observed in January 1957 where the fringe patterns (Figure 14) not only allowed them to determine the diameters of the two emitting sources, but to follow their evolution with the passage of time. They found that the 25 January event always had an apparent diameter >1′ while the diameter of the 17 January outburst remained <1′ throughout the course of the observations.

In a paper presented at the Paris Symposium on Radio Astronomy (Kundu, 1959a) and a long paper in *Annales d'Astrophysique* based on his D.Sc. thesis, Kundu (1959b) provides further details of his solar research at Nancay between 1956 and 1958. During these more extended observations, he differentiated radio plages ('persistent sources') from bursts. Radio plages were found to consist of a narrow bright region, associated with a more diffuse region, the corresponding optical phenomenon being a sunspot surrounded by faculae. Kundu found that the diameters of radio plages ranged between 1.5′ and 12′. Those sources with diameters ~1.5′ were relatively intense and their average brightness temperatures could reach as high as 500,000 K, that is, coronal temperatures (see Figure 15). Sources with larger diameters, (i.e. 10′-12′) had temperatures ~100,000 K.

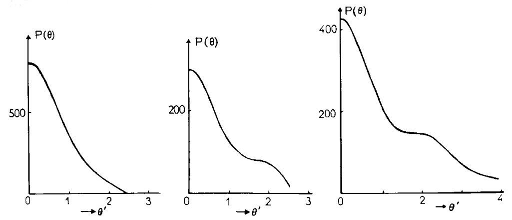

Figure 15: Brightness distributions of three typical radio plage sources; *P(θ)* is in arbitary units and *θ* in minutes of arc (after Kundu, 1959a: 224).

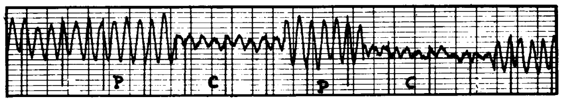

Figure 16: Chart record showing circular polarisation of a radio plage, where P indicates parallel polarisation and C crossed polarisation (after Kundu, 1959a: 233).

This core-halo structure typified radio plages, the core being circularly polarized and the halo unpolarized. The core corresponded to the umbra of a sunspot. The observed coronal temperatures of the brightness peak (core) of a sunspot-associated radio plage implied that the source was optically thick. This finding led subsequently to the conclusion that gyroresonance radiation was involved (see Kakinuma and Swarup, 1962; Zheleznyakov, 1962). In the gyroresonance radiation process, the opacity in the corona is produced by the acceleration of electrons as they gyrate in a magnetic field. The opacity is produced at resonant layers where the frequency matches harmonics of the gyrofrequency: $\nu = \omega_e, 2\omega_e, 3\omega_e$, etc., where $\omega_e = 2.8B$ is the electron gyrofrequency in MHz. Because ω_e is proportional to B, this provided a powerful tool that could be used to measure coronal magnetic fields.

Kundu's doctoral research also showed that the emission from radio plages was sometimes partially circularly polarized (Figure 16), and did not change appreciably in the course of the day. Figure 17 shows a typical example, where the polarized component of the radiation has a diameter $<1.5'$, while the source of the total radiation is much larger. Kundu's measurements showed that the narrow and bright regions in a complex of sources are polarized, while the more diffuse regions do not contribute to any polarization. The later finding that the polarized component of the radiation from persistent sources increases with eruptive activity on the Sun only served to confirm this result.

The appearance of narrow bright regions was found to be associated with periods of intense solar activity. This is shown in Figure 18 where the average fringe amplitude near noon expressed as a percentage of total solar radiation (this number is a measure of the intensity of the source of diameter less than approximately $2'$) is plotted as a function of the number of bursts observed at 9,350 MHz during the same day. There is a good correlation between these bursts and chromospheric eruptions, so the probability of observing eruptions systematically increases with the intensity of narrow sources. Kundu concluded that a persistent source is likely to be an active center—the place of chromospheric eruptions and radio bursts—if it has a very localized bright region $<1'$ in size at centimeter wavelengths.

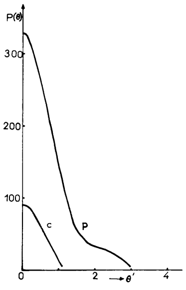

Figure 17: Brightness distribution of Type a sources showing parallel and crossed polarisation. *P(θ)* is in arbitary units and *θ* in minutes of arc (after Kundu, 1959a: 233).

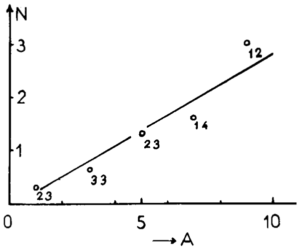

Figure 18: Plot of the average number of bursts observed per day (N) versus the average amplitude of fringes (A) near local noon, expressed as a percentage of total solar radiation. The number of days used in calculating the various points are listed beside the points (after Kundu, 1959a: 225).

In additon to the study of radio plages, between 1956 and 1958 Kundu made a systematic study of solar burst emission at 9,350 MHz, with particular interest in source sizes and their evolution with time.

At this frequency there were at least three distinct types of bursts:

> Type a: This is a simple burst, and typically has a duration of several minutes.
>
> Type b: This burst immediately follows a Type a burst, and is indicated by an enhanced level of emission that lasts longer than the Type a burst.
>
> Type c: This burst exhibits a gradual rise and fall which manifests a weak and gradual intensity increase followed by an equally slow decline. The duration of this burst is longer than that of Type a bursts.

Large bursts or outbursts were also observed at 9,350 MHz, but they were rare and often were complex. They were generally associated with bursts of spectral Type IV seen at metre wavelengths (for example, the events of 16 and 20 November 1956, 1 and 3 June 1957, and 3 and 23 March 1958). They were always polarized. Figure 19 shows the evolution of a large 9,350 MHz burst that was associated with a burst of spectral Type IV at 169 MHz.

Kundu was also able to confirm the existence of the bursts of very weak intensity found by Covington at 2,800 MHz (see Dodson et al., 1954), but which he could not prove to be of solar origin (since with a single antenna it is often difficult to distinguish bursts from external interferences or instabilities produced in the receiver). With the Nançay interferometer it was easy to recognize solar bursts because they manifest generally as an increase in the amplitude of the interference fringes. We now know that weak solar bursts, transients and microbursts exist across the electromagnetic spectrum, from microwaves to X-rays.

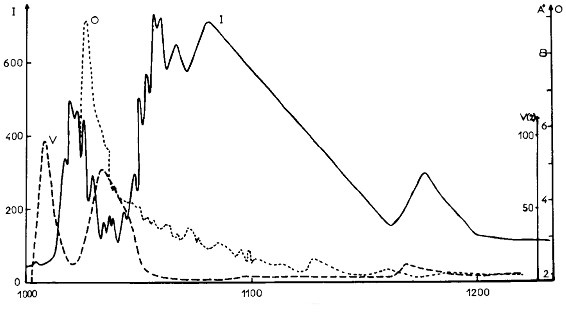

Figure 19: Variations in the intensity (I) and visibility (V) of the 20 November 1956 outburst between 1000 and 1200 UT. Also plotted is the light curve of the associated optical event (O) (after Kundu, 1959a: 230).

Assuming a regular source structure, Kundu used the observed fringe visibility to calculate the effective sizes of the sources of the bursts observed at Nançay. Figure 20 shows a typical simple source (its intensity and fringe visibility). He measured the size of each observed burst at the time of its maximum intensity, and the results are shown in Figure 21 where source diameter is plotted as a function of intensity. It can be seen that source size increases slightly with intensity. Source sizes larger than 2.5′ are rare. Thus, Type a burst sources on average seem to have diameters ~1' for weaker bursts (with intensities <10% of the quiet Sun intensity), and ~1.6′ for more intense bursts. The source sizes of bursts of Types b and c are shown in Figure 22 where the number of bursts of each type corresponding to a certain visibility is plotted, except for some bursts of Type b whose visibilities correspond to a fringe spacing of approximately 2′. It can be seen that the bursts can be separated easily into two families: Type b bursts have a small visibility and thus a large size, while Type c bursts have a very high visibility, on average 70%, corresponding to small sizes (i.e. ~0.8′). The sources of the large bursts associated with Type IV emission were typically found to be ~2′.

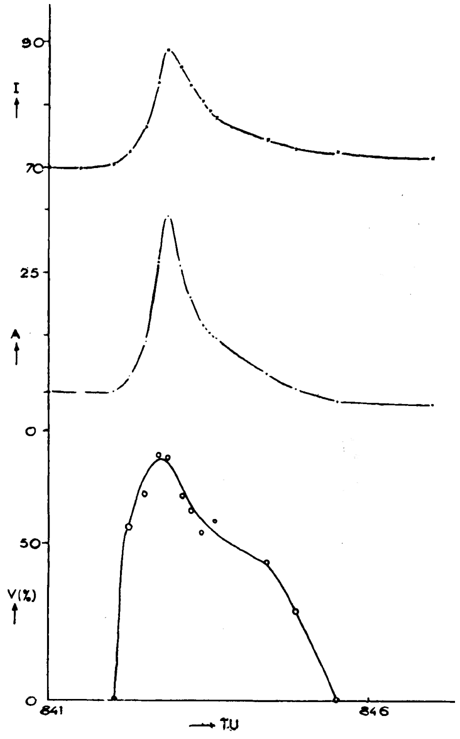

Figure 20: Evolution of a simple burst with time, showing that maximum visibility (V) occurs near the maximum intensity (I). A is the fringe amplitude, and TU is universal time (after Kundu, 1959b: 41).

Kundu was also able to investigate the evolution of source size during the duration of bursts. For a typical burst of Type a, the apparent size was found to be at a minimum about the time the burst reached maximum intensity. However, complex bursts were observed which sometimes showed a remarkably constant visibility despite great variations in intensity. In such cases the emissive sources would have experienced large variations in brightness without any appreciable variations in size. More complex variations of visibility during a burst were usually explained by a combination of the three fundamental types of bursts which are outlined on page 183.

As an example, Kundu studied the evolution in intensity and dimension of the complex burst observed on 20 November 1956 which was associated with a Type IV burst at 169 MHz. The intensity and visibility are plotted in Figure 19 as a function of time. The burst began with a precursor at 10:02:27 UT, and at that time the source was practically a point source, the visibility being 90% for a fringe spacing of 2′. The major radio burst began at 10:08 UT, and reached a maximum at 10:12 UT. At this time the visibility was 20%, indicating that the source had become larger. The major burst seemed to go through a period of minimum intensity and small diameter at 10:20 UT, and then the intensity rapidly increased again and reached a broad maximum around 10:35 UT. After that the intensity began to decrease, and this was accompanied by decreasing visibility. Kundu could only explain these variations of intensity and visibility during the burst by assuming the existence of several different radio sources.

The last phase of emission corresponded to a source of very large diameter, which was produced at the same time as the Type IV emission observed at 169 MHz. These emissions varied in parallel at the two frequencies and certainly were of the same origin. We now know that the Type IV burst is a broad-band continuum which occurs in different phases, and covers a wide range of frequencies from microwave to meter-decameter waves.

Since both the Nançay bursts and optical eruptions had their origin in the chromosphere, Kundu found it interesting to compare their intensities and sizes. The dimensions of optical eruptions were found to be smaller than their radio counterparts, with diameters of about 0.5′ and 1-2′ respectively.

The brightness temperature of Type a bursts was found to reach several tens of millions of degrees, so they are probably not of thermal origin, and the same situation was found to hold for the large bursts associated with Type IV emission. Kundu found that the brightness temperature of bursts of the gradual rise and fall type did not exceed 10^6 degrees, and therefore could be of thermal origin.

Kundu also investigated the polarization of 42 of the bursts observed at Nançay, and he found that 26 (i.e. 60%) were polarized, with the degree of polarization generally varying from a few per cent to 50%. Bursts with polarization exceeding 50% were exceptional. Bursts of the gradual rise and fall type were always circularly polarized, while the large bursts associated with Type IV events were weakly polarized. Moreover, the polarized component of the radiation was found to originate from a source whose intensity was weak and almost constant. Kundu pointed out that it was important to note that after a large burst ended it left behind a radio plage which was strongly polarized (>50%) for long periods—for several hours in some cases.

While metric bursts of Types II and III in general were not polarized, the Nançay observations showed that most of the 9,350 MHz bursts associated with these metric bursts were polarized.

5 DISCUSSION

5.1 Scientific Results

While he and his colleagues were busy setting up their first radio telescopes, Denisse also directed his attention to non-observational matters. Consequently, the first papers published by the young ENS solar group dealt solely with theoretical issues. We believe that some of Denisse's papers are important in the overall history of solar radio astronomy, but because they were written in French, at the time they were published they did not reach as wide an international audience as they undoubtedly deserved. For example, in 1946 Denisse published a paper discussing the role of solar magnetic fields in producing what he termed 'gyro-magnetic radiation' (cf. Kiepenheuer, 1946), foreshadowing by several years pronouncements by Ginsburg (1953) and Shklovsky (1953) on synchrotron radiation, while in 1949 he suggested that coronal temperatures of between 2 and 8 million degrees existed in the corona in regions above sunspots (although he seems unaware—at the time—of the earlier papers by Martyn (1946) and Pawsey (1946) where a coronal temperature of 1 million Kelvin was proposed on the basis of theoretical considerations and radio observations respectively).

5.2 Instrumentation

French experiments in solar radio astronomy mirrored overseas trends, where it was quickly realised that dedicated solar instruments offered significant advantages over recycled WWII equipment. Initial experiments focussed on simple 2-element interferometers, but Christiansen's multi-element grating array in Australia inspired Arsac, Blum, Boischot, Gutmann (later Pick) and Steinberg to consider more ambitious designs.

Of all the early radio telescopes discussed in this paper, we believe that the Kundu Interferometer and the Arsac Interferometer stand out as exceptional. Kundu's 2-element interferometer was the first to use Earth rotation synthesis to produce a one-dimensional distribution of solar radio emission, and it made an important contribution to solar physics (see Pick and Vilmer, 2008). In stark contrast, the Arsac Interferometer did not contribute in any meaningful way to solar research, yet this innovative interferometer occupies an important place in the history of radio astronomy in that it paved the way for all future non-redundancy arrays of this type.

5.3 Heritage Considerations

The IAU's Historic Radio Astronomy Working Group is particularly interested in establishing how many of the early radio telescopes used world-wide prior to 1961 have survived, and it is a sad fact that none of the instruments discussed in this paper still exists.

6 CONCLUDING REMARKS

Of the material contained in the various observational papers discussed here, in our opinion the French solar eclipse observations and Kundu's interferometer observations were both internationally significant.

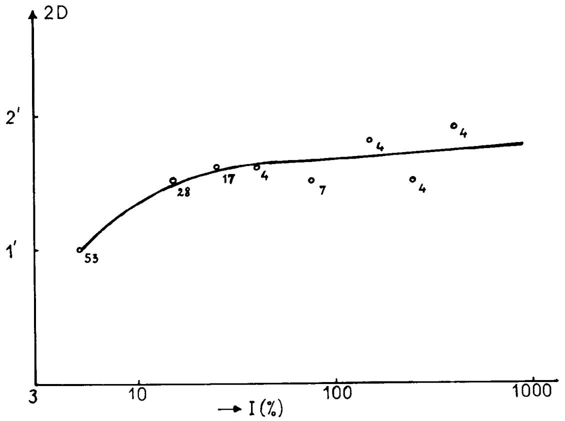

Figure 21: Plot of the average diameter (2D) of bursts as a function of their maximum intensity (I); 2D is in minutes of arc and I as a percentage of total radiation, The number of bursts used in calculating the average for each point is listed beside the point (after Kundu, 1959a: 228).

The eclipse observations revealed the shape of the solar corona at radio wavelengths, while other observations by the ENS team confirmed the finding of previous researchers, namely that limb-brightening occurred at 9,350 MHz (even if their result could not distinguish between the two competing models in vogue at the time). As a result of these investigations and other research carried out at the time, by the end of the 1950s Denisse's group was "… among the most active in the field of solar radio astronomy [internationally], a fact which was demonstrated by the organisation of a symposium on radio astronomy in Paris in 1958 …" (Denisse, 1984: 310).

Meanwhile, observations made with the Kundu Interferometer provided new information at 9,350 MHz on the apparent size, brightness distribution, polarization and evolution of the sources associated with radio plages and bursts, and new clues to their interpretation and their association with corresponding phenomena observed at optical, decimeter and meter wavelengths.

Finally, we must stress that this paper only reviews the early solar radio astronomy at Nançay, which served as a prelude to the construction there of three truly impressive solar research instruments. In 1956 a 32-element East-West solar grating array was completed and three years later it was joined by an 8-element North-South array. Both operated at 169 MHz and were known affectionately as the 'Grand Interféro-

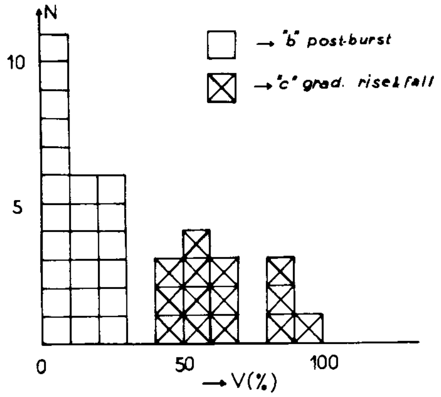

Figure 22: Distribution of the number of bursts (N) of Types b and c as a function of their visibility (V) (after Kundu, 1959a: 229).

mètre' (see Denisse, 1984: 308-309). Meanwhile, the year 1958 marked the completion of another ingenious Nançay radio telescope in the form of a 16-element East-West array which was designed to investigate the one-dimensional distribution of emission across the solar disk at 9,350 MHz (see Denisse, 1984: 307-308). Details of these radio telescopes and their research accomplishments will be the subject of the next paper in this series.

7 NOTES

1. This project was initiated under the auspices of the IAU Working Group on Historic Radio Astronomy in 2006, and three papers have been published to date. The first dealt 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); and the third with the Würzburg antennas that were at Marcoussis, Meudon and Nançay (Orchiston et al., 2007).
2. In 1952, Dapto, Hornsby Valley and Potts Hill were three of the four field stations maintained by the Division of Radiophysics in and near Sydney. The fourth field station was located at Dover Heights. For a review of these field stations, and others established by the Division of Radiophysics between 1946 and 1961, see Orchiston and Slee, 2005.
3. For further details of the establishment of the Nançay field station and the transfer of the radio astronomers from the ENS to Paris Observatory see Orchiston et al., 2007: 225-226.

8 ACKNOWLEDGEMENTS

We are grateful to Laurence Bobis, Josette Alexandre, Daniele Destombes, Amelia Laurenceau, Sandrine Marchal, Dominique Monseigny, Robert Zenagadin (Paris Observatory Library), Suzanne Débarbat (Paris Observatory); and Monique Géara, Marie-Pierre Issartel and Monique Pick (Paris Observatory, Meudon); and Ms Severine Choukroun (James Cook University) for their assistance.

In particular, we would like to acknowledge the Australia-France Co-operation Fund in Astronomy, the France-Australia Program of International Co-operation in Science (PICS) with the support of CNRS/INSU and the French Ministry of Foreign Affairs (France), and James Cook University, for funding this project.

Finally, we wish to thank James Lequeux (Paris Observatory); Ron Stewart and Harry Wendt (James Cook University), Richard Strom (ASTRON, The Netherlands), and Richard Wielebinski (Max-Plank-Institut für Radioastronomie, Bonn) for commenting on the manuscript.

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Dr Wayne Orchiston is an Associate Professor in Astronomy at James Cook University, Townsville. His main research interests relate to Cook voyage, Australian, French and New Zealand astronomical history, with emphasis on the history of radio astronomy, comets, historically-significant telescopes, early astronomical groups and societies, 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* (Springer, 2005). He also has a book on early Australian radio astronomy, co-authored by Woody Sullivan and Jessica Chapman, which (hopefully) will be published by Springer in 2010. Until the Rio General Assembly of the IAU Wayne was Chairman of the IAU Working Group on Historic Radio Astronomy.

Dr Jean-Louis Steinberg began working in radio astronomy with J.-F. Denisse and E.-J. Blum at the École Normale Supérieure after World War II. On his return from the 1952 URSI Congress in Sydney, he began developing the Nançay radio astronomy field station, and from 1960 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.

Dr Mukul Kundu is presently an Emeritus Professor of Astronomy at the University of Maryland. He was educated mostly in India. Like many young men of his generation at the time, he was anxious to go abroad for higher studies. The 1952 URSI General Assembly in Sydney probably oriented him in the direction of radio astronomy. Mukul then decided to go to Paris, on a French Government scholarship, with the objective of becoming a radio astronomer. He joined the École Normale Supérieure, and began working at Marcoussis with Arsac and Alon on the Arsac Interferometer. He then constructed the 2-element interferometer at Nançay that contributed solar data for his Doctor of Science at the Sorbonne. After a Post-doctoral Fellowship at the University of Michigan (Ann Arbor), Mukul accepted Professorships at Cornell University, the Tata Institute of Fundamental Research in Mumbai (India) and finally at the University of Maryland, where he was the Director of Astronomy for seven years.

Dr Jacques Arsac began working in radio astronomy in 1952 in the Physics Laboratory of École Normale Supérieure where he developed and used interferometric antennas for solar radio observations at centimeter wavelengths. He also developed the theory of interferometric antennas and the analysis of their performance for various types of observations. From 1956 onward he specialized in numerical calculations, learnt to use electronic computers, and ran the first Paris Observatory computing centre, using it to reduce astronomical data and contributing a lot to computer science.

Dr Emile-Jacques Blum was a retired astronomer from l'Observatoire de Paris. His main interests lay in radio astronomy technology, in particular the design and construction of sensitive receivers. He was deeply involved in various radio astronomy projects: solar eclipse observation in Africa; solar observations at Nançay with a 32-element meter wave interferometer; and the formation of the Institut de Radioastronomie Millimétrique (IRAM) and the building of its interferometer. Emile-Jacques was a Chairman of URSI Commission V, and served as a member of time-allocation committees in the US (at the NRAO), Germany (MPIfR), and in the Netherlands (ASTRON). It is with great sadness that we report that he died on 22 September 2009, long after this paper was completed but before this issue of the *Journal* went to press.

Dr André Boischot joined the French group of radio astronomers in 1954 at the beginning of the Nançay Observatory. He was first involved with Emile-Jacques Blum in the design and construction of the 32-element E-W 169 MHz solar array. He then worked with Le Grand Radiotélescope at Nançay on non-solar projects. Then, he initiated a new program to observe the Sun and Jupiter at decametric wavelengths and was co-investigator on the NASA 'Voyager' radio astronomy experiment where he studied the magnetospheres of the outer planets.

Journal of Astronomical History and Heritage, 12(3), 189-200 (2009).

GENERAL-PURPOSE AND DEDICATED REGIMES IN THE USE OF TELESCOPES

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Abstract: We propose a socio-historical framework for better understanding the evolution in the use of telescopes. We define two regimes of use: a general-purpose (or survey) one, where the telescope governs research, and a dedicated one, in which the telescope is tailored to a specific project which includes a network of other tools. This conceptual framework is first applied to the history of the 80-cm reflector at the Toulouse Observatory, which was initially anchored in a general-purpose regime linked to astrometry. After a transition in the 1930s, it was integrated into a dedicated regime centered on astrophysics. This evolution is compared to that of a very similar instrument, the 80-cm reflector at the Marseille Observatory, which was converted to a dedicated regime with the Fabry-Perot interferometer around 1910, and, after a period of idleness, was again used in the survey mode after WWII. To further validate our new concept, we apply it to the telescopes at the Washburn Observatory, the Dominion Astrophysical Observatory and the Meudon Observatory. The uses of the different telescopes illustrate various combinations of the two regimes, which can be successive, simultaneous or alternating. This conceptual framework is likely to be applicable to other fields of pure and applied science.

Keywords: telescope, general-purpose regime, dedicated regime, practices

1 INTRODUCTION

The role played by the telescope in the evolution of our knowledge of astronomy often remains hidden, even though it is obviously essential.

A number of studies have been carried out about astronomers' light collectors, for example, William Herschel's telescopes (Bennett, 1976; Hoskin, 2003), and the 12-inch telescope at Lowell Observatory that was used to search for trans-Neptunian planets and led to the discovery of Pluto (Giclas, 1980). More contemporary instruments have also been the subject of historical analysis. Gibson (1991) traced the technical difficulties linked to the construction of the Canadian liquid mirror telescope. The history of the British Isaac Newton telescope, in contrast with that of more recent British telescopes in the Canary Islands, reveals the influence, in both periods, of the scientific and technical context of such a project (Smith and Dudley, 1982). As for the itinerary that led to the construction of the Anglo-Australian 150-inch telescope, it reflects the political stakes which the United Kingdom had to face at the time, and in particular the difficult choice between two possible partners (see Gascoigne et al., 1990; Lovell, 1985). Bell's (2006) study of the construction of large telescopes by the Warner & Swasey Company provides evidence of the ties between science and industry in the field of astronomical instrumentation.

In France, Véron (2003) has shown the difficult installation of the equatorial in the eastern tower of the Paris Observatory. Davoust (2000) has described the construction and use of several telescopes at the Pic du Midi Observatory in a very special local environment that required unusual human qualities. The work of Audouin Dollfus with the large telescope at Meudon shows the successive uses of an instrument of exceptional dimensions (Dollfus, 2006a; 2006b; 2006c). Tobin (1987) has related the history of the Foucault telescope at the Marseille Observatory and has tried to learn lessons from it for the management of future astronomical projects. The large number of these analyses does not, however, exhaust the potential for historical research into any specific instrument.

The goal of the present paper is to examine how telescopes structure, or otherwise influence, research in astronomy, and to establish a general pattern for their often changing role in assisting (or leading) astronomical research. We are concerned with telescopes that were considered large at the time of their first light. The telescopes selected for study are all reflectors, except for the Washburn and Meudon telescopes, which are refractors. The historical period of interest starts with the beginning of astronomical photography (the 1880s), and ends with the advent of modern large telescopes in the 1960s and 1970s.

We first describe a general conceptual framework for evaluating the role of telescopes, and define two regimes, a regime of general use (or a survey regime) and a dedicated regime. We then carry out a detailed assessment of the role of one specific instrument, the 80-cm telescope at the Toulouse Observatory, and establish its successive roles. We then move on to a comparison with another telescope of the same size in a very similar environment, revealing similar roles, but with a different chronological order. Finally, the pattern which emerges from this comparison is tested on the history of other telescopes, taken from the literature, thus providing a conceptual framework for analysing the history of astronomical instruments.

2 THE GENERAL AND DEDICATED REGIMES OF USE

The large reflectors and refractors built toward the end of the nineteenth century by and large match the technical and scientific criteria set up by astronomers. In this sense, large telescopes are comparable to the generic instruments defined by Shinn (1993; 2001): their flexibility, optical quality and their ease of use allowed them to satisfy a large range of demands. Telescopes thus fit in a specific technological context, one strongly marked by the determination of the position of celestial objects—i.e. astrometry. This first regime of use, which we call the 'general regime' or 'survey regime', considers observing as a global activity of the observatory. The instruments are not dedicated to a specific task; rather, they fit in a general scientific pol-

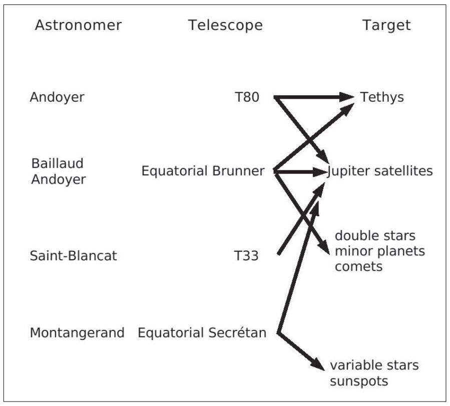

Figure 1: The general-purpose regime at the Toulouse Observatory in 1886-1887.

icy as defined (explicitly or implicitly) by the director, that of gathering measurements. In a sense, it is a survey mode, where the instruments are put to the task of measuring whatever can be measured with them. One can thus state that it is the instrument, not the astronomer, which drives the science that is carried out. The astronomer is content to observe using the available tools.

An example of this general regime can be found in the annual report of the Toulouse Observatory for 1885-1886, which was organized around the instruments (see Figure 1). There were four telescopes, an astronomer was in charge of each of them, and they all participated to the best of their performances in the observation of a series of targets. Except for the 33-cm telescope, they were all used for several programs.

At the other extreme is the dedicated regime, which corresponds to very focused and more oriented scientific practices. Here again, the technical, scientific and political contexts determine and shape the uses of the telescope. A specific kind of celestial target, a new dynamic recruit to the team of astronomers, the emergence of an innovative technology (e.g. the microphotometer), a new scientific program or even an entirely new field which compels teams or institutes to reorient their activities, are among the factors that can impose a dedicated regime upon certain instruments. The telescope is then associated with a definite practice, its mechanical and optical performances are overhauled, and new auxiliary instrumentation is acquired in response to new observational goals. The general scientific policy of the observatory is no longer the dominating factor in the use of the telescope; it is rather a combination of new performances of the telescope and its tailoring to a specific program.

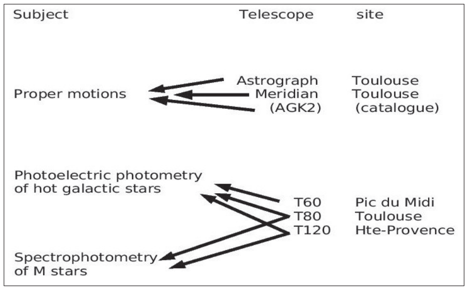

Figure 2: The dedicated regime at the Toulouse Observatory in 1957-1958.

An example of this second regime is found in the annual report of the Toulouse Observatory for 1957-1958, which is now organized by scientific fields (see Figure 2). Astrophysics is divided into two programs, which makes use of three telescopes, only one of which is local. The 60-cm telescope is located at the Pic du Midi Observatory and the 120-cm reflector at the Haute-Provence Observatory. In other words, the astronomers do not satisfy themselves solely with the locally-available telescopes in order to pursue their scientific programs. The latter clearly drive the use of the telescopes.

As pointed out by a referee, the dichotomy in the roles of telescopes can be seen in different ways. This can be the tension between astronomers who want to undertake research on a specific topic of their choice and those who use the available instruments for the purpose(s) for which they were originally designed. This can also be the distinction between scientific programs shaping the instruments and the available instruments determining the programs. But, from a socio-historical point of view, it is essential to consider the telescope as an inanimate actor with a role to play in the conduct of scientific research.

At any rate, we do not propose these generalist and dedicated regimes as two rigid ideals, to which all telescopes have to conform. The main point of this paper is to show the flexibility of these concepts, allowing them to shed new light on the most diverse situations. One of the characteristics of these two regimes of use is precisely the diversity of practical situations and thus of possible combinations of the two regimes: successive, simultaneous and alternating. We insist on the point—and the historical examples that we present bear this out—that there is no unique historical process setting once and for all the uses of a telescope in a quasi-teleological order, moving it in time from the general to the dedicated regime. Again, our empirical approach accounts for a large variety of historical situations, whilst offering a coherent framework for their socio-historical understanding.

3 THE 80-CM TELESCOPE AT THE TOULOUSE OBSERVATORY

We begin with the long history of the 80-cm telescope at the Toulouse Observatory (Figure 3), focusing on the role of the instrument in the order of practices and on its possible implication in scientific policies. We strive to understand how the different uses of such a technical object are related to the successive research projects.

The 80-cm telescope was in fact the final outcome of a long quest to equip the Toulouse Observatory with a large instrument. The initial project, in 1845, called for a mural circle. When, in 1863, the Director of the Observatory learned of Foucault's experiments with an 80-cm mirror, he reoriented his quest in favor of an 80-cm telescope. Numerous hurdles prevented the instrument from being acquired before 1877, and it actually was only put to full use in 1887 (Lamy, 2009).

From 1887 to 1970, the 80-cm telescope fitted into two principal, distinct and successive techno-scientific regimes. Within the first regime, service was organized around the instruments. The purpose of astronomers was to make a detailed inventory of the night sky. The main concern of the Director was thus to put all the instruments of his institution to good use toward that goal. In other words, the technological tools directed scientific activity. After a transitional phase in the 1930s, the second regime was organized around a discipline: astrophysics. The physical knowledge of stars, their composition and their structure dominated most of the scientific activity within the Toulouse Observatory, especially in the period following WWII. From then on, astrophysics structured the service.

We will now attempt to distinguish how the 80-cm telescope was modified and used in these two distinct scientific cultures.

3.1 The First Regime: The Telescope Directs Scientific Activity (1887-1935)

During this first period, the 80-cm telescope was an undifferentiated instrument in the global research strategy of the Toulouse Observatory, which was centred on astrometry. In practice, this meant observing stars and noting their positions, as well as those of planets and their satellites. However, each instrument had a specific role which took into account its particular capacities as far as possible.

The Observatory's services were organized around the instruments and one astronomer was responsible for each. Three astronomers worked at the Toulouse Observatory in 1884, five in 1890 and seven in 1900. These astronomers were helped in the dome by one or several assistants, and by the caretaker in some instances. Between 1880 and 1931, the observers running the 80-cm telescope were, successsively: Benjamin Baillaud, Charles Fabre, Henri Andoyer, Eugène Cosserat, Henry Bourget, Alphonse Blondel and Emile Paloque.

Toulouse Observatory was one of the eighteen institutes participating in the Carte du Ciel project. The astrograph was the principal technical tool of this photographic survey, but the 80-cm telescope was also used in this context, along with all the other instruments at the site. The astronomer Henry Bourget made several "… pictures of photographic calibrations for the international catalogue photographs." (Baillaud, 1903: 53; our translation). In 1903, he noted that "… one easily obtains on the same plate 60 stars belonging to 25 or 30 different photographs of the catalogue." (ibid.). In 1888, the telescope was also used to measure numerous very weak stars in one of Herschel's catalogues (Baillaud, 1889).

Baillaud's field of scientific interest was celestial mechanics. He examined Saturn's satellites with the 80-cm telescope, whose collecting power was an asset in this endeavour. The purpose there was to construct and refine the ephemerides of the satellites. Baillaud (1891: 40; our translation) indicated that "… this work for which this instrument is appropriate will be pursued for a long time with a view to determining elments of the orbits."

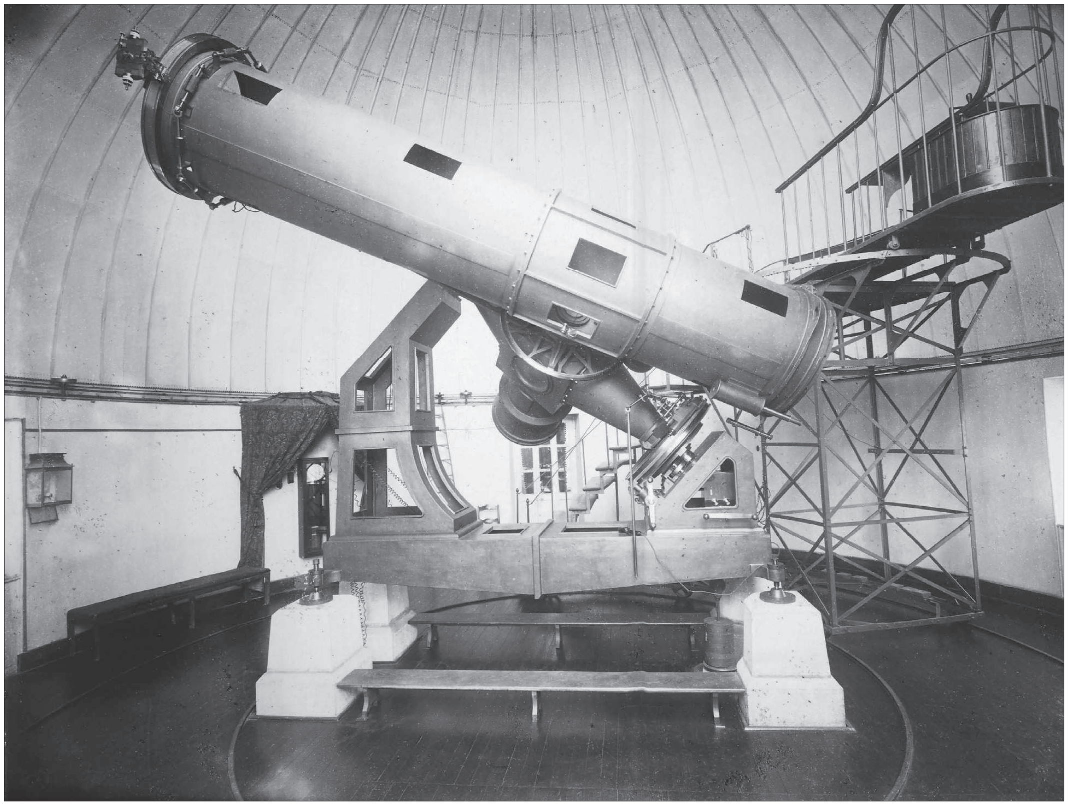

Figure 3: The Toulouse Observatory 80-cm reflector (courtesy OMP Archives).

Baillaud's successors as Director of the establishment after 1908, Eugène Cosserat and Emile Paloque, occasionally pursued this research. Cosserat mentioned in 1910 that he had spent twenty-two evenings that year at the telescope "… continuing the observation of the satellites of the large planets …" (Cosserat, 1910: 62, our translation; cf. Baillaud, 1891). Meanwhile, Paloque explained that he had made eighteen visual observations of Rhea, Dione, Titan, Tethys and Hyperion, as well as "… 32 observations of Jupiter's satellite I; 34 observations of Jupiter's satellite II; 38 observations of Jupiter's satellite III; 32 observations of Jupiter's satellite IV." (Paloque, 1926: 65; our translation).

The telescope was also used under special circumstances. In 1892, the Toulouse astronomers examined Comets Wolf, Denning, Swift, Winnecke, Brooks I, Brooks II and Holmes with this instrument (Baillaud, 1892).

This 'classical' use of the telescope centering on astrometry and on survey work does not necessarily mean that the large collecting power of the instrument was wasted: the photographic work on the star clusters and nebulae for the *New General Catalogue*, begun in the 1890s (Bourget, 1900), is visible evidence of the desire to make the most of its technical and visual potential.

Bourget, who was in charge of the telescope at the time, first concentrated his efforts on developing photographic techniques, making all sorts of attempts and trying all kinds of practical combinations. In 1895, the telescope received "… minor modifications intended to assist its use for celestial photography." (Baillaud, 1896: 38-39; our translation). However, the flexing of the tube caused by the guiding telescope disturbed photographic operations (Baillaud, 1897). The year 1898 was decisive because it saw "… the question of photography beyond its trial period and definitely solved." (Bourget, 1898; our translation). Further technical improvements were made in the years that followed. Three items were introduced that collectively allowed: the stopping at a distance of the clockwork movement; the hour angle to be locked and unlocked from a given point in the dome; and the telescope to be moved in hour angle during an exact number of 2-minute lapses of time (Baillaud, 1899). Taking photographs with repeated short exposures was simplified by the building of an automatic shutter, which was run by a metronome, thus ensuring a constant exposure time.

Bourget was trying to innovate in an extremely competitive scientific field. He confessed that he had "… never dreamt of rivalling the clever observers who … have obtained such fine images of nebulae and clusters." (Bourget, 1900; our translation). His purpose was completely different. He felt that "… a good use of the telescope would be to try to obtain the best possible small images, appropriate for precise micrometric measurements." (ibid.). Forced to do without the guiding telescope, he suggested following "… the guide star, with the help of the slow-motion levers, behind the sensitive plate through a hole made in the gelatine." (ibid.). The Toulouse astronomers judged this solution satisfactory because "… the loss of one star on the photograph is greatly compensated for by the improvement of the images." (Baillaud, 1898: 42; our translation).

Bourget (1900) began a programme of photographing galactic nebulae and clusters. These images "… were made for the purpose of measuring the positions of the stars they contain." (Baillaud, 1899: 55; our translation). He therefore used "… a micrometer … on a microscope with a movable plate … which was placed at his disposal by the [Toulouse] Faculty of Sciences." (ibid.). The experimental setup designed for the Carte du Ciel project inspired Bourget, who realized that it would be "… very interesting and hardly inconvenient to print on the images a graticule analogous to those used for the sky survey." (ibid.). Furthermore, he "… imagined a procedure which allowed the photographic printing of the graticule, in bright red, on an already developed image." (ibid.).

This scientific undertaking begun by Bourget was pursued sporadically after his departure for the Marseille Observatory in 1907. In 1909, Eugène Cosserat (page 67; our translation), explained that he had "… used the telescope to obtain images of clusters NGC 1960, NGC 2099, NGC 5846, NGC 6093 …", and in 1926 Emile Paloque (page 64; our translation) mentioned that he had "… located the images of clusters and nebulae already photographed by H. Bourget in 1898 and 1899."

To emphasize how subtle the distinction between the two regimes of usage of a telescope can be, we point out that if Baillaud had based his analytical perturbation theory of the minor planet Pallas on observations made at one of the telescopes rather than on archival data, this would have been a case of a telescope being used in the two regimes simultaneously.

3.2 An Era of Transition: Paul Lacroute, the 80-cm Telescope and the Genesis of Astrophysics at the Toulouse Observatory (1935-1945)

One astronomer who played a considerable role in the genesis of a genuine astrophysical project at the Toulouse Observatory was Paul Lacroute. Already in 1934 the Director, Emile Paloque (1934: 173; our translation), wished "… earnestly for a future appointment which will bring the Observatory an astronomer/physicist who can get the most out of this [80-cm telescope] …" Paloque's prayers were answered when Paul Lacroute, a physics graduate with a Doctor of Science, was named 'trainee assistant-astronomer' and started work at the Observatory on 1 February 1935; Paloque (1935) immediately assigned the 'great Gautier telescope' to him.

Lacroute decided to use the telescope for astrophysical research. To do this, he renewed the technical equipment associated with the telescope, which until then was strictly for photography. From then on, auxiliary astrophysical equipment was adapted to the telescope, and the technical chain of data analysis was expanded by the acquisition of measuring instruments.

A radial-velocity spectrograph (Figure 4) was ordered from the Strasbourg Observatory in 1936 and delivered the following year (Paloque, 1936). In 1937 and 1938, Lacroute obtained "… 163 images of stellar spectra, about a hundred of which were long exposures, associated in particular with the study of hot stars with variable emission lines." (Paloque, 1938: 171; our translation). The variability was evidence of transient phenomena in the atmospheres of such stars. Furthermore, Lacroute drew up plans for a high-dispersion spectrograph (Paloque, 1936). Finished in November 1938, this instrument was immediately mounted on the telescope, and Lacroute was able to continue "… to study particularly interesting irregular variables." (Paloque, 1939: 137; our translation).

Measuring the precise positions of the centres of the lines in these spectra required the use of a recording micrometer, and in 1939 the Caisse Nationale de la Recherche Scientifique, a new institution created in 1934 by Jean Perrin (Picard, 1990), provided a subsidy for the purchase of "… a recording microphotometer … from the English company 'Casella' …" (Paloque, 1939: 137; our translation). The technical adjustments also aimed for easier comparison of the stellar spectra with the reference spectra, which included lines of known wavelengths used to determine the other lines. During 1940-1941, Lacroute developed an assembly so that he could juxtapose the two spectra. In the process, he "… recut and polished the small prisms with sharp edges that allowed a better juxtaposition of the stellar spectra and the comparison spectra on the plate." (Paloque, 1941: 146; our translation).

The astrophysical research programme carried out by Lacroute led him to an important discovery in 1942. Helped by the Dutch astronomer, Willem Dirks, a refugee in France during WWII, the Toulouse astronomer noticed that "… the spectrum of the star 67 Ophiuchi, presented P Cygni type emission lines." (Lacroute and Dirks, 1942; cf. Paloque, 1942: 176). The P Cygni profiles proved the existence of an expanding gas shell around the star.

Lacroute's work and the scientific direction he moved towards transformed astronomical practice not only in the 80-cm telescope dome, but in the very organization of the Observatory. In 1942, the Director, Paloque, asserted that the purpose of "… the efforts made by Mr Lacroute with remarkable activity and rare competence …" was to organise a complete spectrographic service (Paloque, 1942: 175; our translation). It was in fact an astrophysical service, to which the instrment had become subordinated, but Paloque retained the instrumentalist's mindset peculiar to the first techno-scientific level. It is therefore no surprise that he had not initiated the new regime. With Lacroute, the instrument was used for specific and innovative observations which were no longer integrated into an overall organization. Its scientific use gradually became autonomous with respect to the other instruments.

Passage from practices centred on astrometry to the deployment of the new astrophysical discipline was accelerated at the Toulouse Observatory by the impossibility of exploiting the results previously obtained with the 80-cm telescope. In 1943, Lacroute obtained several photographic plates of clusters in order to "… study the influence of centering on the accuracy of star positions measured on these images." (Paloque, 1942: 130; our translation). His purpose was to find out whether there was "… any point in deducing stellar motion from the comparison of new images taken at the Telescope with old images of clusters." (ibid.) taken by Bourget. Lacroute noted that "… the result of this study was clearly negative, the slightest defect in centering causing prohibitive errors in the measured positions." (ibid.). Because of centering defects, Bourget's first-epoch plates could not be used for measuring proper motions. Thus, the final attempt to use the 80-cm telescope in a classical astrometric undertaking was a failure and confirmed the wisdom of the techno-scientific change begun by Lacroute.

3.3 The Second Regime: The Telescope in the Service of a Science Project (1945-1970)

Lacroute left the Toulouse Observatory in 1945 to join the Strasbourg Observatory (Paloque, 1946), and his efforts to organize astrophysical activity around the 80-cm telescope were pursued and increased by Roger Bouigue, who replaced him in 1947.

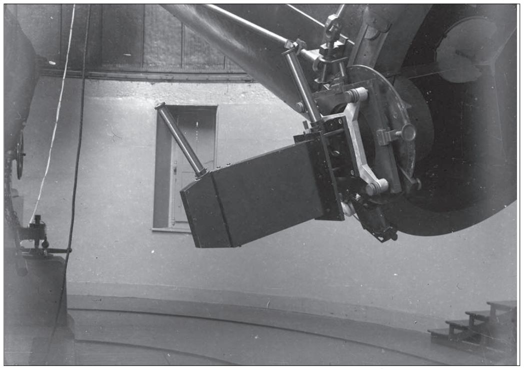

Figure 4: Lacroute's spectrograph (courtesy OMP Archives).

Under the impetus of Bouigue, the auxiliary instrumentation and the mechanisms for gathering information developed considerably, thus expanding what Latour (1989: 606) has called the 'metrological chain'. The 1950s were especially fruitful for the development of spectrographs adapted to the telescope. In 1952, a recording system "… of the comparison spectrum was entirely reconstructed." (Paloque, 1952: 179; our translation). Thus, the spectrum of iron was obtained differently. Henceforth, fluorescent tubes were used to produce other comparison spectra (ibid.). Now it was possible to record stars of magnitude 7, "… in particular those whose spectra presented wide atomic lines." (Paloque, 1952: 180; our translation). In 1955, Bouigue drew up plans and calculated the optics for a "… spectrograph with prisms capable of being associated with the 80-cm telescope … which should allow the study of weak stars over a fairly wide spectral range (4000 to 8000 Å)." (Paloque, 1956: 5; our translation). By the following year, several nights were dedicated to obtaining the spectra of cold M-type stars with the new spectrograph (Paloque, 1957), and at the same time astronomers obtained "… a Soleillet-type sampling spectrograph covering the entire spectral range of 3600-8000 Ångstroms with a perfectly flat plane." (Paloque, 1957: 225; our translation). The end of the decade was particularly important for the astrophysical equipment on the 80-cm telescope. During the 1959-1960 academic year, Bouigue started the construction of an electronic spectrocomparator as well as a double-grating spectrograph with double dispersion for variable stars. The former instrument "… should allow the rapid and precise measurement of stellar spectra accompanied by a comparison spectrum with a view to determining the stars' radial velocity." (Paloque, 1960: 344; our translation). Meanwhile, the double-grating spectrograph was intended for the " …

systematic study of spectra of cold variable stars … [in order to] specify the evolution of atmospheric characteristics in the course of these stars' pulsations." (ibid.).

Bouigue also innovated in the development of photoelectric photometers. In 1952 and 1953 he prepared a "… cell with a Lallemand electron photomultiplier which, associated with coloured filters, should permit the determination of intensity of luminosity of bands with much more advantageous conditions than the spectrograph." (Paloque, 1953: 157; our translation). Installation of this new apparatus (Figure 5) required the creation "… from scratch of a photometer adapted to the focus of the large telescope in order to make photometric measurements of stars and nebulae in seven different spectral bandwidths." (Paloque, 1954: 189; our translation). In 1954, a Meci electronic recorder was associated with the Lallemand cell in order to obtain "… photoelectric measurements of very luminous stars … in various spectral bandwidths." (Paloque, 1955: 195; our translation).

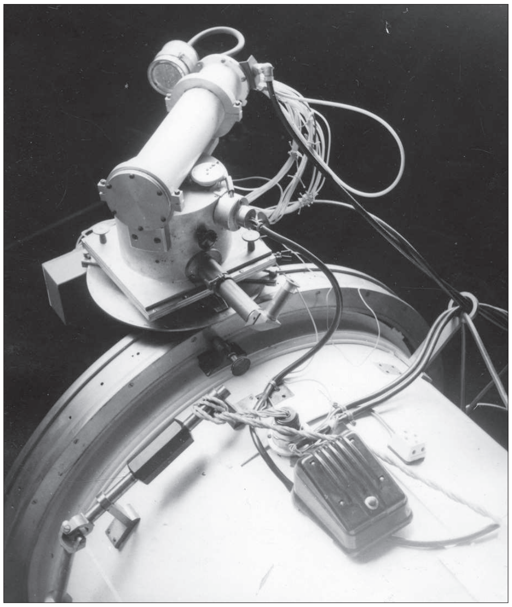

Figure 5: The Lallemand electron photomultiplier (courtesy OMP Archives).

In the same period, the telescope itself underwent only two transformations: the addition of a mounting plate at the focus in 1956 (Paloque, 1957), and the change from a Newtonian to a false Cassegrain focus (Bouigue, 1966). These modifications were not required for scientific reasons but were justified by a desire for greater comfort for the observer. The longer focal length meant that the astronomer was no longer required to observe from the top of a high ladder, and the mounting plate simplified the attachment of auxiliary instrumentation at the focus. Thus, the telescope was no longer the object of innovation in this era of scientific optimization, for it had reached its technical maturity and was used to the maximum of its intrinsic capability.

The addition of the auxiliary instrument even further extended the network in which the telescope was included. Maintaining these instruments required the recruitment of new specialised technical personnel, so four positions for technicians and assistants were created for the astrophysical division or were transferred from the Carte du Ciel group between 1950 and 1962. Furthermore, two scientists were hired in 1956 and 1957 to make observations and to carry out the new research programme.

The setting up of an astrophysical division required the creation of a network of actors and auxiliary instruments that constituted a number of intermediaries between the observations and the scientific results. The telescope was integrated into a techno-scientific network that aimed at imposing astrophysics as the heart of scientific activity at the Toulouse Observatory.

As a result, the range of astrophysical research at the Observatory was expanded, and the telescope was used in collaborative studies with other observatories. Thus, from 1954 (Paloque, 1955) the Toulouse Observatory and the Marseille, Pic du Midi and Haute-Provence Observatories participated in "… photoeletric measurements of photographic and visual magnitudes of galactic stars." (Paloque, 1960: 343; our translation). Similarly, in 1958-1959 the Toulouse Observatory and its 80-cm telescope took part in a campaign organized by the Stockholm Observatory to examine the star β Lyrae (Paloque, 1959). From this time on, research projects were part of national and international collaborations and exchanges.

This greater exchange of information and scientific data spurred the growth in Toulouse of a culture of technical exchange around the 80-cm telescope. This reflector and its auxiliary equipment were gradually inserted into a national network of instruments, and Paloque (1952: 180; our translation) noted that "… the very satisfying results obtained with this telescope give Toulouse Observatory important possibilities that are currently unique in France, which has attracted several Parisian researchers looking for spectra."

In 1956-1957, an astronomer at the Milano-Merate Observatory, Pietro Broglia, came to Toulouse in order to learn how to carry out photoelectric observations and manufacture interference filters (Paloque, 1957). In this way, the Toulouse researchers spread the competence acquired with the telescope. They also went to other institutes to gather photometric and spectroscopic data needed for their research. Exchanges were particularly frequent with the Haute-Provence Observatory.[1]

When Bouigue became Director of the Toulouse Observatory in 1961 the astrophysical division became a priority, and from then on its activities were listed first in the annual reports (e.g. see Bouigue, 1962: 286-287). Light pollution finally put an end to the use of the 80-cm telescope in the early 1970s.

In summary, the history of the 80-cm telescope reveals that this reflector went through two distinct regimes of usage in the course of its lifetime. It was first a general-purpose instrument used in a wide range of exploratory and/or inventory projects, which did not often make full use of its technical potential. Then, after a latent period which was linked to the absence of motivated users, it became the main tool of a wide-ranging astrophysical research project, until environmental factors eventually led to its demise.

The question that now arises is whether this history, and the pattern of use that it reveals, are specific to this instrument, and thus only of anecdotal interest, or if, on the contrary, it is but one example of a general pattern for the evolving role of telescopes in astronomical research.

4. COMPARISON WITH THE HISTORY OF THE 80-CM TELESCOPE AT THE MARSEILLE OBSERVATORY

It is apt to start our critical assessment of the above pattern by comparing it with one associated with the history of an identically-sized telescope used in a rather similar context at another French observatory.

While the history of Marseille Observatory may be rather different from that of the Toulouse Observatory, the two institutes were in fact on an equal footing in terms of funding, staff and instruments in the period of interest. The 80-cm telescope at the Marseille Observatory (Figure 6) came into operation in 1864, more than twenty years earlier than the Toulouse reflector, and was finally closed down in 1965, a few years before the Toulouse telescope stopped being used. During the period under discussion the two institutes had comparable numbers of scientific staff: between three and five astronomers.

The initial use of the Marseille telescope was similar to that seen at Toulouse. Indeed, the Director of the Marseille Observatory, Edouard Stephan (selected by Le Verrier in 1866), was a graduate of the École Normale Supérieure, just like Tisserand and Baillaud. He began with a programme to inventory nebulae, but the telescope was also used to observe comets, occultations of stars and transits of Mercury (Tobin, 1987). These programmes were typical of the general-purpose or exploratory regime.

Figure 6: The Marseille Observatory 80-cm reflector (courtesy OAMP Archives).

Significant changes then occurred at the Marseille Observatory through the influence of three academics from the Faculty of Sciences, Charles Fabry, Alfred Pérot and Henri Buisson, who dedicated themselves to furthering astrophysics. They developed an interference etalon that would be called the Fabry-Pérot filter and was used to measure radial velocities. In 1902, they applied their procedure to the Sun, but it was not necessary to use a telescope since a simple heliostat was sufficient to capture solar light (Fabry and Buisson, 1902; Fabry and Perot, 1902). In 1911, they turned their attention to the Orion Nebula using the 26-cm equatorial, and noted: "We hope to be able to employ it [their filter] with instruments which are more powerful and better adapted to the purpose, in particular with a reflecting telescope." (Fabry and Buisson, 1911; our translation). This eventually came to pass in 1914 when Fabry, Pérot, Buisson and a new collaborator, Henry Bourget, used the Marseille Observatory's 80-cm telescope to obtain fourteen images with 1-2 hour exposure times (see Buisson and Fabry, 1914). A question then arose about how the Marseille observers managed to obtain such long exposures since Baillaud in Toulouse claimed it was impossible. The answer lay in the use of interferogrammes, which meant that tracking defects had less effect on the quality of the images.

The Marseille astronomers thus were twenty years ahead of their colleagues in Toulouse, and had moved to a different level of practice where the instrument was integrated into and subordinate to a specific scientific project. Another remarkable innovation is that they decided to publish their results in English in four issues of the *Astrophysical Journal*, thereby reaching an international audience, which the Toulouse astronomers never did, with one notable exception (see Lacroute, 1942). However, this research did not last. Fabry, Pérot and Buisson were not on the staff of the Marseille Observatory, which made it difficult to institutionalize a service entirely dedicated to astrophysics. Then the outbreak of WWI prevented the development of large-scale scientific initiatives at both the Marseille Observatory and the Toulouse Observatory.

After the War, the Marseille astronomers no longer used their telescope, which was in poor condition (Fabry and Buisson, 1911). This is rather surprising, since one of the Directors during this period was Bourget, who had previously put the Toulouse reflector to good use with his photographic inventory of nebulae.

The Marseille telescope was only used once more when Robert Jonckheere joined the Observatory staff at the beginning of WWII. An experienced observer of binary stars since his youth (he was born in 1888), he resumed observing these systems and systematically measuring the separations and position angles of the components (Jonckheere, 1941a; 1941b; 1941c). However, his publications only listed the measurements themselves, with no astrophysical applications, which Jonckheere left to future generations of astronomers. In other words, this use of the telescope falls in the survey mode. The history of use of the 80-cm Marseille telescope is therefore rather different to that of its Toulouse counterpart. We can identify the two regimes—general-purpose and dedicated—but in the present case, they appeared in a cyclical order. The first regime, from 1866 to 1907, was essentially one of general-purpose, searching for and cataloging new nebulae, as well as observing targets of opportunity. The telescope then found itself in the dedicated regime quite early on (from 1914) compared to the situation at the Toulouse Observatory, thanks to the very innovative project introduced by Fabry, Pérot and Buisson. After a long period of inactivity (1914-1941), the telescope was then used by Jonckheere for a survey project, in the spirit of the general-purpose regime.

This return to scientific practice centered on the instrument and astrometry may be partially explained by Jonckheere's training. Unlike Baillaud, Lacroute and Stephan, who were graduates of the École Normale Supérieure, he was self-taught, with no academic degrees or scientific training, and he was therefore more inclined to pursue themes of interest to amateur astronomers, thus using the telescope in the framework of the first scientific regime. Another more compelling reason is that, after WWII, the astronomers at the Marseille Observatory preferred to use the larger aperture telescopes at the recently-founded Haute-Provence Observatory for their astrophysical research.

We now examine historical accounts of other large telescopes to put the above results in the broadest possible context.

5. THE CASE OF OTHER TWENTIETH CENTURY TELESCOPES

5.1 The 15.6-inch (39.6-cm) Refractor at the Washburn Observatory

The succession of regimes for this telescope is identical to the one that typifies the Toulouse instrument. In the early days of the Washburn Observatory, namely between 1884 and 1922, the *Publications of Washburn Observatory* essentially report survey work with the refractor (and the meridian instrument): micrometric observations of double stars and of faint stars near bright stars with known proper motions, observations of long-period variable stars, and of the minor planet Eros in 1900-1901 (see Leibl and Fluke, 2004). These programmes are characteristics of the first, general-purpose, regime.

The appointment of Joel Stebbins as Director in 1922 changed all this. Like Lacroute, who brought innovative projects and a spectrograph to the Toulouse Observatory, Stebbins contributed to the Washburn Observatory a new scientific project and new auxiliary instrumentation, namely a photoelectric photometer (ibid.). His first task was to test and improve the photometer, and then to search for small-scale light variations from known spectroscopic binaries. He then developed a project to monitor bright variable stars, particularly eclipsing binaries.

After this transition period, in 1930 to be precise, Stebbins embarked with two colleagues, Charles M. Huffer and Albert E. Whitford, on a project to investigate the reddening of stars, star clusters and galaxies, using the 15.6-inch refractor and the Mount Wilson 60-inch and 100-inch telescopes (ibid.)—just as the Toulouse astronomers also used the Haute-Provence and Pic du Midi telescopes for their projects. One outcome of their research was the law of interstellar reddening (ibid.). In this dedicated regime, the 15.6-inch refractor was only one among several telescopes used in a global strategy to pursue a scientific project.

5.2 The 72-inch (1.83-m) Reflector at the Dominion Astrophysical Observatory

This telescope presents an interesting intermediate case in our binary classification, in that the two regimes are simultaneously present after 1927 (see Batten, 2004).

The 72-inch telescope became operational in 1918, and was essentially used over the years for taking stellar spectra (Wright, 1968). The first scientific project, by J.S. Plaskett, involved the spectroscopic observation of binary stars, mostly of O-type, in order to determine stellar masses (Wright, 1968: 269). This type of research continued uninterrupted at least until the 1980s (with W.E. Harper and later Alan Batten), although observations were also carried out with the 48-inch reflector after it went into operation in 1962. This survey work fits into the first regime, despite the fact that another telescope was used, because the 72-inch could very well have been used. In 1927, Plaskett and J.A. Pearce initiated a survey of radial velocities of O- and B-stars in order to determine the solar motion and later the constants of galactic rotation (Wright, 1968: 276). Other projects of the 1920s and 30s involved the physics of emission lines in early-type stars, which was carried out by H.H. Plaskett and R.K. Young (Wright, 1968: 275). While not of survey type, these studies still fit into the first regime, since they made use of the available instrument with no alterations, thus letting the instrument lead research.

The arrival of C.S. Beals in 1927 marks the beginning of the second regime, but not the end of the first one. He implemented important changes to the existing auxiliary instrument, increasing the dispersion of the spectrograph and devising a method for including spectrophotometric calibration spots on the photographic plates, facilitating a study of the intensity and shape of spectral lines (Wright, 1968: 277). In order to record the data from the plates, he further developed a microphotometer in 1936 and an intensitometer in 1944. The science that he did with these data was perhaps not very different from that of Plaskett and Young, but the difference lay in the strategy: he adapted the telescope to his project, while the others worked the other way around. After the departure of Beals in 1946, the work in this regime was pursued by Andrew McKellar and Kenneth Wright (Wright, 1968: 280-281).

Further initiatives in the spirit of the dedicated regime included more adaptations of the spectrograph for new (high) dispersions in 1938, 1946 and 1955; observations with other telescopes (at the McDonald Observatory and the Curtis-Schmidt telescope at Portage Lake Observatory in Michigan); and the acquisition in 1962 of a 48-inch (1.22-m) telescope to be used as an experimental adjunct to the 72-inch reflector.

One may wonder why the changes made to the telescope by Beals and his co-workers did not eliminate the first regime of usage, which continued along with the second one. A possible answer may be found in a statement by Wright, who became Director in 1966. In his view, the research scientists were expected "… to select problems that are within the capabilities of the instruments at the Observatory …" (Wright, 1968: 271), suggesting that the telescope should direct research, while "… the general policy [was] to encourage each research scientist to carry on investigations in the fields in which he is most interested …" (ibid.) leaving room for personal initiatives, and thus for another regime of usage. But, he concluded: "... there is a strong tendency to continue along the general lines that have been established over the years." (ibid.).

5.3 The 83-cm Refractor at the Meudon Observatory

The history of the large refractor at the Meudon Observatory has been studied in detail by Dollfus (2006a; 2006b; 2006c). This instrument provides another example of passage from a general-purpose to a dedicated regime.

Jules Janssen established this Observatory toward the end of the nineteenth century to explore the new field of physical astronomy, and the giant refractor, built in 1897, was destined to explore the physical properties of celestial objects by way of both visual and photographic observations (Dollfus, 2006c). The instrument was perfectly adapted to this task, thanks to its long focal length and high optical quality.

The first observations, in 1898 and 1899, were of planets. The astronomers considered at one point conducting a "… systematic survey of planetary surfaces …" (Dollfus, 2006c:79; our translation), and organising it into a permanent monitoring service, but, at the time Meudon Observatory did not have the resources for such a project. The photography of star clusters became an important field of investigation for the large refractor at the turn of the century, and its optical qualities enabled it to resolve the central regions of clusters into stars (Dollfus, 2006c). At about the same time, it was possible to photograph stars surrounded by nebulosity. To Dollfus (ibid.) all of these experiments were meant to validate the potential of the refractor.

Henri Deslandres, who arrived in Meudon in 1897, was a spectroscopist. Although Janssen was still the Director, he was already 75 years old, so we can safely assume that Deslandres was *de facto* in charge, and this is reflected in the fact that all the instruments would be used for spectroheliography and the measurement of radial velocities. Direct photographic observations, for which the refractor was ideally suited, were soon discontinued (ibid.), and the telescope was mainly used to identify spectroscopic binaries. However, it was occasionally used for other purposes: spectroscopic studies of Nova Persei in 1901, the rotation of Uranus in 1902, observations of Comet Borelly in 1903 and of Jupiter in 1903 and 1904 (see Dollfus, 2006c: 90-94, 96-97, 98, 99-100). These investigations, together with those made with other instruments at the Observatory, clearly put the large refractor in the general-purpose regime.

After 1903, Deslandres devoted himself to spectroheliography and lost interest in the refractor, marking an important break in the use of the instrument (Dollfus, 2006c).

The large refractor was only used anew to the full extent of its visual potential with the arrival of Eugène-Michel Antoniadi, a wealthy independent astronomer. From the end of 1910 through into the 1930s, he studied the planet Mars in detail, making drawings and maps of its surface, and he finally put an end to the controversy over Schiaparelli's 'canali' (ibid.). He also made detailed drawings of Mercury, the surface of which is notoriously difficult to observe as it is so close to the Sun, and he occasionally studied Jupiter and Saturn (ibid.).

In 1924, Bernard Lyot, the inventor of the coronagraph, decided to apply his newly-designed polarimeter to the study of polarised light reflected off planetary surfaces, and mounted it on the large Meudon refractor, thus initiating a field of research that would be pursued well into the 1980s by the Meudon planetary astronomers, albeit mostly with other telescopes (ibid.).

Occasionally the large refractor was also used to observe other celestial objects, such as cometary nuclei or doubtful double stars, targets where its optical qualities were fully exploited.

After WWII, Paul Muller, a newly-arrived astronomer from the Strasbourg Observatory, temporarily modified the regime of usage of the large refractor in order to pursue his lifelong work on visual double stars. Between 1956 and 1974, under the sponsorship of the IAU, he secured 1000 position angles and separations for these stars (ibid.). Later he was transferred to the Nice Observatory, where he continued his quest with the 76-cm refractor at that institute. Just like Jonckheere at the Marseille Observatory, he limited his publications to measurements and the computation of orbital elements, putting the telescope in the survey regime of usage.

The large refractor returned to the dedicated regime in 1965, when, under the impetus of Jean Focas and in conjunction with similar observations made at the Pic du Midi Observatory, it was again used to study planetary surfaces. The highlight of that period is probably the analysis of the Martian atmosphere by Shiro Ebisawa, between 1973 and 1989. Drawings and photometric measurements obtained using the large refractor enabled him to study the seasons, as well as clouds and dust storms on the red planet (ibid.).

If one sets aside the post-WWII relapse into the general-purpose regime, very much in phase with a similar pattern for the 80-cm reflector at the Marseille Observatory, the large refractor at the Meudon Observatory displays the now-familiar pattern of passage from a general-purpose regime of observations for their own sake to the dedicated regime of exploration of planetary surfaces, where the instrument is perfectly adapted to the goal—imaging—and progressively becomes one element in a multi-telescope strategy for acquiring the necessary data for a single coherent project of planetary astronomy.

6 CONCLUDING REMARKS

We have analysed the history over almost a century of the 80-cm reflector at the Toulouse Observatory, and revealed its changing role in the conduct of astronomical research. In the first half-century of its existence, this was a general-purpose telescope, used for a multifaceted exploration of the night-sky and of the Sun. The telescope was then leading research, as the duty of astronomers was to make the best use of it, collecting data for future—but at that stage mostly undefined—research. The arrival of Pierre Lacroute, an astrophysicist, changed this role in the 1930s, and the telescope became dedicated to the study of stellar spectra for astrophysical purposes, until its demise in the early 1970s. In this second regime of usage, the telescope was only one of several tools in a strategy to pursue an astrophysical project.

In order to look for a common pattern in the use of telescopes, we then briefly examined the history of similar instruments at other observatories over the same time span. The 80-cm reflector at the Marseille Observatory was a good starting point since this instrument was identical in aperture, and because it was at a provincial French observatory it was used in a very similar scientific context. This reflector was used in the general-purpose regime for most of its lifetime. Only in 1914 did it make a brief incursion into the dedicated-purpose regime, when Fabry and his collaborators used it to test and exploit their now-famous interferometer.

The two regimes of usage can be identified in the history of other telescopes, generally moving from general-purpose to dedicated regime, with occasionally a relapse back to the former. For the 15.6-inch refractor of Washburn Observatory, the change to a dedicated project, the photometry of stars and the law of interstellar reddening, occurred in 1922 with the arrival of Stebbins. With the 72-inch telescope at the Dominion Astrophysical Observatory (DAO) it happened in 1927 with the arrival of Beals, and it occurred in 1910 with the 83-cm refractor at the Meudon Observatory when Antoniadi joined the staff.

The common point of all these regime changes is the arrival of a new astronomer on the staff. Only in two cases does the newcomer provoke a relapse back to the general-purpose regime. In one case, that of the DAO 72-inch, the two regimes continued alongside each other, presumably because old habits die hard.

The two regimes of telescope usage reflect the way scientists progress, first by exploring the field, gathering data, classifying them, and only later by pursuing specific leads suggested by the patterns emerging from these data. Our proposed conceptual framework for analysing the history of telescopes is thus relevant to the period when astronomy moved from systematic, instrument-led exploration to more focussed, project-led research.

The trend for telescopes to move from general to dedicated purpose continues to this day, when large multi-purpose telescopes such as the four ESO VLTs and the two Kecks in Hawaii, are used to explore the cosmic frontier in all fields, while other telescopes, such as the SLOAN 2.5m telescope at Apache Point Observatory, ESA's Hipparcos space astrometry mission, or the Wilkinson Microwave Anisotropy Probe of NASA, have been designed for specific tasks. However, the situation is now much more complex than in the past century, and our simple conceptual framework generally does not apply, as the various actors around large telescopes have different goals. The managers of telescopes are concerned with optimising the outputs of their instruments in terms of data and publications, while for science teams the telescope is but one tool in their strategy.

While recent works in the social studies of science provide numerous examples of instruments built—in part or totally—by scientists to pursue their own research (Clarke and Fujimura, 1996), analyses of the structuring effect of an instrument completely organising the research of a scientific realm are scarce (but see Vinck, 1992), and the main contribution of this paper is perhaps to show that the historical analysis of a scientific instrument can combine these two approaches with profit.

We have revealed a permanent structuring tension between institutionalised science policies and the relative autonomy of astronomers in their research projects, leading to a more intense (and possibly efficient) use of the telescope. Such a tension is probably even more striking in contemporary research, as we alluded to above. The variety and multiplicity of contexts allows us to better understand how one or the other component of the tension prevails, and provides a wider view of the actors' fields of action and of potentially constructive outside effects (such as institutions and research programs).

The use of a 'long time span' (Braudel, 1969) in the study of instruments provides a balance between the macro-approach which tends to underestimate local arrangements, and the micro-analysis which may neglect the wider stakes of science policies. In maintaining the interplay between macro and micro, one can grasp, for a given instrument, the importance of individual opportunities, of collective choices and the mode of integrations of technological innovations, as well as paradigm changes and other mutations in science. The role of these various elements depends on the epoch and the context, and at a given stage they define the prevailing potentials and stakes.

In closing, we suggest that the concept of the two different types of regimes—general purpose or exploratory and dedicated—as presented here be further tested and extended by investigating the interplay between the academic and industrial spheres over the same period. Surely the instrument-makers must have influenced the path of scientific research, or was it the other way around?

7 NOTES

1. For example, Bouigue, Chapuis, Pédoussaut and Rochette made three observing runs in January, May and July 1959 with the 1.2-m telescope at the Haute-Provence Observatory (Paloque, 1959), while in October 1959 and June 1960 Bouigue and Pédoussaut used the large spectrograph with the 1.93-m telescope (Paloque, 1960).

8 ACKNOWLEDGMENTS

We thank one of the referees, Dr Alan Batten, for very valuable comments which led to major improvements to this paper.

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Journal of Astronomical History and Heritage, 12(3), 201-210 (2009).

C. RAGOONATHA CHARRY AND VARIABLE STAR ASTRONOMY

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Abstract: C. Ragoonatha Charry, the First Assistant at Madras Observatory from 1864 to 1880, was not only a noted Indian observational astronomer but also someone who emphasized the need for incorporating modern observationally-based improvements into the traditional Indian methods of astronomical calculations. He was one of the first to argue for the establishment of an independent modern Indian observatory for education and training. He is credited with the discovery of two variable stars, R Reticuli and one whose identity is now the subject of debate. In this paper we provide background information about Ragoonatha Charry and his work at the Madras Observatory, and then discuss his variable star discoveries.

Keywords: Indian astronomy, Madras Observatory, Ragoonatha Charry, solar eclipses, variable stars, R Reticuli, V Cephei, U Cephei

1 INTRODUCTION

The phenomenon of stellar variability is of great importance in many areas of astrophysics, including stellar structure, stellar evolution, distance scales (through period-luminosity relations), dust formation, etc. The systematic study of variable stars began in the mid-nineteenth century, there only being eighteen known variable stars in 1844 (Hogg 1984). The status of variable star research around this time has been summarized by Clerke (1903), Hogg (1984) and Orchiston (2000), amongst others, and it was only pursued by a few enthusiasts, such as Norman Pogson, Joseph Baxendall and Friedrich Argelander.

The study of variable stars was not always thought appropriate for British colonial government-supported observatories like the Madras Observatory in India Originally set up in 1786 as a private observatory by William Petrie, an officer in the British East India Company, in 1810 it came under the control of the Surveyor General of Madras (Kochhar, 1991). Although the Observatory "… had a chequered history for more than a hundred years …" (Kochhar, 1985: 288), its main purpose was to produce catalogues of stellar positions from meridian observations (Taylor, 1832-1848). This situation changed to a degree in 1861 when Norman R. Pogson (1829–1891) was appointed Government Astronomer. Pogson was a pioneer variable star observer and was well known for developing the stellar magnitude scale. He introduced the observation of variable stars as a regular part of the Observatory's research programme[1] and inspired people like C. Ragoonatha Charry, one of the Indian staff members, to enthusiastically pursue this line of work. In this paper we provide biographical information on Ragoonatha Charry before discussing his variable star discoveries.

2 C. RAGOONATHA CHARRY: A BIOGRAPHICAL SKETCH

Chinthamani Ragoonatha Charry[2] (Figure 1) was a rather private person, so not much is known about his non-professional life. However, Dikshit (1981: 181) gives his date of birth as 17 March 1828 (even though this information is missing from his RAS obituary–see Obituary, 1881)

According to Venkateswaran (2009), Ragoonatha Charry came from a family of panchang (almanac) makers, and despite his apparent expertise in interpreting and analyzing Sidhanthic astronomy texts, Dikshit (1981: 181) points out that Ragoonatha Charry was not very proficient in Sanskrit.

Figure 1: Ragoonatha Charry at Madras Observatory (from the collection of Ms Cherry Armstrong, the great-great-granddaughter of N.R. Pogson).

Ragoonatha Charry became a skilled observer by hard work and devotion. He joined the Madras Observatory at the age of 18 (Venkateswaran, 2009) and eventually rose to the position of First (or Head) Assistant to the Astronomer. He not only made calculations and observations at the Observatory and discovered two new variable stars, but when he was off duty he continued to observe at his own residence with his own instruments.[3] The 1867 issue of the *Madras Almanac* reveals that Ragoonatha Charry lived in Nungumbakam village close to the Observatory. Pogson (1872b) remarked in a footnote to his log sheets listing observations of an occultation of Venus on 3 November 1872 that Ragoonatha Charry observed the event "… from his private residence about five eighths of a mile distant nearly due south of the observatory."

A self-taught man, Ragoonatha Charry (1868b) acquired the mathematical knowledge to be able to accurately predict the occultation of stars in the Sun's path during the total solar eclipse of 1868. According to Pogson (1861a), Ragoonatha Charry "… possessed sufficient skill and energy to make additional observations, worthy of the reputation of the Observatory and beneficial to science."

Ragoonatha Charry holds a special place in the annals of Indian astronomy in that he was the first Indian-born astronomer to publish a paper—albeit a short one—in the *Monthly Notices of the Royal Astronomical Society* (Ragoontha Charey, 1859) and was the first Indian to become a Fellow of the Society (Obituary, 1881). He was proposed by Pogson and by E.B. Powell, the Director General of Public Instruction in the Madras Presidency, and was elected on 12 January 1872.

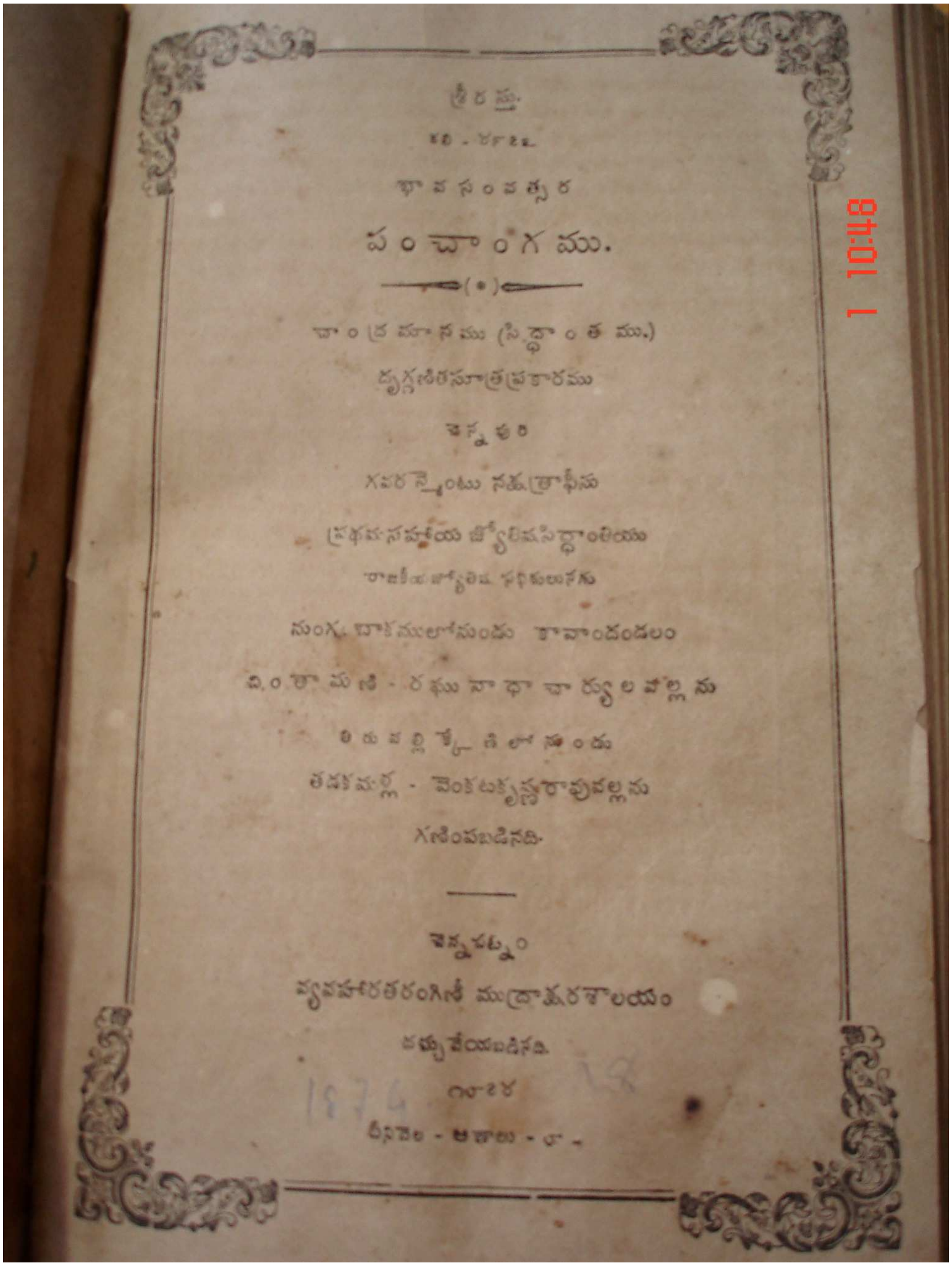

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Figure 2: An example of one of the almanacs, in the language of Telugu, prepared by Ragoonatha Charry at his own expense (courtesy Theosophical Society, Chenni).

Not only was Ragoonatha Charry a keen observer (who devoted almost his whole life to observational astronomy at the Madras Observatory), but more importantly, he was a passionate promoter of modern science and astronomy and a reformer who endeavored to integrate modern observational results and phenomena into the classical Sidhanthic astronomy which was traditionally practiced at that time. His efforts in formulating and bringing out the *Drigganita Panchang* (an almanac based on observations—see Figure 2) for several years is well described by Venkateswaran (2009). The author of his Obituary (1881) commented on his ambitious efforts to write a two-volume treatise titled *Jyotisha Chintamani* that would contain rules, formulae and tables based on British methods of calculation for the guidance of Sidhantis. Ragoonatha Charry (1874) also championed the cause of observational astronomy by urging people to raise funds "… to establish an observatory, to serve as a school for the instruction of Hindu students desirous to qualify in practical astronomy." He further emphasized (ibid.):

> I earnestly commend this movement (raising funds for an observatory as well as to help publish his treatise) to all native noblemen and wealthy gentlemen in the Presidency (Madras), as well as throughout India, who are interested in the improvement of their fellow countrymen, and beg them to join heartily in a design which aims at promoting a most fascinating branch of knowledge, the cultivation of which although under besetting difficulties and imperfections, is now and always has been highly prized by Hindus throughout the country.

Limited information is available about Ragoonatha Charry's family. Dikshit (1981: 182) mentions that his son Chinthamani Raghava Charry assisted him in the preparation of the *Drigganita Panchang* for the year 1880. Meanwhile, in 1877 Ragoonatha Charry had arranged for his brother-in-law, P. Raghavachari, to join the staff of the Madras Observatory, and just like his distinguished relative he too would eventually rise to the rank of First Assistant (ibid).

We know that Ragoonatha Charry participated in a range of socially-beneficial activities. For example, he was the Executive Committee President of the Madras Hindu Janopakara Nithee (the General Benefit Fund) established at Pursewakum on 1 February 1861. The management of the Fund was entrusted to a Committee of sixteen members (*Madras Almanac*, 1867). In addition, along with his Madras Observatory colleague, T. Mootoosawmy Pillay, Ragoonatha Charry served as an Executive Committee Trustee of the Madras Hindu Draviya Sakara Nidhi (Saving Fund) that was established in Nungumbakam on 1 July 1861 (ibid.). For twelve years he edited the astronomical section of the Asylum Press Almanac (Obituary, 1881), and he is also known to have given public talks on various astronomical and other scientific topics (ibid.).

3 RAGOONATHA CHARRY'S CAREER AT THE MADRAS OBSERVATORY

Ragoonatha Charry (Figure 3) had a career at the Madras Observatory that spanned about forty years. He was recruited by T.G. Taylor in 1847 (Dikshit, 1981: 181) and worked with successive Directors, W.S. Jacob (who communicated his first paper to *Monthly Notices of the Royal Astronomical Society*), W.K. Worster, J.F. Tennant and N.R. Pogson. All four were impressed by his astronomical skills.

Figure 3: In this photograph, we believe Ragoonatha Charry is the person wearing the white turban seventh from the left. Seated beside him and to his right is N.R. Pogson (with the beard, but without a hat). This photograph was possibly taken at the Madras Observatory during 1871, around the time of the December total solar eclipse (from the collection of Ms Cherry Armstrong, great great grand-daughter of N.R. Pogson).

Ragoonatha Charry's main mentor at Madras Observatory, however, was Pogson. Soon after his arrival at Madras, Pogson announced the discovery of the minor planet 'Asia', the first from this part of the world (Pogson, 1861a; 1861b), and made complimentary remarks about Ragoonatha Charry's participation: "… the second observation, on 20 April, was taken and reduced by my fourth native assistant, Ragoonatha Charry, who readily comprehends and most willingly executes whatever I may recommend to his notice."

Pogson also encouraged Ragoonatha Charry's zeal in communicating modern developments in astronomy to the general public and making them aware of the physical nature of celestial events so as to dispel traditional superstitions. The two pamphlets that Ragoonatha Charry prepared for the benefit of the general public about the 18 August 1868 and 12 December 1871 total solar eclipses that were visible from South India (e.g. see Ragoonatha Charry, 1868a) received considerable support. The one describing the 1871 eclipse, which was brought out in four regional languages, was strongly endorsed and recommended by Pogson, who applied to the Chief Secretary of the Madras Government for financial assistance:

> … consider it well calculated to instruct and at the same time to dispel the superstitious fears of the ignorant native masses, while it goes further and by its quotations from the puranahs, and other weighty arguments show that the absurd notions which render eclipses so alarming are not authorized by their own religious writings. He also shows by comparison of results, the vast inferiority and great inaccuracy of the calculations of Hindoo astronomers and urges them to abandon their worthless methods and antiquated tables and avail themselves of modern improvements. (Pogson, 1871a).

The 1868 eclipse played an important role in expanding astronomical knowledge of the solar corona (e.g. see Orchiston et al., 2006), when the element helium was discovered. Ragoonatha Charry was given the responsibility of conducting observations from Vunparthy, a village located forty-five miles north of Kurnool. He unfortunately experienced cloudy weather and could only comment on the degree of darkness witnessed during the eclipse.

Ragoonatha Charry was one of the key people chosen for the Madras Observatory's expedition to Avenashy (in the Coimbatore District) to conduct observations during the 1871 total solar eclipse. Pogson (1871a) describes his role:

> … general observations, consisting of careful micrometrical measurements of the cusps, of conspicuous prominences, of the extent and figure of corona, amount of darkness, visibility of stars, and accurate times of the various phenomena, may be chiefly entrusted to C. Ragoonatha Charry, the first Native assistant.

During the 6 June 1872 annular solar eclipse, which was visible from the Madras Observatory, Ragoonatha Charry made similar coronal observations with the Lerebours equatorial (Pogson, 1872a).

However, Ragoonatha Charry's principal role at the Madras Observatory was to make routine observations of stars and to reduce them for the Madras Catalogues, which he did until 1878, when his deteriorating health prevented him from continuing. The main instrument that he worked with was a meridian circle, which was installed at the Observatory in 1862 (Sen, 1989).[4] By the end of 1878, 35,681 observations had been made, a fair number of them by Ragoonatha Charry.

4 RAGOONATHA CHARRY'S VARIABLE STAR WORK

Soon after Pogson joined the Madras Observatory as Government Astronomer in 1861 he included variable stars and minor planets in the main observational programmes of the Observatory. At this time, the total number of known long period variables was 55 (although it rose to 60 in 1862; see Pogson, 1861c). Pogson was a pioneer variable star observer, discovering 21 new variables while at Oxford and Madras Observatories. During his time at Madras Observatory he published annual variable star ephemerides in *Monthly Notices of the Royal Astronomical* Society, and he also prepared a catalogue of observations he made of thirty-one different variable stars which was published posthumously in 1908 through the actions of Brook and Turner.

Pogson included several known variable stars in the regular observing programmes of the Madras Observatory, even with the meridian circle. For example, the irregular variable R Coronae Borealis was observed at different times between 20 May and 4 July 1863, and was found to vary between magnitude 6.1 and 9.0. Ragoonatha Charry contributed four of these observations on three occasions, the others being made by his Indian colleague, Mootoosawmy Pillay. The magnitude scale adopted for these observations was earlier devised by Pogson (see Pogson, Brook and Turner, 1908). Ragoonatha Charry's observations were later utilized by Webbink (1978) in re-identifying the recurrent nova U Scorpii that was discovered as a variable by Pogson on 20 May 1863.

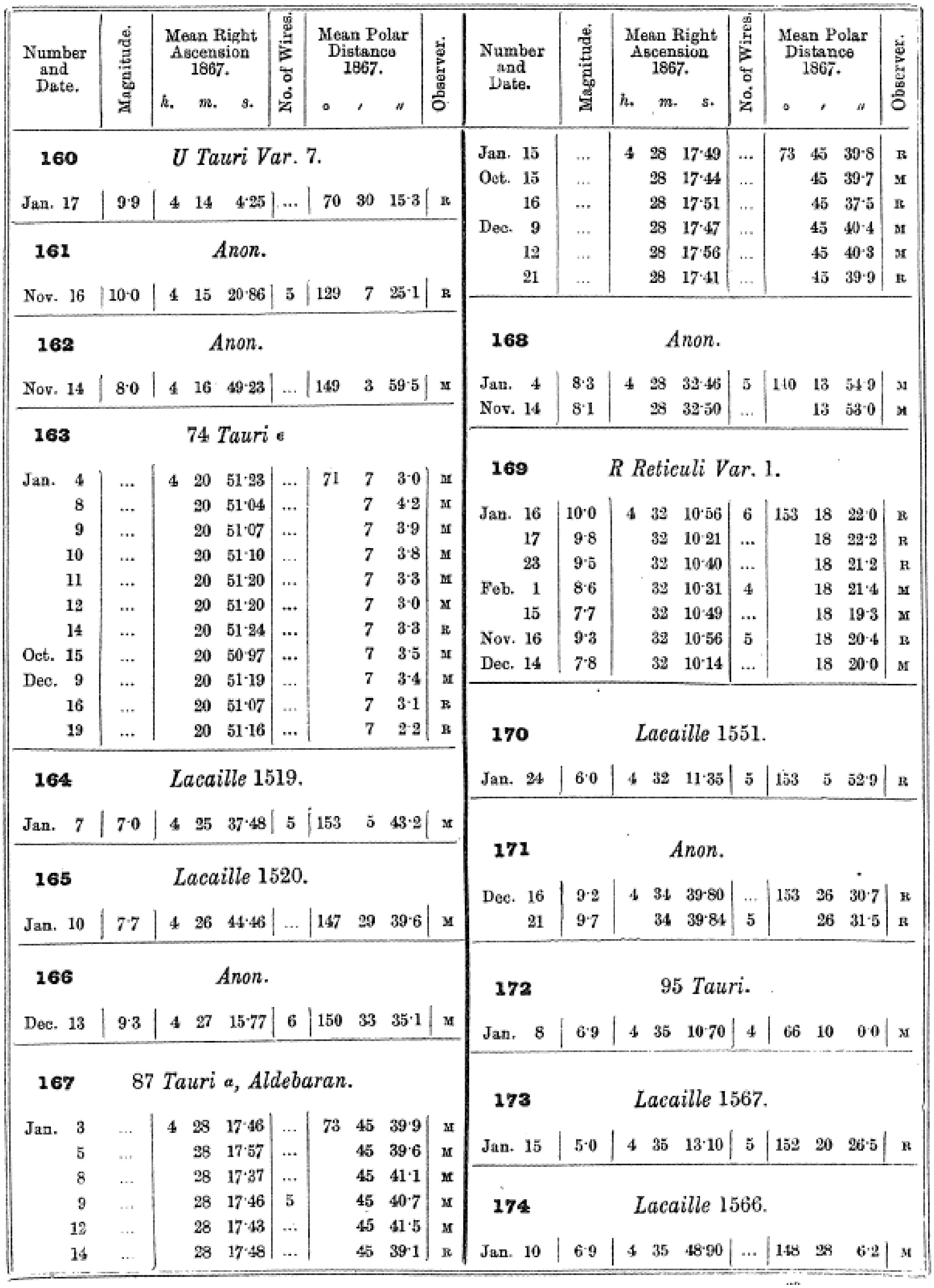
Because of this new and exciting area of activity undertaken by Madras Observatory, Ragoonatha Charry became an experienced variable star observer. It is no surprise, therefore, that he should discover new variable stars, and these are discussed below.

4.1 R Reticuli

Ragoonatha Charry discovered the variability of R Reticuli in January 1867. Pogson (1868) describes this event in the *Annual Report of the Madras Observatory*: "The detection of a new and interesting variable star, far south, is due to the First Native Assistant C. Ragoonatha Chary."

R Reticuli was first observed by Mootoosawmy with the meridian circle on 9 February 1864, and seemed like an ordinary star of magnitude 8½, but when next looked for, in January 1866, it was no longer visible in the dark field of the meridian circle telescope, which was 5.5 inches in aperture. It must therefore then have been fainter than magnitude 12. It was, however, observed again on 16 January 1867, this time by Ragoonatha Charry, and its variability was thereby established. Subsequent magnitude estimates made over twenty-six different nights up to 7 April 1868 showed that it attained a maximum brightness of 7¾ about the middle of February, and that its period was about nine months. For epoch 1 January 1860 the co-ordinates of this star were Right Ascension 4h 32m 6.1s and North Polar Distance 153° 19′ 14″. Figure 4 lists the observations of R Reticuli that were made at the Madras Observatory in 1867.

R Reticuli was later closely followed at both Madras and Harvard Observatories (see Pogson, Brook, Turner, 1908, and Campbell, 1926), and is now known to be a large amplitude Mira-type variable with a period of 278.32 days, a $(B-V)_0$ of 1.34 and $E_{(B-V)} = 0.11$. The spectral type varies between M4e and M7.5e. Allen et al. (1989) discovered it to be a SiO maser source at 86 GHz.



Number and Date.	Magnitude.	Mean Right Ascension 1867.			No. of Wires.	Mean Polar Distance 1867.			Observer.
		h.	m.	s.		°	′	″	
160	*U Tauri Var.* 7.								
Jan. 17	9·9	4	14	4·25	...	70	30	15·3	R
161	*Anon.*								
Nov. 16	10·0	4	15	20·86	5	129	7	25·1	R
162	*Anon.*								
Nov. 14	8·0	4	16	49·23	...	149	3	59·5	M
163	74 *Tauri* ε								
Jan. 4	...	4	20	51·23	...	71	7	3·0	M
8	...		20	51·04	...		7	4·2	M
9	...		20	51·07	...		7	3·9	M
10	...		20	51·10	...		7	3·8	M
11	...		20	51·20	...		7	3·3	M
12	...		20	51·20	...		7	3·0	M
14	...		20	51·24	...		7	3·3	R
Oct. 15	...		20	50·97	...		7	3·5	M
Dec. 9	...		20	51·19	...		7	3·4	M
16	...		20	51·07	...		7	3·1	R
19	...		20	51·16	...		7	2·2	R
164	*Lacaille* 1519.								
Jan. 7	7·0	4	25	37·48	5	153	5	43·2	M
165	*Lacaille* 1520.								
Jan. 10	7·7	4	26	44·46	...	147	29	39·6	M
166	*Anon.*								
Dec. 13	9·3	4	27	15·77	6	150	33	35·1	M
167	87 *Tauri* α, *Aldebaran.*								
Jan. 3	...	4	28	17·46	...	73	45	39·9	M
5	...		28	17·57	...		45	39·6	M
8	...		28	17·37	...		45	41·1	M
9	...		28	17·46	5		45	40·7	M
12	...		28	17·43	...		45	41·5	M
14	...		28	17·48	...		45	39·1	R
Jan. 15	...	4	28	17·49	...	73	45	39·8	R
Oct. 15	...		28	17·44	...		45	39·7	M
16	...		28	17·51	...		45	37·5	R
Dec. 9	...		28	17·47	...		45	40·4	M
12	...		28	17·56	...		45	40·3	M
21	...		28	17·41	...		45	39·9	R
168	*Anon.*								
Jan. 4	8·3	4	28	32·46	5	140	13	54·9	M
Nov. 14	8·1		28	32·50	...		13	53·0	M
169	*R Reticuli Var.* 1.								
Jan. 16	10·0	4	32	10·56	6	153	18	22·0	R
17	9·8		32	10·21	...		18	22·2	R
23	9·5		32	10·40	...		18	21·2	R
Feb. 1	8·6		32	10·31	4		18	21·4	M
15	7·7		32	10·49	...		18	19·3	M
Nov. 16	9·3		32	10·56	5		18	20·4	R
Dec. 14	7·8		32	10·14	...		18	20·0	M
170	*Lacaille* 1551.								
Jan. 24	6·0	4	32	11·35	5	153	5	52·9	R
171	*Anon.*								
Dec. 16	9·2	4	34	39·80	...	153	26	30·7	R
21	9·7		34	39·84	5		26	31·5	R
172	95 *Tauri.*								
Jan. 8	6·9	4	35	10·70	4	66	10	0·0	M
173	*Lacaille* 1567.								
Jan. 15	5·0	4	35	13·10	5	152	20	26·5	R
174	*Lacaille* 1566.								
Jan. 10	6·9	4	35	48·90	...	148	28	6·2	M

Figure 4: Madras Observatory observations of R Reticuli made in 1867 (after Pogson, 1887: 249).

4.2 Ragoonatha Charry's Mysterious Second Variable Star Discovery

Ragoonatha Charry's obituary that appeared in the *Madras Mail* on 7 February 1880 mentions that he also discovered another variable star, V Cephei, in 1878. This discovery is also mentioned in the obituary for Ragoonatha Charry that appeared in *Monthly Notices of the Royal Astronomical Society* (Obituary, 1881) but the source is attributed to the *Madras Mail*. However, the *Madras Almanac* of 1880 lists the new variable star as U Cephei. Surprisingly, no mention of the discovery of any new variable star (V Cephei *or* U Cephei) is made in Pogson's annual reports of Madras Observatory for 1878 or 1879. This is strange since Pogson liked to champion variable stars, and took great pleasure in writing about the discovery of R Reticuli.

Moreover, the discovery of the variability of V Cephei (V = 6.59, B−V = 0.05, U−B = 0.05, spectral type A3V) is normally credited to S.C. Chandler in 1882 (Chandler, 1890; 1896), who found a variation of 0.7 magnitudes and assumed the star to be either a long period or an irregular variable. Hoffleit (1985) discusses the variability of V Cephei in detail, as some early observers, including W.J. Luyten, found this star to vary by ~0.5 magnitude whereas neither E.C. Pickering nor Harlow Shapley could find any evidence of variation in its light. Nor does the spectral type (A3V) support the existence of pulsation. Milton, Williams, and Hoffleit (1988) discussed the nature of V Cephei on the basis of photometric observations and were able to show that the star did not vary by more than 0.02 magnitudes during a 428-day interval. They concluded that it was most unlikely that this star was a variable.

Let us now examine the discovery of the variability of U Cephei. This is generally credited to W. Ceraski (1880), who discovered the variation on 23 June 1880 (i.e. after Ragoonatha Charry's death). This star is a well known Algol-type binary with a period of 2.49 days. Soon after the discovery, Pogson's brother-in-law and nephew, Joseph Baxendell and Joseph Baxendell Junior, respectively, observed this star (see Yendell, 1903). Had the variability of this star been discovered earlier at the Madras Observatory it is hard to believe that they would have been unaware of this fact, yet they make no mention of it. Other early observations of U Cephei are discussed by Yendell, (1903) and Shapley (1916), but neither mentions Ragoonatha Charry as the discoverer.

So which variable star—if any—did Ragoonatha Charry discover in 1878? Upon consulting the *Results of Observations of the Fixed Stars Made with the Meridian Circle at the Government Observatory*, *Madras*, *in the Years 1877*, *1878*, *1879* (Pogson and Smith, 1893) we find an entry, "U Cephei, var 5" (see Figure 5) which lists the times of observations of this star, its magnitude, the mean positions for 1878 and the observer. It was observed on five different occasions by the following observers: Raghavachari (R), Ragoonatha Charry (C.R) and Mootoosawmy Pillay (M). The position of the object as listed by all the observers is the same, but the magnitude is said to have varied from 5.0 to 9.0. The fainter magnitudes (i.e. 8.2 and 9.0) were recorded by Ragoonatha Charry.

The same star was observed in 1880 (Figure 6) and listed in *Results of Observations of the Fixed Stars Made with the Meridian Circle at the Government Observatory*, *Madras*, *in the Years 1880*, *1881*, *1882* (Pogson and Smith 1894) as "U Cephei, Var. 5".[5] On this occasion it was observed on five different dates by Mootoosawmy Pillay, and varied between magnitudes 6.5 and 7.0 magnitude (i.e. 1.5 to 2 magnitudes fainter than the brightest that was observed in 1878). Usually 'Var. 5' refers to the fifth variable discovered in the constellation. In Argelander's notation it should refer to V Cephei rather than to U Cephei (which was fourth variable discovered). More importantly, the coordinates given in Pogson's 1887 and 1893 catalogues do not match those of either U Cephei or V Cephei; indeed, the star referred to in the Madras Observatory catalogues is more than 2 hours west of and 13° south of V Cephei and more than 3 hours west of and more than 11.5° south of U Cephei.

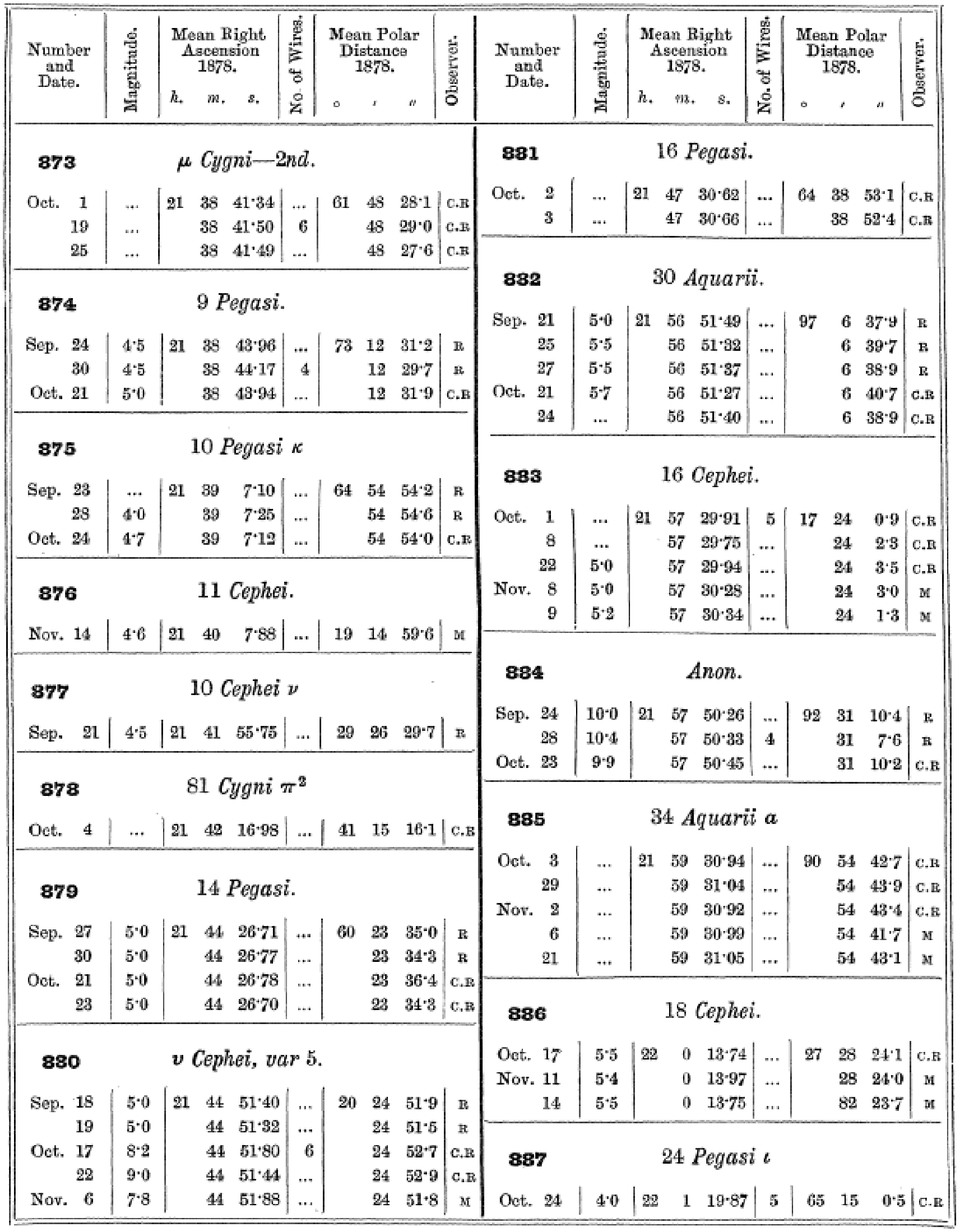
This being the case, what is the name of the star that is mentioned in the two Madras catalogues? A search of a 10 arc minute field around the reported position revealed the presence of HR 8342 (= HD 207636). We calculated the mean position of this star for epoch 1878 using the proper motion given by Simbad (Hipparcos) as α = 21h 44m 51.5s and δ = + 69° 35′ 7.2″. By comparison, the position of the variable star listed in the Madras catalogues is α = 21h 44m 51.4s and δ = + 69° 35′ 8.1″. The coordinates match very well indeed.

So the Madras variable can most likely be identified with HR 8342. However, HR 8342 is not known to be a variable, either in light or in radial velocity. The three measurements listed in Simbad on different occasions show a mean value of -2 ± 1 km s^{-1}. The spectral type is A0 V. The Hipparcos parallax gives a distance of 151 ± 10 parsecs and with a V = 6.45 the Mv obtained is 0.56, which is consistent with the spectral type of A0 V (Allen, 1973). The A0 V stars are not known to be variable, and certainly not by four magnitudes. The possibility that it could be a binary also seems unlikely. For example, the Algol system U Cephei has a primary of B8 V and a similar magnitude, V = 6.92. It shows light variations ranging from magnitude 6.9 to 9.2. However, the infrared colors clearly show an excess (for a B8 V star) suggesting the presence of a companion. The colors of U Cep are B−V = 0.00, V−J = 0.45, V−H = 0.56 and V−K = 0.67, whereas HR 8342 shows the following colors: B−V = −0.008, V−J = 0.05, V−H = 0.01 and V−K = 0.036, almost text book colors for an A0 V star without any color excesses. Thus, it is difficult to understand the light variability reported by Ragoonatha Charry and the other Madras observers. Yet they were experienced observers, so their magnitude estimates cannot be easily ignored.

The variability of 'U Cephei, var 5.' in the Madras catalogues therefore remains a mystery and the credit for the discovery of the variability of this star (what ever it happens to be) by Ragoonatha Charry must remain in doubt. Furthermore, it is somewhat surprising that observations of this star were not continued—let alone commented on—later, either by Pogson or by other astronomers at the Madras Observatory following Ragoonatha Charry's death in February 1880, as variable stars remained on the observing program.

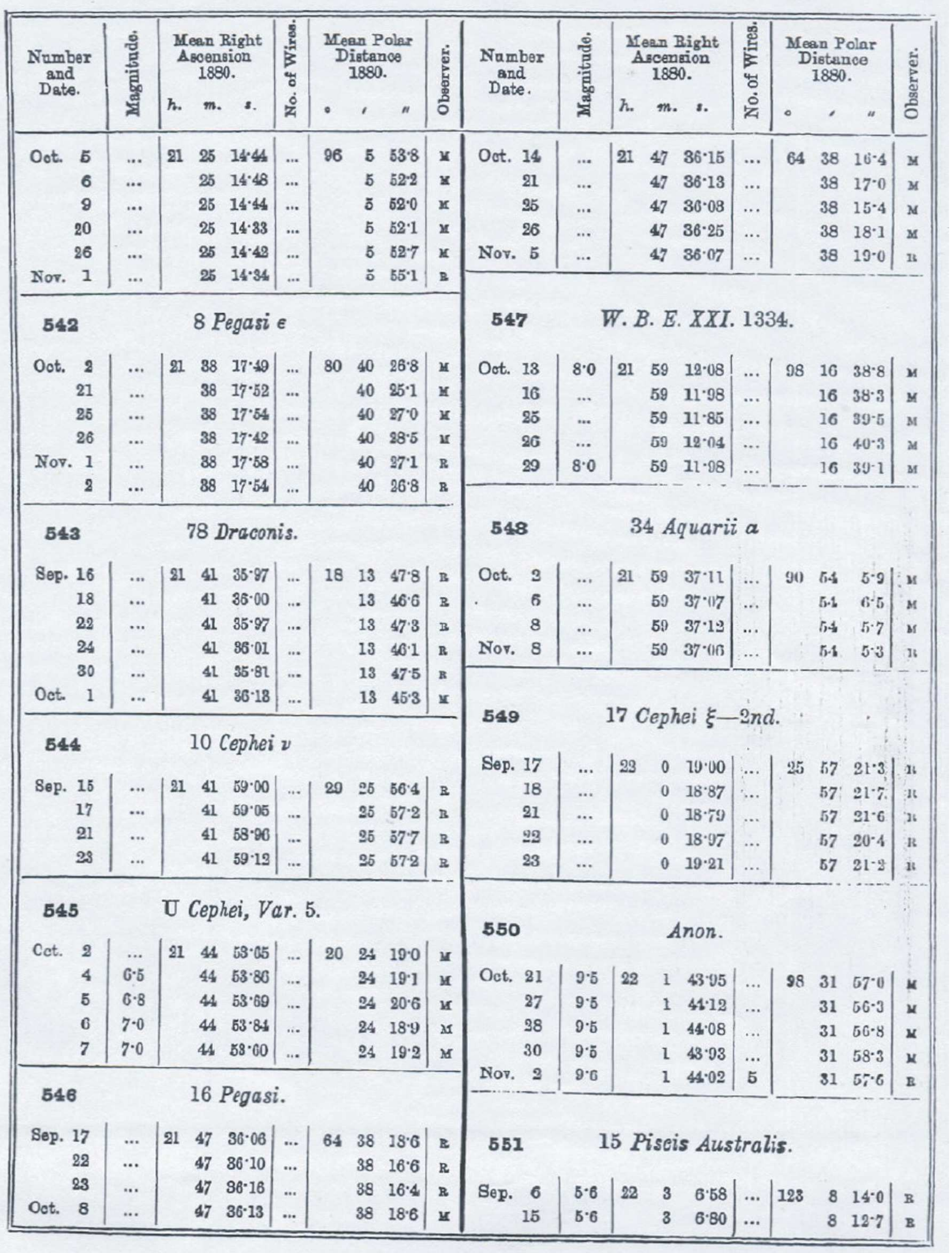
5 CONCLUDING REMARKS

Rajesh Kochhar (1992; 1993) has outlined the three-phase development of science in India, from the time of initial European settlement through to the emergence of a purely Indian scientific tradition. During his long service at the Madras Observatory, Ragoonatha Charry was able to span two of these phases. First he was a prominent Indian astronomical assistant in the 'peripheral native stage' when Indians were hired and trained by Europeans to successfully perform scientific activities. But later in his career Ragoonatha Charry also could claim to belong to the 'Indian response' phase, as he passionately sought to promote the emergence of a modern—yet distinctly Indian—style of astronomy. In a public lecture that he gave at the Pacheappah's Hall in Madras on 13 April 1874 his plea for a native observatory reflects this:



Number and Date.	Magnitude.	Mean Right Ascension 1878.			No. of Wires.	Mean Polar Distance 1878.			Observer.
		h.	m.	s.		°	′	″	
873		*μ Cygni—2nd.*							
Oct. 1	...	21	38	41·34	...	61	48	28·1	C.R
19	...		38	41·50	6		48	29·0	C.R
25	...		38	41·49	...		48	27·6	C.R
874		9 *Pegasi.*							
Sep. 24	4·5	21	38	43·96	...	73	12	31·2	R
30	4·5		38	44·17	4		12	29·7	R
Oct. 21	5·0		38	43·94	...		12	31·9	C.R
875		10 *Pegasi κ*							
Sep. 23	...	21	39	7·10	...	64	54	54·2	R
28	4·0		39	7·25	...		54	54·6	R
Oct. 24	4·7		39	7·12	...		54	54·0	C.R
876		11 *Cephei.*							
Nov. 14	4·6	21	40	7·88	...	19	14	59·6	M
877		10 *Cephei ν*							
Sep. 21	4·5	21	41	55·75	...	29	26	29·7	R
878		81 *Cygni* π^2							
Oct. 4	...	21	42	16·98	...	41	15	16·1	C.R
879		14 *Pegasi.*							
Sep. 27	5·0	21	44	26·71	...	60	23	35·0	R
30	5·0		44	26·77	...		23	34·3	R
Oct. 21	5·0		44	26·78	...		23	36·4	C.R
23	5·0		44	26·70	...		23	34·3	C.R
880		*υ Cephei, var* 5.							
Sep. 18	5·0	21	44	51·40	...	20	24	51·9	R
19	5·0		44	51·32	...		24	51·5	R
Oct. 17	8·2		44	51·80	6		24	52·7	C.R
22	9·0		44	51·44	...		24	52·9	C.R
Nov. 6	7·8		44	51·88	...		24	51·8	M
881		16 *Pegasi.*							
Oct. 2	...	21	47	30·62	...	64	38	53·1	C.R
3	...		47	30·66	...		38	52·4	C.R
882		30 *Aquarii.*							
Sep. 21	5·0	21	56	51·49	...	97	6	37·9	R
25	5·5		56	51·32	...		6	39·7	R
27	5·5		56	51·37	...		6	38·9	R
Oct. 21	5·7		56	51·27	...		6	40·7	C.R
24	...		56	51·40	...		6	38·9	C.R
883		16 *Cephei.*							
Oct. 1	...	21	57	29·91	5	17	24	0·9	C.R
8	...		57	29·75	...		24	2·3	C.R
22	5·0		57	29·94	...		24	3·5	C.R
Nov. 8	5·0		57	30·28	...		24	3·0	M
9	5·2		57	30·34	...		24	1·3	M
884		*Anon.*							
Sep. 24	10·0	21	57	50·26	...	92	31	10·4	R
28	10·4		57	50·33	4		31	7·6	R
Oct. 23	9·9		57	50·45	...		31	10·2	C.R
885		34 *Aquarii α*							
Oct. 3	...	21	59	30·94	...	90	54	42·7	C.R
29	...		59	31·04	...		54	43·9	C.R
Nov. 2	...		59	30·92	...		54	43·4	C.R
6	...		59	30·99	...		54	41·7	M
21	...		59	31·05	...		54	43·1	M
886		18 *Cephei.*							
Oct. 17	5·5	22	0	13·74	...	27	28	24·1	C.R
Nov. 11	5·4		0	13·97	...		28	24·0	M
14	5·5		0	13·75	...		82	23·7	M
887		24 *Pegasi ι*							
Oct. 24	4·0	22	1	19·87	5	65	15	0·5	C.R

Figure 5: Madras Observatory observations of U Cephei made in 1878 (after Pogson and Smith, 1893: 147).



Number and Date.	Magnitude.	Mean Right Ascension 1880.			No. of Wires.	Mean Polar Distance 1880.			Observer.
		h.	m.	s.		°	′	″	
Oct. 5	...	21	25	14·44	...	96	5	53·8	M
6	...		25	14·48	...		5	52·2	M
9	...		25	14·44	...		5	52·0	M
20	...		25	14·33	...		5	52·1	M
26	...		25	14·42	...		5	52·7	M
Nov. 1	...		25	14·34	...		5	55·1	R
542 8 *Pegasi* ε									
Oct. 2	...	21	38	17·49	...	80	40	26·8	M
21	...		38	17·52	...		40	25·1	M
25	...		38	17·54	...		40	27·0	M
26	...		38	17·42	...		40	28·5	M
Nov. 1	...		38	17·58	...		40	27·1	R
2	...		38	17·54	...		40	26·8	R
543 78 *Draconis.*									
Sep. 16	...	21	41	35·97	...	18	13	47·8	R
18	...		41	36·00	...		13	46·6	R
22	...		41	35·97	...		13	47·3	R
24	...		41	36·01	...		13	46·1	R
30	...		41	35·81	...		13	47·5	R
Oct. 1	...		41	36·18	...		13	45·3	M
544 10 *Cephei* ν									
Sep. 15	...	21	41	59·00	...	29	25	56·4	R
17	...		41	59·05	...		25	57·2	R
21	...		41	58·96	...		25	57·7	R
23	...		41	59·12	...		25	57·2	R
545 U *Cephei, Var.* 5.									
Oct. 2	...	21	44	53·05	...	20	24	19·0	M
4	6·5		44	53·86	...		24	19·1	M
5	6·8		44	53·69	...		24	20·6	M
6	7·0		44	53·84	...		24	18·9	M
7	7·0		44	53·60	...		24	19·2	M
546 16 *Pegasi.*									
Sep. 17	...	21	47	36·06	...	64	38	18·6	R
22	...		47	36·10	...		38	16·6	R
23	...		47	36·16	...		38	16·4	R
Oct. 8	...		47	36·13	...		38	18·6	M
Oct. 14	...	21	47	36·15	...	64	38	16·4	M
21	...		47	36·13	...		38	17·0	M
25	...		47	36·08	...		38	15·4	M
26	...		47	36·25	...		38	18·1	M
Nov. 5	...		47	36·07	...		38	19·0	R
547 *W. B. E. XXI.* 1334.									
Oct. 13	8·0	21	59	12·08	...	98	16	38·8	M
16	...		59	11·98	...		16	38·3	M
25	...		59	11·85	...		16	39·5	M
26	...		59	12·04	...		16	40·3	M
29	8·0		59	11·98	...		16	39·1	M
548 34 *Aquarii* α									
Oct. 2	...	21	59	37·11	...	90	54	5·9	M
6	...		59	37·07	...		54	6·5	M
8	...		59	37·12	...		54	5·7	M
Nov. 8	...		59	37·06	...		54	5·3	R
549 17 *Cephei* ξ—2*nd.*									
Sep. 17	...	23	0	19·00	...	25	57	21·3	R
18	...		0	18·87	...		57	21·7	R
21	...		0	18·79	...		57	21·6	R
22	...		0	18·97	...		57	20·4	R
23	...		0	19·21	...		57	21·2	R
550 *Anon.*									
Oct. 21	9·5	22	1	43·95	...	98	31	57·0	M
27	9·5		1	44·12	...		31	56·3	M
28	9·5		1	44·08	...		31	56·8	M
30	9·5		1	43·93	...		31	58·3	M
Nov. 2	9·6		1	44·02	5		31	57·6	R
551 15 *Piscis Australis.*									
Sep. 6	5·6	22	3	6·58	...	123	8	14·0	R
15	5·6		3	6·80	...		8	12·7	R

Figure 6: Madras Observatory observations of U Cephei made in 1880 (after Pogson and Smith, 1894: 42).

> In Europe, excluding Russia, there now exist fifty-four public and ten private Observatories spread over an area of less than two million square miles. In India with a surface of one and half million miles we have but one, that one wholly supported by the State … I recommend no more than that a modest but thorough place of instruction and study should be founded where theoretical knowledge can be united to actual practical work ... Such places exist in hundreds in Europe, but nowhere is the need for them greater than in India. Not much money, a little zeal, a little steadfastness of purpose, wed these to a regard for science, and soon would the metropolis of Southern India be graced with an Institution which would be an honor to the country. (Cited in Obituary, 1881: 182).

S.M.R. Ansari (1985) has stated that observatories like the ones at Madras, Bombay and Calcutta remained in effect "… alien outposts of a foreign science …" and were a kind of 'island' which solely served British science. As we have seen, Ragoonatha Charry was one person who strove constantly to spread the benefit of these Observatories to the local public and not let them remain as 'islands'. Whenever a major celestial event occurred, such as a total solar eclipse or a transit of Venus, he took the opportunity to publish pamphlets, not only in English but also in various local languages, explaining the phenomena and how native astronomical methods and calculations could be improved with better data. In his pamphlet on the 1874 transit of Venus he states:

> It is written principally for information of such of my countrymen as have not had the advantage of any regular course of scientific reading ... Although the class of phenomena to which the Transit of Venus belongs is mentioned in Hindu treatise on Astronomy, especially of the Sidhanta Siromani, yet the Sidhantis or Hindu astronomers are really not familiar with the nature of this particular occurrence and cannot predict it with even a rough approach to accuracy, happening as it does at such strange and rare intervals. (Ragoonatha Charry, 1874).

Ragoonatha Charry wrote the English version in the style of a dialogue as he was accustomed to discussing astronomical facts and methods orally with Hindu professors. He intentionally wrote the other language versions, Sanskrit, Canarese, Tamil, Telugu, Urdu, Malayalam and Marathi in a different style, explaining that in order to cater for the native public "… it was found convenient to vary this arrangement." (Obituary, 1881: 181).

The 'cherished object' of Ragoonatha Charry's life was to publish a two-volume monograph

> … upon Astronomy which should embody the corrections, equations and formulae established by European [modern] research together with what is proper to retain from our own works, and thus to construct a manual accessible to Hindu astronomers ... (ibid.).

Regrettably, ill health took him away on 5 February 1880 (Obituary, 1881), before he could complete this work, but he maintains a notable place in the history of Indian astronomy.

6 NOTES

1. We should point out, however, that E.B. Powell (1861), an avid amateur astronomer and the Director General of Public Instruction in Madras, made observations of the enigmatic variable, η Argus (now η Carinae), from 1853. Taylor (1832) and Jacob (1847; 1849) also observed η Argus from Madras and Pune respectively.
2. Variations on the spelling of elements of Chinthamani Ragoonatha Charry's name include: Chintamanny (Obituary, 1881: 180), Ragoonathachary (Ananthasubramanian, 1991: 102), Raghunathachari (Salwi, 1988: 190), Charey (Ragoonatha Charey, 1859), Chary (Ragoonatha Chary, 1868b) and Cintamani Raghunatha Acarya (Dikshit, 1981: 181). We used the spelling of his name as it appears in his signature.
3. Nowhere do Ragoonatha Charry or his contemporary colleagues at the Madras Observatory discuss the nature of these instruments, so regretfully we have no information at all about them.
4. This instrument was modelled on one designed by George Biddell Airy for the Royal Observatory at Greenwich (see Satterthwaite, 2001).
5. This catalogue was prepared by Charles Michie Smith, and published after Pogson's death.

7 ACKNOWLEDGEMENTS

The authors would like to thank Dr A.V. Raveendran for his advice and help. We appreciate the generosity of Ms Cherry Armstrong in making available a collection of photographs of N.R. Pogson, her great, great, grand-father and his family to us and donating them to IIA Archives. We also would like to thankfully acknowledge the help received from the Tamilnadu Archives and the Theosophical Society in Chenni. We appreciate greatly the help received from Wayne Orchiston in the preparation of this paper.

Finally we wish to thank the Department of Science and Technology (DST) of the Government of India for financial assistance through project SR/S2/HEP-26/06, and the referees for their helpful comments.

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Journal of Astronomical History and Heritage, 12(3), 211-223 (2009).

PETER MILLMAN AND THE STUDY OF METEOR SPECTRA AT HARVARD UNIVERSITY

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Abstract: During the 1930s meteor astronomy entered a new era when the Canadian astronomer, Peter Millman, began investigating the spectra of meteors for his post-graduate studies at Harvard University. Whilst experimenting with different lenses, prisms, shutters, photographic plates, and observational techniques, Millman constructed a number of different meteor spectrographs, and by conducting systematic photographic surveys between November 1931 and February 1933 almost tripled the number of meteor spectra known to exist. Through these efforts, in less than two years he was responsible for single-handedly launching a whole new field of meteor investigation.

Keywords: Peter M. Millman, Harvard University, meteor astronomy, meteor spectra

"Goe, and catche a falling starre." John Donne
(quoted in Levy, 2001: 46).

1 INTRODUCTION

Throughout the millennia human beings have seen and wondered at bright streaks of light blazing across the sky, stars seemingly tumbling from their celestial realms. For centuries these shooting stars, or meteors, were thought to be a component of the Earth's atmosphere, and their extraterrestrial origin was only established at the end of the eighteenth century (see Beech, 1995). Excellent summary histories of meteor astronomy have been published by Hughes (1982; 1990). Meanwhile, Olivier (1925) provides a detailed yet very readable account of the state of meteor astronomy in 1925 and Lovell's (1954) masterful *Meteor Astronomy* documents the main advances made during the nineteenth century and first half of the twentieth century. Beech (1992: 218) reminds us that

> Our present understanding of the meteoric phenomena has not been won easily. Just as the other branches of science have had to claw their way from the pit of ignorance, so meteor astronomers have had to founder and flail in their quest to understand the humble shooting star. It is along the tortuous path that joins the most ancient of times with the present that the makings of meteor astronomy are found.

The aforementioned books by Lovell and Olivier reveal that through into the 1920s astronomers were concerned with establishing the magnitudes, paths, heights and velocities of sporadic meteors. Reported velocities posed a special problem and debate raged around whether these meteors originated in the Solar System or hailed from interstellar regions. "Criticism and counter-criticism effectively led to an impasse …" (Lovell, 1954: 247) which was only resolved with the advent of radar meteor astronomy.

Meteor streams were the other special area of interest for astronomers, as they sought to identify different showers, determine hourly rates and meteor velocities, calculate orbital elements of the streams, and investigate radiant positions—especially those that moved with the passage of time. Some streams, certainly not all, were known to be associated with comets.

These early investigations of sporadic and shower meteors relied almost entirely upon naked eye observations, for although photography had been introduced to astronomy as early as 1840 (Lankford, 1984; Norman, 1938) and spectroscopy in the early nineteenth century (Hearnshaw, 1986), initially neither of these tools was applied systematically to the study of meteors (at least in combination). Consequently, as late as 1930 only eight photographs of meteor spectra were known to exist anywhere in the world (Millman, 1932), and these had not been carefully studied so they had not contributed in a meaningful way to meteor science.

One of the men responsible for changing this situation was a young Canadian astronomer, Peter Millman. In 1929 he headed to Harvard College Observatory where he subsequently established a systematic program to collect all known photographs of meteor spectra, add to their number, and glean from them all he could learn about these extraterrestrial visitors. In just two years he was responsible for capturing 15 new meteor spectra, almost tripling the number in existence. By the end of this pioneering period, he had developed innovative techniques for the study of meteors and had begun to lay the foundation for a specialized branch of science that would expand greatly following World War II.

2 THE EARLY LIFE OF PETER MILLMAN

Peter Mackenzie Millman was born on 10 August 1906 in Toronto, Canada, the eldest son of Robert and Edith (Middleton) Millman. When Peter was 2 years old his parents moved the family to Japan to engage in missionary work with the Anglican Church of Canada. It was in that Far Eastern country over the following sixteen years that Peter discovered a love for the heavens and an interest in astronomical observing:

> There, though at a latitude but little less than New York, the sky seems sometimes to be filled with stars seldom observed here, and the brilliant Canopus rises for an hour or more above the southern horizon to add his luster to the brilliancy of the winter heavens. (Millman, 1926: 198).

Observations of Mars made from the slopes of Mount Fuji in the summer of 1924 led to his first professional publication at the age of 20, in the *Journal of the Royal Astronomical Society of Canada* (Millman, 1926).

Figure 1: Peter Millman and Margaret Gray, on their wedding day; Shapley is on the far right (Millman Family records).

Returning to Canada, Millman attended the University of Toronto, completing his B.A. in 1929. During the summers in these years he worked as an assistant at the Dominion Astrophysical Observatory in Victoria, British Columbia. This work led to Peter's first original, though modest, scientific publication, a reduction of binary star data (Millman, 1928a). During his undergraduate years, Millman also published a paper on "The quality of the light of the eclipsed Moon" (Millman, 1929) and a brief note on an interesting mirage seen on 31 July 1927 in the Strait of Juan de Fuca near Victoria (Millman, 1928b). These were the modest beginnings of a career that would soon see the pioneering of a virtually new branch of astronomy—meteor spectroscopy (Halliday, 1991). The beginning of that path lay to the south, in Cambridge, Massachusetts.

3 THE BIRTH OF METEOR SPECTROSCOPY AT HARVARD

When Millman completed his undergraduate degree at the University of Toronto, no Canadian universities offered graduate programs in astronomy (Jarrell, 1988), so he headed to the United States in order to further his studies. He enrolled at Harvard University (Hoffleit, 1999; Hogg, 1990) at a time when a number of men and women, now well-known in astronomical circles, were on the staff or were fellow graduate students. These included Cecilia Payne, Helen Sawyer (later Hogg), Ernst Öpik and Fred Whipple.

The Harvard program was headed by Harlow Shapley, the famous astronomer who had used globular clusters to identify the center of the Milky Way and determine the Earth's location within the Galaxy. Shapley became a mentor to the young student.

While in Cambridge, Millman had to check into the University's Stillman Infirmary for a tonsillectomy, and this is where he met a Canadian nurse, Margaret (Peggy) Gray (Crook, 1989). On 10 July 1931 the young couple married (Figure 1). Peggy's parents were forced to remain in Nova Scotia, so it was Harlow Shapley who stepped in and gave away the bride (Barry Millman, personal communication, 2006).

3.1 Harlow Shapley and the Importance of Meteor Research

Shapley at this time had an interest in meteors, primarily as they related to the overall nature and structure of the Universe. Speaking before the National Academy of Sciences of the United States, he remarked that

> The nature of the interstellar and intergalactic media through which radiation, stars, clusters, and galaxies move is found to be of so much significance in our understanding of galactic distances and structure that fundamental research on the contents of space has become necessary. For several years at the Harvard Observatory we have studied one aspect of the problem—the meteors. Investigation of these multitudinous small bodies directly bears not only on knowledge of their own physical nature and their place in the cosmic structure, but as well on the question of the content of interstellar space; and indirectly such investigations may contribute to the solution of the general problem of "planetesimals" in the origin of the solar system, and of the structure of the upper terrestrial atmosphere. (Shapley et al, 1932: 16).

He recognized that "An indication of the significant role that meteoric matter may play in the universe only begins to appear when we correlate terrestrial fireball phenomena, spectrophotometry by the newer methods, and the study of nebulae." (Shapley, 1928: 101). Shapley must also have been aware that some meteor showers were associated with comets and that the spectral characteristics of comets had been known for decades (e.g. see Chambers, 1910; Olivier, 1930; Young, 1888). Meteor spectra, therefore, would allow comparisons to be made, and the chemical composition of those meteors that did not result from cometary disintegration could be established. By combining photography and spectroscopy, technological advances now allowed the emergence of a whole new field of meteoric investigation.

In spite of the stated importance of meteor spectra, at a 1932 conference on astrophotographic problems Shapley (1932: 611) reported that "In the Harvard collection only about one spectrum plate in 20,000 shows spectra of meteors, but with special cameras it is hoped to get one spectrum out of every fifty to a hundred attempts."

Shapley was keen to pursue this line of enquiry, and he directed Millman's doctoral research in this direction. In the autumn of 1931 he assigned the young Canadian the task of collecting and analyzing meteor spectra. At this time, little had been published on meteor spectra. During the second half of the nineteenth century a number of well-known astronomers, including A.S. Herschel, Konkoly and Secchi had reported making fortuitous visual observations of meteor spectra in the course of other observing projects, and their combined conclusions were summarized by Millman in 1932:

> 1. The observed types of spectra seemed to show no particular correlation with the radiant to which the meteor belonged.
> 2. As we would expect, the greatest detail was observed in the spectra of the brightest meteors.
> 3. As far as can be judged the trains had the same types of spectra as the nucleus but of much lesser intensity. For this reason lines could often be picked out in the train that could not be seen in the nucleus owing to the great strength of the continuous spectrum in the latter. In the fading train only the strongest parts of the spectrum remained.
> 4. The nucleus of a meteor almost always had an apparent continuous spectrum, usually with one or more colours abnormally strong. The train spectrum showed the continuous characteristic in a much weakened condition and had bright lines corresponding to the strong parts of the nuclear spectrum. The continuous appearance, however, was often lacking altogether in the train.
> 5. With the exception of the continuous spectrum, the most general feature of meteor spectra was a strong orange-yellow line which appeared in at least three quarters of the observations and was commonly attributed to sodium.
> 6. After the yellow line, the next most common feature was a strong green line similar to the magnesium green line. This would appear with or without the yellow line and, when definitely predominant, gave the meteor an emerald green colour.
> 7. Other bright lines frequently appeared. Two lines in the red near the positions of the lithium lines occasionally occurred, also two more lines in the green which appeared with or without the red lines. In a few meteors a large number of bright lines were observed in the green and blue. (Millman, 1932: 113-114).

The successful visual characterization of the spectrum of an unexpected transient phenomenon like a meteor was an observational challenge—to say the least—and what was clearly required was a permanent record. Yet despite the fact that only eight photographs of meteor spectra were known in 1930—obtained mostly by chance—Millman immersed himself in the task of carefully investigating these. His primary aim was to establish the wavelengths and intensities of the visible emission lines, and identify these with known elements. This would provide valuable pointers to the chemical composition of these eight meteors.

3.2 Millman's Analysis of Existing Meteor Spectra

Millman (1932) listed these known meteor spectra chronologically from I to VIII, and some information about them is presented here in Table 1.[1]

In his long and masterful 1932 paper, published by Harvard College Observatory, Millman (1932: 114) summarized the already-published accounts relating to the first eight spectra in Table 1. Emission lines of hydrogen were identified in Spectrum I. The strongest emission lines in Spectrum II were the H and K lines of calcium, but weaker lines were associated with magnesium and potassium. Five of the lines in Spectrum III were thought to be due to helium, and a sixth line to thalium. Eighteen lines were identified in Spectrum IV, the two brightest being the H and K lines of calcium. Nothing had been published about Spectra V, VI and VII, while the two brightest lines in Spectrum VIII were (once again) the H and K lines of calcium, with all remaining lines associated with iron.

Millman (1932: 118-119) then proceeded to carry out his own analysis of these eight spectra, but this proved a non-trivial exercise. He only had access to two of the photographs (for Spectra I and V), and in the remaining cases he had to rely on direct copies, some of which were not distinct enough for easy analysis.

The work of measuring the spectral lines for these recordings had only been done for three of the eight spectra and Millman had to make the actual measurements for the others. This was no easy task, primarily due to the low resolution and the limited dispersion in the photographs, "… ranging from 150 to 450 angstrom units per mm. between Hγ and H$_\zeta$." (Millman, 1933d: 152).

Measuring the intensities of the spectral lines also proved to be problematic. For four of the spectra, Millman was able to make use of a Moll microphotometer. Calibration curves were obtained from stellar spectra where they were present on the photographic plates. In general, A0 stars were employed for this, a small correction factor having to be employed where different classes of stars had to be used. In one case no stellar spectra at all were available and an estimate was made by comparing the meteor spectrum directly with stellar images. Millman (1932: 117) was forced to concede that all of these methods left something to be desired:

> It must be admitted that none of the above calibrations were of the most satisfactory type but they were the best available under the circumstances, and while not yielding intensities of a high degree of accuracy, the intensities should be more trustworthy than eye estimates.

Table 1: Known photographs of meteor spectra, as at early 1932 (after Millman, 1934c: 279).

No	Date	Place	Shower
I	18 June 1897	Arequipa, Peru	
II	11 May 1904	Moscow, Russia	
III	12 August 1904	Moscow, Russia	Perseid
IV	12 August 1907	Moscow, Russia	Perseid
V	18 May 1909	Arequipa, Peru	
VI	10 August 1920	Mt Wilson, USA	Perseid
VII	7 March 1924	Mt Wilson, USA	
VIII	29 Sept 1924	Bergedorf, Germany	
XI	9 January 1913	Harvard College Observatory, USA	

The other spectra were not clear enough to be examined by the microphotometer. In these cases Millman was required to rely on eye estimates. However, in spite of all these problems, "A set of relative positions and intensities for the lines in each of the nine spectra was thus obtained." (ibid.).

More problems remained to be solved, however, for in order to compare the eight different spectra, Millman had to account for the different dispersion scales used in each case. Three of them had previously been provided, by Schwassmann for Spectrum VIII and Blajko for Spectra II and III. Millman determined the dispersions for the remaining photographs by using the positions of three hydrogen lines (usually Hβ, Hγ and Hδ) for anywhere from four to thirteen early type stars that were present on the images near the meteor trails. From the values for these lines, he determined a Hartmann dispersion formula that allowed for the calculation of the distance between any two wavelengths in the meteor spectra. Once the Hartmann formula had

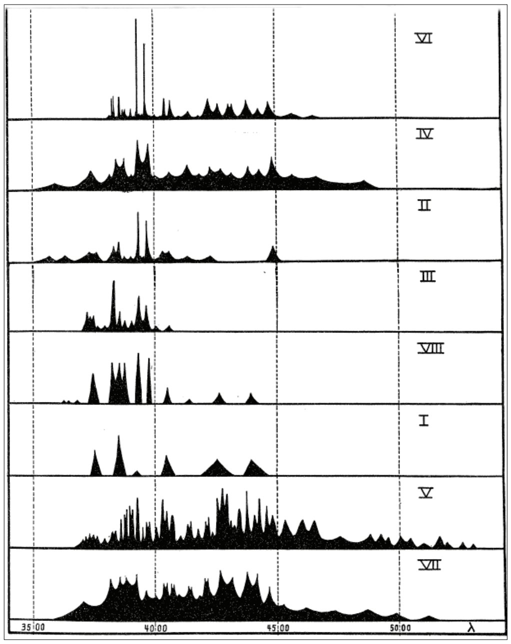


Figure 2: Distribution of spectral lines in the eight historical photographs of meteor spectra (adapted from Millman, 1932: 133).

been determined, it could be used to identify all wave-lengths in the meteor spectra based on a single wave-length determined by comparison with laboratory data (Millman, 1932).

Millman's efforts in analyzing prior meteor spectra were so meticulous that he was able to correct an earlier error. Spectrum III, obtained by Blajko in Moscow on 12 August 1904, appeared to show a significantly different pattern of lines than the other existing spectra. Millman (1932: 119-120) demonstrated that in the initial analysis, the spectrum had been placed on the dispersion scale too far to the red, and that correcting for this error brought the spectrum into correspondence with the others:

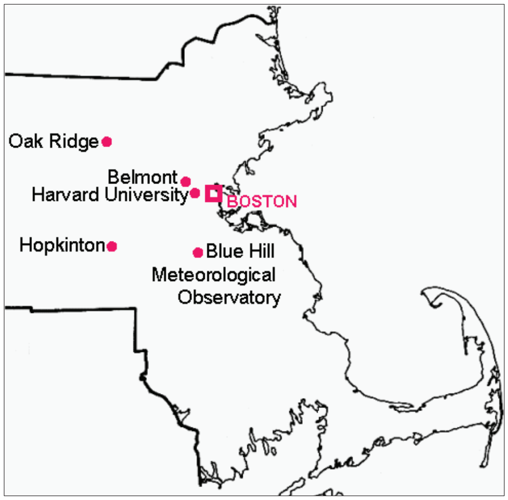


Figure 3: Massachusetts localities mentioned in the text.

> Spectrum III was now the only one for which no satisfactory final wave-lengths had been determined. Blajko determined preliminary wave-lengths from measurements of the chart plate and then, by shifting these preliminary wave-lengths by 10 to 14 Angstroms he found coincidences with five helium lines. This explained five of the meteor spectrum lines and gave final wave-lengths for the others but resulted in no further satisfactory identification. All possible combinations of elements were tested by the writer in an attempt to explain the other lines in this spectrum, without success. The identification with helium seemed rather uncertain from a theoretical standpoint, as helium is only present in meteorites in very minute quantities, and the excitation potential of the helium lines is high, so that they are not produced easily. The lines might arise from atmospheric helium but no evidence of atmospheric lines appears in the other spectra.
>
> It was noted that, if the whole spectrum could be shifted on the dispersion scale about fifty Angstroms to the violet, there would be no difficulty in identifying all the lines. To test the possibility that the spectrum was originally placed too far to the red on the dispersion scale, measurements on the chart plate were made by the writer to determine an approximate wave-length of the line λ4017 in Blajko's preliminary table. Using two stars on either side of the meteor trail, four values were obtained, giving a mean wave-length λ3980 ± 2. Now, by shifting this preliminary determination by eleven Angstroms, coincidences of all the meteor lines with known lines appearing in other meteor spectra were obtained. The original error in the preliminary wave-lengths may have arisen from a slight difference in scale between the chart and spectrum plate, from poor images on the chart plate, and from the fact that one of the bright stars near the meteor trail is a double and hence the overlapping of the spectra must be allowed of in using it as reference point.

Millman (1932: 118-119) also disputed some of the other conclusions reached by the earlier researchers. He found that

> Spectra II, IV, and VIII each contained two lines brighter than all the others and, when the preliminary wave-lengths were computed, it was found that they closely agreed with those of the H and K lines of ionized calcium … [Spectrum VI] exhibited two bright lines of similar appearance … [and] It was assumed … that these were [also] the H and K lines …
>
> Spectra I, III, V, and VII were more difficult cases as none of them showed any outstanding feature which could be at once recognized … [However] On comparison with the spectra of various elements common in meteorites the lines in Spectrum V were seen to be grouped similarly to the strongest parts of the iron spectrum … [and] The resemblance between the two spectra … seemed to justify proceeding on the assumption that the majority of lines in Spectrum V were produced by iron. This view was greatly strengthened by a consideration of Spectrum VII. The latter was at once seen to be very similar to Spectrum V …
>
> The collective evidence of the presence of iron in all nine spectra has seemed so strong, however, that the writer has advanced it as the best and most probable identification of the majority of lines …
>
> The six lines of Spectrum I seemed to agree well with the iron spectrum …

From his investigation of the wavelengths of the various spectral lines in Spectra I-VIII, Millman (1932: 132) was able to demonstrate that they were predominantly produced by iron and calcium, with magnesium, manganese, chromium, aluminium and possibly silicon responsible for some lines in a few of the spectra. Interestingly, the three spectra associated with Perseid shower meteors were "… not noticeably more alike than are the other six. III and VI both show magnesium definitely and all three show strong calcium." (Millman, 1932: 136). Figure 2 shows the wavelength distribution of the identified lines in the eight spectra.

Despite this promising start, Millman (1935a: 149) saw the importance of increasing his observational data set, and in 1931 he began a quest to obtain more photographs of meteor spectra.

3.3 Initial Observations at the Blue Hill Meteorological Observatory

In order to achieve this, Millman set up four cameras equipped with prisms at the nearby Blue Hill Meteorological Observatory, whose situation "…is far superior to Cambridge since it has an altitude of 635 feet and is fairly well removed from city lights and haze." (Millman, 1932: 115). For Massachusetts localities mentioned in the text see Figure 3.

Millman intended to begin his observing program with that year's Leonid meteor showers. However, not for the last time in his career, the weather proved uncooperative with a week of heavy cloud cover. Observing sessions were postponed until later in the year. A total of 120 plates was eventually exposed for a cumulative time of 85 hours over five nights (11 and 13 November, and 7, 12 and 14 December 1931). During the November observations the cameras were directed towards the radiant of the Leonid showers while during December they were pointed in the region of the Geminid radiant. In each case visual observations were made concurrently with the photographic work. This effort resulted in the recording of the ninth spectrum then known to exist (see Figure 4):

> A bright meteor spectrum was photographed with Camera A on the night of December 14.[2] This meteor was slow and fully as bright as Jupiter. No other meteors of similar magnitude were observed to cross the fields covered by the cameras and no other meteor was photographed. (Millman, 1932: 115).

In fact, another meteor *had* been photographed, and was discovered later when Millman carried out a second inspection of plates exposed on 12 December 1931 during the Geminid shower. More meteor spectra would follow as Millman completed his doctorate under a fellowship from the Royal Society of Canada, and he then remained at Harvard for one more year as Agassiz Scholar (Millman, n.d.).

3.4 Observing at Flagstaff

Between 25 February 1932 and 26 February 1933, Millman helped arrange for the operation of three spectrographs at Flagstaff, Arizona, as part of the Harvard-Cornell Meteor Expedition of 1931-1933.

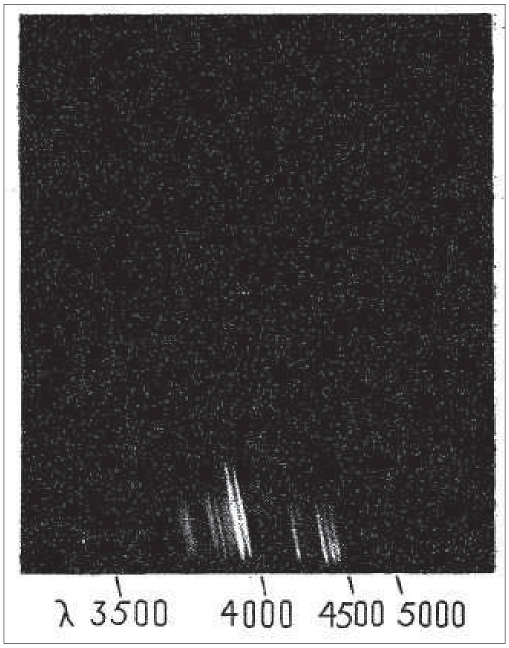


Figure 4: The first meteor spectrum photographed by Peter Millman, on 14 December 1931 from the Blue Hill Meteorological Observatory (after Millman, 1932).

Each of these cameras covered approximately 1400 square degrees of the sky and was directed at altitudes of thirty degrees. Two cameras faced south and one towards the north, with each aligned so that the prisms dispersed light horizontally. Exposure times generally ranged between one and two hours. In all, 788 plates were exposed over a total of almost 1351 hours, resulting in the capture of five meteor spectra (Millman, 1935a).

During the 1932 Leonid showers, additional cameras were set up at various locations. Millman observed with seven from Oak Ridge, Massachusetts, one of which had a rotating shutter. The nearby stations at Hopkinton and Belmont (see Figure 3) formed a triangle with ~35km sides for height determination by triangulation of any meteors observed simultaneously from more than one station. Observations were also made in Flagstaff and at Fort Worth in Texas. Non-spectrographic observations were also conducted from Brooklyn, New York, the meteorological station on Mt. Washington, and by Peter Millman's brother, John, in Saskatoon, Canada (Millman, 1933b). This effort resulted in another 96.8 hours of exposure time distributed across 398 plates, and produced eight more meteor spectra. In less than two years, Millman succeeded in increasing the total number of known meteor spectra from 8 to 23 (see Table 2).

Table 2: The fifteen new meteor spectra photographed by Millman during 1931-1933 (after Millman, 1932; 1935a).

U.S. Locations	Dates	Number of Spectrographs	Plates Exposed	Hours Exposed	Meteor Spectra Recorded
Blue Hill, MA	11-13 November; 7-14 December 1932	4	120	85	2
Flagstaff, AZ	25 February 1932 - February 1933	3	788	1351	7
Oak Ridge, MA	15-18 November 1932	7	224	61	5
Hopkinton, MA	15-16 November 1932	3	90	14.4	0
Belmont, MA	15 November 1932	1	11	4	0
Ft. Worth, TX	15-16 November 1932	2	11	6	1

4 DEVELOPING EQUIPMENT AND METHODS FOR METEOR SPECTROSCOPY

In beginning his meteor spectrophotography program at Harvard, Peter Millman was virtually developing a new branch of astronomy. Accordingly, he could not simply rely on methods developed by others in overcoming the many practical difficulties he faced. In attempting to systematically photograph such transient phenomena as meteor spectra, he needed to determine for himself what equipment and techniques would successfully accomplish his goals. He did this through an extensive program of trial and error that eventually allowed him to select suitable lenses, prisms, shutters, and photographic plates, as well as methods for focusing and directing his cameras. Shapley made sure that the Harvard College Observatory supplied the necessary equipment, either by approving the purchase of new items or by drawing on its existing collection of surplus optical components.

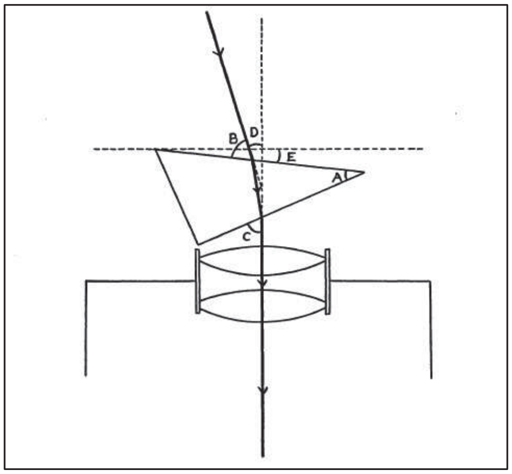


Figure 5: Diagrammatic representation of the optical system of Millman's meteor spectrograph, showing the prism completely covering the camera lens (after Millman, 1933a: 300).

4.1 Lenses and Prisms

The spectrographs Millman developed during the pioneering years employed prisms that combined with the lenses of his cameras to provide his optical systems. His primary concern in their function was to maximize the dispersion of the meteor light in order to provide the greatest opportunity for identifying and analyzing the spectral lines. As he stated, "To photograph one meteor spectrum in good definition is far more important than to secure ten that are of only average quality." (Millman, 1933a: 301). He therefore chose the components of his optical systems carefully in order to maximize the information that would be revealed.

When selecting a lens, Millman needed to find a balance between dispersion and speed. A slow lens would produce maximum dispersion, yet would produce significant absorption of the meteor's light. A fast lens would minimize absorption but would produce little dispersion:

> The difficulty encountered here was the small dispersion and low resolution that it was necessary to work with, the dispersions ranging from 150 to 450 angstrom units per mm. between Hγ and H_{ζ} . (Millman, 1935a: 152)

Through his observing experience at Harvard, Millman concluded that the practical range of dispersion for his meteor spectra was 0.5 to 1.5 mm from Hβ to Hγ. The upper limit for achieving such dispersion he found to be a focal ratio of f/4.5. Early in this period Millman (1933a) achieved his best results with two f/4.5 lenses, the Zeiss Tesssar and the Voigtlander Skopar, but he would later also successfully employ Xenar Schneider, Moia Helimar Series I, Zeiss Tessar IC and Boyer Saphir lenses (Millman, 1932).

The same balance between dispersion and speed needed to be achieved with the prism to be used. Millman's prisms were of glass or high-quality quartz with a refracting angle of ~30°. If it was much smaller than this, the prism would not produce sufficient dispersion of the spectral lines to allow for identification; if it was much larger, the absorption of the glass or quartz would severely reduce the speed of the system (Millman, 1933a).

Once a proper lens and prism had been selected, they needed to be mounted correctly to create an efficient spectrograph. The prism was held in front of the lens in such a way as to cover it entirely (Figure 5). For an f/4.5 lens of 25 cm focal length, the most efficient prism over the whole photographic spectrum would be one of ultraviolet crown glass set at an angle of 30-40°. Alternatively, a light flint prism set between 20° and 30° degrees could be used, although this was not as efficient at short wavelengths. A suitable angle could be determined empirically by testing the refraction of the light by the prism while still outside of the spectrograph:

> … the angle of minimum deviation, may be found to the required degree of accuracy by setting the prism on edge on a large piece of white paper on which has been drawn a single straight line and then studying the way the light is bent by observing this line through the prism. (Millman, 1933a: 302).

However, although the angle of mounting was important, of even greater concern was the stability of the prism:

> The exact angle at which the prism is set, however, is not nearly so important as making sure that the prism is firmly mounted so that its position with respect to the lens will not vary in the slightest throughout the course of the observation. This last point cannot be too strongly stressed. (Millman, 1933a: 302).

4.2 Rotating Shutters

Millman also made use of a rotating shutter, a piece of equipment introduced at Harvard Observatory by W.J. Fisher for the photographic recording of meteors (see Lovell, 1954: 198) and passed on to Millman in the autumn of 1932 (Millman and Hoffleit, 1937). The shutter was driven by a synchronous motor, covering the lens a set number of times (typically 20 to 30 times) per second. This effect broke the image of the meteor train on the photograph into segments, allowing computation of the apparent angular velocity of the meteor based on the rotation rate of the shutter. If the meteor was simultaneously observed from a second station, an actual velocity could be determined (Millman, 1936a). Important information could also be revealed about the persistent train of the meteor. So successful did Millman (1936a: 103) find this method that he expressed the hope that, "… all meteor photographers will, where possible, equip their cameras with rotating shutters."

4.3 Plates

Shortly after embarking upon his work in meteor spectroscopy, Millman (1935b: 116) wrote:

> Important advances in astronomical photography are very closely dependent upon improvements in the speed and grain of photographic emulsions. Nowhere is this truer than in meteor photography where increased efficiency cannot be attained by the use of larger instruments or longer exposures. The meteor photographer should always be on the lookout for plates which combine great speed with fairly small grain.

From the earliest days of his work, Millman was true to his own advice. His difficulty arose from the fact that because spectrophotography involved recording images of individual wavelengths, the photographic plate used needed to be sensitive across a broad band of the spectrum. No single film was entirely satisfactory and Millman constantly experimented with new plates.

To record around the blue end of the spectrum, Millman began by employing the Cramer Hi-Speed plate which was fastest in the blue region but was well-suited for photography only between λ3800-λ4800. Another film, the Cramer Iso-Presto had a similar blue sensitivity and also added a band in the yellow-green range, but Millman found it considerably more prone to sky fog. Barnet produced the Super Press Plate which was slightly faster in the blue region than the earlier Cramer Hi-Speed and also showed some sensitivity to yellow wavelengths (Millman, 1933a).

Although all Millman's spectra were captured using Cramer plates—5 on Hi-Speed and 10 on Iso-Presto (Millman, 1932)—the best plate technically was probably Ilford's Hypersensitive Panchromatic plate, which had been specially sensitized for meteor work. Millman (1933a: 303) tested it and found these plates to be highly satisfactory:

> They are practically as fast in the blue as the Hi-Speed and have a comparatively even gradation through the green and yellow with a slight maximum near λ6000. They seem particularly suitable plates for covering the whole spectrum except for the deep red, and should be well adapted to photographing the sodium yellow and magnesium green lines which, although the most prominent parts of the visual spectrum of meteors, have not yet been photographed.

Films suitable for recording the visual spectrum at long wavelengths proved more difficult to find and in fact Millman would not obtain satisfactory films until shortly after his departure from Harvard, when he returned to his native Toronto. The red region was of particular interest to Millman because visual observers in the nineteenth century had reported strong lines in this part of the spectrum but those lines had not been identified photographically and their source remained uncertain. To identify them, "… a good photographic meteor spectrum extending to λ 6500 or beyond is the only solution." (Millman, 1934a: 35). It was not until 1935 that Millman found such a film, when the Ilford Hα II plate came on the market. It was sensitive in the red region as far as λ6800, with peak sensitivity close to the Hα line. Millman (1934a: 36) remarked that this film "… is very fast for a plate sensitive so far into the red."

4.4 Focusing and Directing the Camera

Focusing the spectrograph was a problem. Star trails could not be used since in spectroscopy the trails were dispersed and not sharp enough to determine if the focus of the camera was properly adjusted. Millman overcame this challenge and focused his spectrograph by directly judging the sharpness of stellar spectra themselves. He generally considered the prominent hydrogen Balmer lines, commonly assessing them in the bright spectra of Sirius in the winter and Vega in the summer (Millman, 1937).

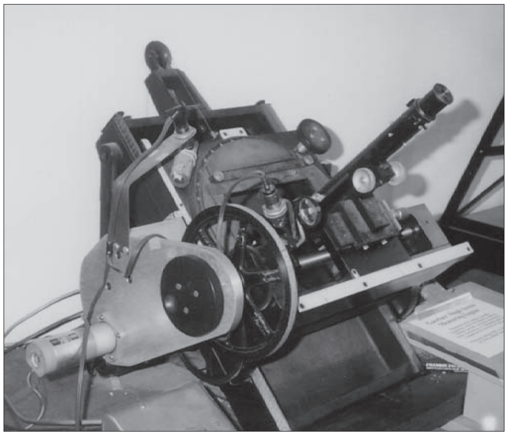


Figure 6: A Gaertner measuring engine, like the one used by Millman (courtesy: McCormick Museum).

In addition to proper focusing, Millman (1933a) also pointed out the importance of the selection of the direction in which to aim the camera. He suggested that on an average night any region of the sky >30° above the horizon was acceptable, with some slight advantage for spectrophotography of altitudes around 40-45°.

While photographing during a meteor shower, it was best to aim the camera near the radiant, "… in spite of the fact that casual observations would lead one to think that the brightest meteors appear at some distance from the radiant." (Millman, 1933a: 303-304). This is because the slow angular velocity close to the radiant produced better photographic results, in spite of the more spectacular visual appearances at a greater distance. Millman (1933a) also suggested that, if the radiant of the shower was near to one horizon, extra cameras could be usefully directed at the opposite horizon.

In all cases, since the most likely direction of motion of meteors is downward, the spectrograph's prism was positioned with the thin edge vertical (ibid.).

5 ANALYSIS OF THE NEW SPECTRA

To Millman, success in obtaining meteor spectra was not an end in itself, as these were research tools that would yield information on the chemical composition of meteors and hint at their origin within the Solar System, and they could also be used to investigate the

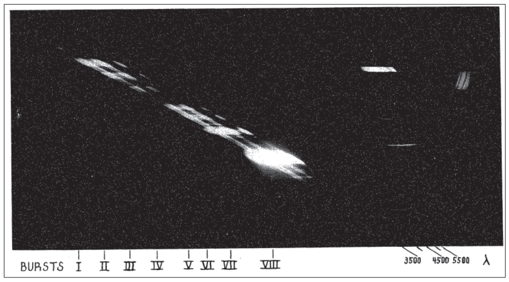


Figure 7: Photograph of Spectrum XXIV, captured by Millman on 26 February 1933 (after Millman, 1935a: 165).

properties of the ionosphere (Millman, 1933d). To do this Millman carried out a detailed analysis of each of the newly-obtained spectra, recording the positions and intensities of the different spectral lines, and identifying the associated elements.

He started by using a measuring machine, either a Hilger or more commonly a Gaertner single-screw measuring engine (Figure 6), a device designed by Frank Schlesinger in the early part of the twentieth century and built by the Gaertner Scientific Corporation of Chicago. The Gaertner engine was designed to allow for rapid measurements by relying on a single bisection by the microscope reticle lines which would then permit the measurement to be read from a dial. A rotating stage was provided to allow for measurements in different coordinates. Finally, to deal with the problem of measuring images with breadth, a reversing eyepiece was provided that would reverse the image 180°, so that measurements could be made from both sides of an object and then averaged. Millman took full advantage of these features in carrying out his analysis of the nine meteor spectra available to him:

> The spectra were so placed on the machine that the dispersion was parallel to the motion of the screw, since in most cases the meteor trail changed greatly in intensity and quality throughout its length. By this arrangement the lines of the meteor spectra were not necessarily perpendicular to the direction of the screw motion, but it had the advantage that a single set of measures represented lines impressed by the meteor simultaneously. The cross wire was turned parallel to the meteor spectrum lines and these were made to appear perpendicular in the field of view by use of a reversing eyepiece. Three settings were made on each line in a spectrum. It was then reversed by means of the eyepiece and the measurement repeated. The mean of the six settings was taken as the final setting for a line. (Millman, 1932: 117).

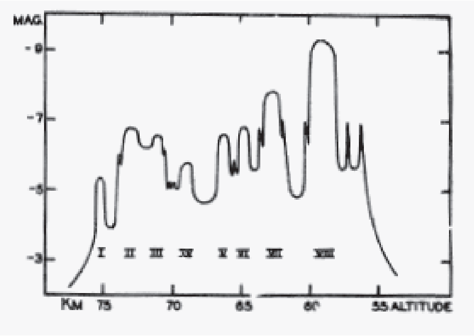


Figure 8: Plot of changes in total intensity along the flight path exhibited by the meteoroid that produced Spectrum XXIV (after Millman, 1935a: 155).

Millman thus measured each spectrum at least six times, three times from each end. When possible, dispersions were calculated from stellar spectra visible on the plates. A difficulty arose, however, from differences in the scale of dispersion in different parts of the plates. This was particularly troublesome since many of the cameras used covered a large area of the sky and a significant portion of the spectra were located at the outer edges of the plates. Millman's growing experience with meteor spectrum photography, however, helped him overcome this problem:

> Fortunately … known lines could almost always be recognized by an examination of the spectrum, and slight adjustments to the scale of the dispersion could then be made. This is not the most satisfactory procedure and it was followed only when all the available information concerning the dispersion had been obtained from measures of stellar spectra and where the writer was certain of his line identifications. (Millman, 1935a: 152).

A further difficulty in determining dispersion came from the fact that meteor spectra were generally at some angle to the direction of dispersion. To deal with this, Millman attached a photographic glass reticle to the plate with its lines parallel to the emission lines of a stellar spectrum. Meteor lines were then measured parallel to the reticle lines which served as a zero point.

Another problem related to measuring the intensity of the emission lines. Where possible, the Moll microphotometer was employed for making these readings. Characteristic curves were determined if stellar spectra were suitable, less accurate standard curves if they were not. However, in many cases, sky fog on the plate proved too great for microphotometer measurements to be made, in which case eye estimates had to be relied on (Millman, 1935a).

5.1 Spectrum XXIV

As an example of Millman's detailed work, his analysis of the twenty-fourth spectrum, the final one recorded during the Harvard program, may be considered (Figure 7). This spectrum was obtained on 26 February 1933 on the second-to-last plate of the Flagstaff observation program. It was taken on a Cramer Iso Presto plate using a camera equipped with a Boyer Saphir 150 mm f/4.5 lens and a 30-degree Hilger flint prism (Millman, 1935a). Millman (1933c) reports that

> The exposure was on the north pole, being one hour in length. The camera was on a stationary mount so that the stars made circular trails about the pole. Polaris is the very bright star in the upper right, about one and a half inches from the edge … The dispersion is horizontal with the violet end of the spectrum to the left, the red end to the right. The hydrogen lines are clearly visible in the star at the extreme right.

The recorded meteor was estimated to have a visual magnitude that began at +2 and peaked at –9, its duration was 4.5 seconds, and it left a persistent train for 2 seconds. The meteor streak covered just over 24° on the sky. By comparing the photograph taken at Flagstaff and a visual sighting at nearby Padre, it was estimated that the meteor became visible while at a height of about 90 km above the Earth and disappeared at 52 km altitude. During this fall it showed eight large bursts and numerous smaller ones (Figure 8). Analysis of the spectrum revealed 63 measurable lines. Millman's careful reduction was typical of his work:

> Microphotometer tracings of the spectrum were made at twelve points on the trail. They were located with reference to the bursts as follows: before I, I, after I, 2, after 2, 4, after 4, 6, 7, 8, after 8. Twenty two tracings in all were made, two or three slit widths being used at most of these positions. The characteristic curve for the plate was determined from the tracings of eight spectra of stars with known magnitudes. Most of these stars were of Class A, and in the reduction allowance was made for the declination of the star, its class, its distance from the plate center, and the angle which its motion made with the direction of the dispersion. Separate characteristic curves were drawn for each wave-length measured in the stellar spectra, and as all of these were seen to be of the same shape they were combined. The resulting mean characteristic curve has been derived from seventy five points in good agreement. For this reason the writer feels great confidence in the intensity measures of this spectrum and considers them superior to those of any other spectrum studied. (Millman, 1935a: 162-163).

The meteor trail was recorded at an angle of only 28° to the direction of dispersion, requiring the use of a reticle as described above. Millman (ibid.) improvised an ingenious method to accomplish this before using the results to determine the intensities at various points along the trail:

> The twenty two tracings were measured by means of a reticle formed of accurate graph paper (20 squares to the inch) treated with Vaseline. The reticle was clamped securely over the tracing in a frame and readings in both coordinates made to the tenth of a division. This method is much more rapid and probably more accurate than the usual way of measuring traces. Reduction to magnitudes was made by means of the characteristic curve, converted to tabular form for this purpose. The intensity curve of the meteor spectrum at each of the twelve points was then plotted on a large scale, in terms of magnitudes. The curves obtained from tracings made at the same point but with differing slit widths agreed excellently, the chief difference being the greater resolution given by the narrower slits. The agreement further indicates the reliability of these intensities.

6 RESULTS OF THE HARVARD PROGRAM OF METEOR SPECTROPHOTOGRAPHY

Millman's observing program in connection with Harvard College Observatory produced outstanding results (Table 2). In total 1,244 plates were exposed for a cumulative time of 1,521 hours. This work more than doubled the total number of meteor spectrum photographs, adding 15 to the previous total of 9. Such a result translated into one spectrum for every 82.9 plates exposed (requiring an average of 101.4 hours exposure time), comfortably within Harlow Shapley's stated aim of "… one spectrum out of every fifty to a hundred attempts." Of the 24 meteor spectra known by the end of 1933, Millman had been directly involved in capturing at least 7 of them (29%) and had organized the programs that had obtained 8 others (33%), thus accounting for 62% of the meteor spectra then in existence. He also carried out the initial reductions for all these new spectra and re-evaluated the previous spectra, including correcting the incorrect identification of the emission lines of one of them. Millman clearly had, almost single-handedly, transformed the capture and study of meteor spectra from a haphazard and largely-neglected field into a sound science based on effective methodology.

Millman (1932: 139) noted that his analysis of all these spectra revealed a composition of meteors in keeping with what had been deduced from the analysis of meteorites. All the lines identified could be matched to elements known to be present in meteorites. Iron, nickel, calcium, magnesium, manganese, and chromium were definitely identified and probable identifications were made of sodium, silicon, and aluminium (Millman, 1935a). In summing up his study of the spectra, Millman (1932: 140) concluded that, "… we find in them when viewed as a whole just about what we would expect from a consideration of … the average constitution of meteorites." This reference to meteorites is interesting given that some meteor showers were known to be associated with specific comets. Yet comets never entered Millman's discussions (or, presumably, his thoughts). This is rather hard to explain.

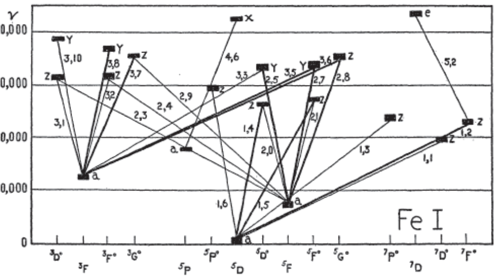


Figure 9: Grotian diagram showing the energy levels of iron that give rise to multiplets identified in meteor spectra (after Millman, 1932: 137).

7 THEORETICAL WORK ON METEORS AT HARVARD

In addition to his observational work, Peter Millman also attempted to determine the significance of his data by linking them to findings in other fields of astronomy and physics.

7.1 Atomic Physics, The Thermodynamic Environment, and Light Production of Meteors

Millman analyzed the multiplets (transitions between atomic energy levels) suggested by the iron lines (Figure 9) in order to gain information about the thermal environment of meteors. He found that almost all corresponded to shifts from one of the three lowest levels of the iron atoms. He then used five ratios of these multiplets between λ4000 and λ4500 (outside this range changes in plate sensitivity, small resolution, and poor definition made the spectral lines unsuitable for the task) to obtain the effective temperatures of the meteors. The resulting curve is shown in Figure 10, and from it Millman (1932: 146) concluded that, although "… the spectra showed very little detail and hence the determination of the excitation was very uncertain …", it could still be stated that

> In the four cases where microphotometer intensity measurements were made, the iron vapor was at states of

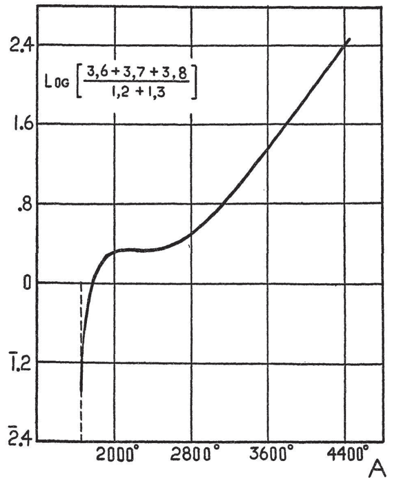
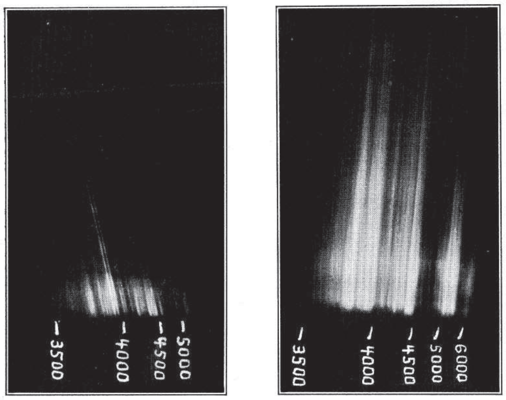


Figure 10: Graph comparing the excitation indicated in meteor spectra with the effective temperature of the surrounding meteor vapour (after Millman, 1932: 143).

> excitation corresponding to furnace temperatures ranging from 1680 degrees to 2800 degrees absolute. In the spectra where eye estimates of intensity were made, the iron vapor in two cases had the excitation corresponding to a minimum temperature of 3400 degrees absolute. (ibid.).

Although these estimates are considerably below today's calculated values (Lewis, 1997), they mark the first serious attempt to use spectroscopy as a tool to analyze the thermal environment of a meteor.

Millman also used the spectra he had obtained to consider the source of meteor luminosity, something which was an open question at the time. He found that his work generally supported the theory of Ernst Öpik, who claimed that a meteor's light arose from a coma that formed from vapor released by the meteor as it descended through the atmosphere, either by impacts between air molecules and particles in the coma or from thermal radiation produced by particle impacts within the coma itself (Millman, 1935a). Millman pointed out that under these conditions the vapor would be in a low state of excitation and produce a spectrum dominated by emission lines coming from the lowest atomic levels. Lines from various ionized states, especially those arising from the first ionized state of easily ionized elements would also be expected. Millman found that these predictions were in broad agreement with his observations.



A METEOR SPECTRUM, TYPE Y A METEOR SPECTRUM, TYPE Z

Figure 11: Millman's classification of meteor spectra. On the left is Type Y, with strong calcium H and K lines, and on the right Type Z, which is dominated by iron (after Millman, 1936b: 385).

7.2 Meteoric Bursts, Spectral Classification and the Nature of the Atmosphere

Millman had not forgotten that one of the initial justifications Shapley had offered for the study of meteors was that it would reveal information about the upper atmosphere. In line with this, he considered the question of the cause of meteor bursts such as those described above in connection with Spectrum XXIV. After considering several earlier suggestions for the production of meteor bursts, including the gradual heating of the core and its splitting, he concluded that, "It is probably incorrect … to take any one cause as the origin of all bursts in meteor trails." (Millman, 1935a: 176). He then offered his own suggestion:

> We already know, from a study of the motion of meteor trains, that considerable turbulence exists in the atmosphere at great heights, and it is quite possible that the physical properties of the air in these regions may be less uniform than has hitherto been supposed. (ibid.).

Millman also designed a classification scheme for spectra which he hypothesized had a connection with atmospheric conditions. He was able to divide his spectra (with the exception of Spectrum III) into two types, Type Y, in which the most prominent spectral feature was the H and K lines of ionized calcium, and Type Z, in which ionized calcium lines were absent and the spectrum was dominated by iron lines (Figure 11). He then noted a correlation between the spectral type and altitude for the eight meteors whose heights had been determined. He found that the five meteors which appeared above 80 km were all Type Y, while the three below that altitude were each Type Z (Figure 12), and he remarked: "Though the observational evidence for this correlation is not large, it seems unlikely that it appears purely by chance." (Millman, 1935a: 171).

Millman rejected the obvious hypothesis that the Type Z spectra, with their predominance of iron spectral lines, represented iron meteorites (which lacked significant amounts of calcium), while the Type Y spectra corresponded to stony meteorites, which had a significantly greater calcium content. He pointed out that while Type Z spectra represented 64% of the first fourteen sporadic meteors photographed, iron meteorites made up only 5.4% of the total meteorites then known. "Type Z would seem to be of too frequent occurrence to be produced by iron meteorites." (Millman, 1935a: 171). Secondly, he noted that elements not commonly found in iron meteorites had been identified in Type Z meteor spectra.

Instead, Millman (1935a: 171-172) considered the possibility that the difference in the two types of spectra related to the atmospheric conditions under which the luminosity was being produced, rather than the compositions of the meteoroids themselves:

> We find that the average height of the lower ionized layer, the maximum intensity of the aurora, noctilucent clouds, persistent meteor trains, and the greatest number of meteors all occur in the same region of the earth's

> upper atmosphere, that between altitudes of 80 and 120 kilometers. This concurrence of phenomena should be regarded as significant. It is highly probable that the ionized condition at this height has a definite bearing on meteoric problems, a supposition which is certainly not weakened by the fact that spectra of Type Y seem to occur in and above the ionized layer whereas those of Type Z are below it.

8 CONCLUDING REMARKS

When Peter Millman began his Ph.D. studies at Harvard in 1931 he had no prior interest in meteors, let alone meteor spectra (Millman, 1963: 119). Rather meteor spectroscopy was assigned to him by Shapley. Yet it is obvious that Millman made an excellent fist of the task at hand: when he began his research, meteor science was a relatively insignificant branch of astronomy that relied almost entirely upon visual observations, and meteor spectroscopy was virtually non-existent. By the time he completed his Ph.D.—just two years later—Millman had begun to transform meteor spectroscopy from an astronomical afterthought into a systematic scientific field with an established methodology. Through his personal efforts in this period, 15 meteor spectra were recorded (Table 3), adding to only 9 previously in existence and thereby increasing the available data-bank by 167%. In the words of Ian Halliday (1994: 214):

> Although some sporadic attention had been paid to the spectra of meteors early in this century, it was Millman's research that established the fundamentals.

Moreover, in a relatively short period of time, Millman acquired what can only be described as a passion for meteor spectra if we are to believe the following admission that he included in a paper published in 1936:

> There is no branch of astronomical photography that has a greater appeal to the sporting instinct than the photography of meteor spectra. This is because no one can predict when, or in what part of the sky, a bright meteor will appear, and when it does appear the whole phenomenon rarely lasts longer than two or three seconds. A program of meteor photography thus resolves itself into something very much like a fishing expedition, where the observer sets up a camera instead of throwing out a line and then leaves the shutter open, hoping that a bright meteor will cross that part of the sky towards which the camera is directed. The thrill of securing a particularly fine meteor spectrum is also closely akin to the elation experienced in landing a fish of record weight. (Millman, 1936b: 384).

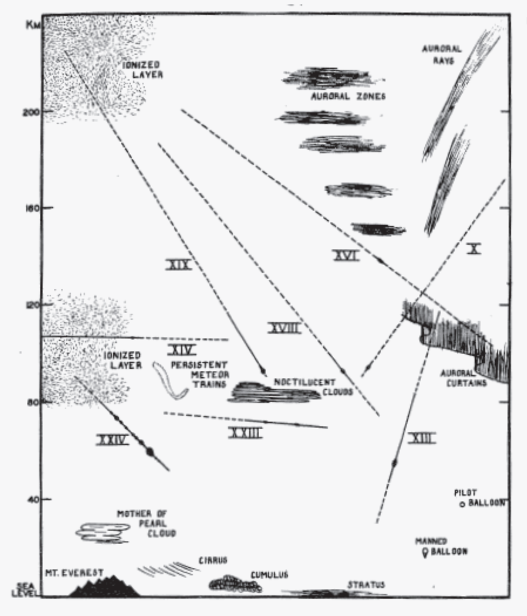


Figure 12: Diagram showing the heights of the meteors that produced the spectra examined by Millman (Roman numerals). There is a correlation between spectral category and the height at which the meteor appeared in the atmosphere (after Millman, 1935a: 155).

After completing his work at Harvard in 1933, Millman returned to Canada to accept an appointment as a lecturer at the University of Toronto and astronomer at the affiliated David Dunlap Observatory. Although he continued to study meteor spectra throughout his career in Canada (e.g. see Millman, 1968; Millman et al., 1973), Millman expanded his portfolio considerably, including regular photographic observations, vis-

Table 3: Details of the fifteen meteor spectra recorded during the Harvard observing program, 1931-1933 (adapted from Millman, 1935a).

Spectrum	Date	Equipment	Associated shower	Plates Used	Lines in Spectrum
		Camera A	Blue Hill MA		
IX	15 Dec. 1931	Lens: Voigtlander Skopar, 30 mm aperture, 135 mm focal length, 4.5 aperture ratio Prism: 30° Average dispersion: H_δ-H_γ 450 au/mm	Geminid	Cramer Hi-Speed	42
		Camera B	Ft. Worth TX		
XX	16 Nov. 1932	Lens: Xenar Schneider, 50 mm aperture, 175 mm focal length, 3.5 aperture ratio Prism: 20° Average dispersion: H_δ-H_γ 900 au/mm	Leonid	?	9
		Camera C	Blue Hill MA		
X	12 Dec. 1931	Lens: Zeiss Tessar, 61 mm aperture, 165 mm focal length, 2.7 aperture ratio Prism: 15° Average dispersion: H_δ-H_γ 1050 au/mm	Geminid	Cramer Hi-Speed	7
		Camera K	Oak Ridge MA		
XV	16 Nov. 1932	Lens: Moia Helimar Series I, 37 mm aperture, 165 mm focal length, 4.5 aperture ratio Prism: 35°, crown Average dispersion: H_δ-H_γ 470 au/mm	Leonid	Cramer Iso Presto	12
XVI	16 Nov. 1932		Leonid	Cramer Hi-Speed	9
XIX	16 Nov. 1932		Leonid	Cramer Hi-Speed	12

		Camera LT	Oak Ridge MA		
XVII	16 Nov. 1932	Lens: Zeiss Tessar IC, 56 mm aperture, 250 mm focal length, 4.5 aperture ratio Prism: 30°, flint Average dispersion: H_δ-Hγ 260 au/mm	Leonid	Cramer Iso Presto	12
XVIII	16 Nov. 1932		Leonid	Cramer Iso Presto	7
		Camera T	Flagstaff AZ		
XIII	26 May 1932	Lens: Zeiss Tessar, 61 mm aperture, 165 mm focal length, 2.7 aperture ratio (often at 3.5) Prism: 22°, crown Average dispersion: H_δ-Hγ 500 au/mm	--	Cramer Iso Presto	28
XXII	17 Nov. 1932		Leonid	Cramer Iso Presto	12
XXIII	22 Feb. 1933		--	Cramer Iso Presto	8
		Camera U	Flagstaff AZ		
XII	29 Apr. 1932	Lens: Boyer Saphir, 33 mm aperture, 150 mm focal length, 4.5 aperture ratio Prism: 35°, Hilger, flint Average dispersion: H_δ-Hγ 410 au/mm	--	Cramer Iso Presto	24
XIV	27 May 1932		--	Cramer Iso Presto	42
XXI	17 Nov. 1932		Leonid	Cramer Iso Presto	14
XXIV	26 Feb. 1933		--	Cramer Iso Presto	64

ual observations (made mainly by his 'army') and radar observations of meteors; he also carried out considerable research on meteorites (see Jarrell, 2009). Mainly through his efforts and commitment, and by serving as a catalyst for others, Millman turned Canada into one of the world's leading nations involved in meteor astronomy and meteoritics (see Russell, 1991). Yet, until Z. Ceplecka, A.F. Cook, and J.A. Russell began working in the field in the late 1940s and during the 1950s, few astronomers world-wide acquired Millman's passion for meteor spectra, and it largely remained his 'domain' right up until his retirement from active research only weeks before his death in 1990.

When he began studying meteor spectra in 1931 Millman's aim was to learn more about the properties of the associated meteoroids and to use their passage through the Earth's atmosphere to investigate certain properties of the ionosphere. By the time he completed his life's work, he had succeeded admirably on both counts. Meanwhile, the bipartite scheme involving Y and Z spectra that he developed in 1935 largely stood the test of time. Nearly thirty years later he wrote:

> A study of all available data has indicated that this original classification scheme is still useful … [though it needs to be] revised slightly to adjust it to the panchromatic emulsions now generally used. (Millman, 1963: 121).

Although the work of this pioneering Canadian astronomer may be little remembered today, it is rarely that a researcher can legitimately be said to have laid the foundations for an original method of studying the heavens. Peter Mackenzie Millman was one such researcher, and we salute his important contribution to meteor astronomy.

9 NOTES

1. This table actually contains nine entries, for in early 1932 Miss L.L. Hodgdon found a photograph of a meteor spectrum on a 1913 plate housed in the archives of the Harvard College Observatory. Millman (1934b) named this Spectrum XI, since it was 'discovered' after the two Blue Hill meteor spectra were photographed.
2. This meteor spectrum was actually photographed on the morning of 15 December and is entered under this date rather than 14 December by Millman in his later lists of meteor spectra (e.g. see Millman, 1934b).

10 ACKNOWLEDGEMENTS

Grateful acknowledgement is given to the many people who assisted during the researching of this paper, including: Alex Hons, Dr Andrew Walsh and Associate-Professor Graeme White from James Cook University; Dr Ralph Chou from the Royal Astronomical Society of Canada for direction in finding resources; Professor David Hughes for kindly supplying references and for reading and commenting on the manuscript; Professor Richard Jarrell from York University, Toronto, for sharing his research on Millman's Canadian observing program; Jacqueline Radigan and Brian Zarudny for proof-reading and support; staff from the Gerstein Library of the University of Toronto and those who maintain the NASA ADS website for provision of resources; and finally, Peter Millman, Ian Halliday and B.A. MacIntosh from the McCormick Museum for providing illustrations.

Above all, our deepest appreciation must be extended to the Millman family: Cynthia Millman Floyd, for sharing her memories of her father; Rowland Floyd for his extraordinary efforts in arranging contacts with the children of his father-in-law; and Barry Millman for opening his home and his memories and generously sharing the records of his father. Without their assistance, this paper would have missed a great deal of the spirit of Peter Millman's pioneering years.

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2009JAHH...12..224J

Journal of Astronomical History and Heritage, 12(3), 224-234 (2009).

CANADIAN METEOR SCIENCE: THE FIRST PHASE, 1933-1990

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Abstract: Canadian meteor science, encompassing visual, photographic, spectrographic and radar studies of meteors, along with research on impact structures and the retrieval of meteorites, was widely respected during the second half of the twentieth century. There is no question that the leadership of Peter M. Millman made the research field possible. Yet a combination of changes to government institutions, budgetary constrictions, university department priorities and shifting research interests led to the field's near demise in Canada not long after Millman's death.

Keywords: Canada, meteor astronomy, meteorites, radar, Peter Millman, D.W.R. McKinley, Ian Halliday

1 INTRODUCTION

During most of the twentieth century, Canadian astronomy was dominated by stellar spectroscopy and radio astronomy (Jarrell, 1988). More peripheral areas, such as extra-galactic research and cosmology, came late. Least cultivated of all was planetary astronomy, with one significant exception: meteor science. For nearly a half-century, Canadian work in this area was innovative and highly respected. Then, it nearly faded away. Scientific fields are typically built by a network of key players, but small fields, or scientific fields in relatively small national contexts, can owe their origin and energy to a single person. Such was the case for Canadian meteor science. The original Canadian research programmes, initiated wholly or in part by Peter Millman, had largely run their courses before his death in 1990. We can consider the research programmes of this period, 1933 to the late 1980s, as the first phase of Canadian meteor science. It was almost entirely prosecuted by government scientists until changing priorities, along with the departures and deaths of the principals, brought the programmes to an end. A second phase, still in progression, began in earnest in the 1990s, prosecuted largely by university-based astronomers and geologists with few or no connections to the researchers of the first phase.

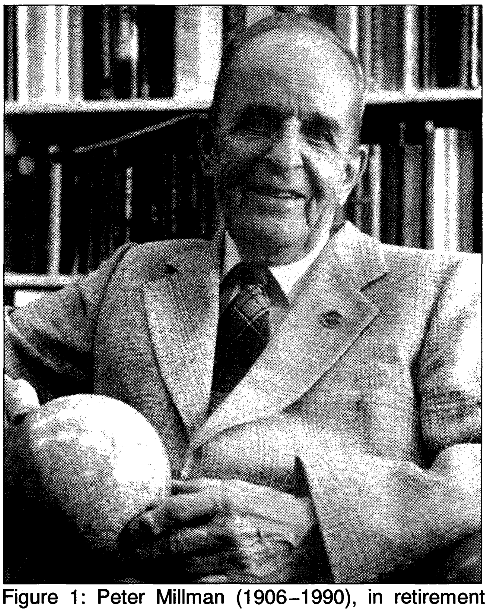

Figure 1: Peter Millman (1906–1990), in retirement (after Halliday, 1991b: 180).

Before the 1930s, meteors and meteorites elicited little interest in Canada. The pages of the *Journal of the Royal Astronomical Society of Canada*, and its predecessor journals, published from 1890, carried news items on meteor showers or meteorite falls but no research papers. Its founding Editor, University of Toronto Professor Clarence Augustus Chant, was aware of meteor research published in contemporary journals. He simply inserted news or articles from other journals. Many of these were by the renowned English meteor expert, William F. Denning. This changed, briefly, in 1913. A train of bright, daylight fireballs was visible in much of Canada that year, and Chant (1913) collected as many accounts as he could and summarized the observations in the *Journal.* In the first twenty-seven years of the *Journal* (1907-1934), before Millman became a regular contributor, just 25 articles on meteors or meteorites appeared, while in the next twenty-seven years (1934-1961), 147 articles appeared, the majority by Millman and his co-workers.

Peter Mackenzie Millman (Figure 1) was born in Toronto on 10 August 1906, but grew up in Japan, the son of Canadian missionaries (Halliday, 1991a, 1991b, 1994; Jarrell, 2007). His interest in astronomy grew during his secondary education at the Canadian Academy in Kobe, leading him to return to the University of Toronto in 1925. He joined the Royal Astronomical Society of Canada (RASC) that same year. Four years later, he graduated in astronomy with the Society's Gold Medal. He was fortunate during his undergraduate years to serve for three summers as a student assistant at the Dominion Astrophysical Observatory (DAO).

Most Canadian astronomers in the first quarter of the century were trained by Chant, but as astronomy was taught by only two people, he was unable to develop a graduate programme. His best students were directed to either Harvard, where he took his own Ph.D. (in physics) or to California, where he had spent a summer at Lick Observatory in order to learn new techniques. In 1929, Millman moved to Harvard, where Harlow Shapley was building up a Ph.D. programme; Millman obtained an A.M. in 1931 and a Ph.D. in 1932. Shapley had a handful of meteor spectra, taken some years earlier as part of the Harvard patrol, but never analysed, and he proposed that Millman study them for his dissertation (see Tors and Orchiston, 2009). Clearly captivated by meteor science, Millman remained a further year as Agassiz Scholar.

While Millman was at Harvard, Chant and his associate, R.K. Young, were creating the David Dunlap Observatory (Figure 2). With a major, new telescope—it would be the second-largest reflector in the world—Chant began to expand the Department of Astronomy. In 1933, Millman was called to Toronto to join the staff. In the following year, Frank and Helen Sawyer Hogg joined the Department. Frank Hogg was a fellow Canadian and Shapley's first Harvard Ph.D. graduate. Millman had known both Hoggs at Harvard. Because of Young's and Frank Hogg's interests, the Observatory's research programme centred on stellar radial velocities and Millman, like all members of staff, was expected to participate regularly, but he also was able to develop his own specialty. At the time, he was the only Canadian astronomer studying meteors.

2 ORGANIZING AMATEURS

The amateur holds a unique position in astronomy, unlike any other science except perhaps biology, where naturalists play a supporting role. The discovery of comets and novae, the monitoring of variable stars and observations of meteors and fireballs have long been grist for the amateur's mill (e.g. see Dunlop and Gerbaldi, 1988; Edberg, 1992; Percy and Wilson, 2000). In meteor astronomy, amateurs played a key supporting role in North America from the late 1920s. How this partnership worked in the United States differed from how it evolved in Canada. A single professional, Millman, stands at the centre of the Canadian story.

One of his first activities on his return to Canada was to recruit, train and coordinate his amateur 'army' of visual observers. While his graduate studies had concentrated upon photographic and spectrographic work, he was also interested in visual observations. He had organised visual observers at Harvard in 1932. When he began teaching at Toronto in the fall of 1933, he immediately sought volunteers to observe the Leonids in November and the Geminids in December (Millman, 1934a). Student volunteers were available and, because of his connection with the RASC, and the proximity of the country's largest branch of that Society, he could tap amateur assistance. The first recruits to his army were few: only five observed the Geminids, but one night of the Leonids brought out thirty-two observers. Millman's preferred method was to set out five or six observers facing outwards in a circle, with a timekeeper/recorder in the centre. This ensured all-sky coverage. His base of operations was the uncompleted David Dunlap Observatory, which was then sufficiently far from Toronto to have reasonably dark skies.

At this time, Charles Olivier's American Meteor Society was reorganising itself into regions, with Directors planning observing sessions and coordinating data collection across the USA, a scheme that Millman thought efficient. He remarked:

> It should be mentioned in this connection that Canada is about untouched territory as far as systematic meteor observations are concerned and that a real aid to astronomical research may be rendered by amateurs in various parts of Canada who would be willing to act as local representatives of the Royal Astronomical Society of Canada in the collecting of meteor observations and in the planning of observational programmes. (Millman, 1934b: 330).

Millman's plea was answered with observations of the 1934 Perseids. In addition to the David Dunlap group, RASC centres in Montreal, Ottawa, Toronto, Hamilton and Winnipeg assisted, with a total of forty-five observing groups with 132 individuals making nearly 6,300 observations. In Ottawa, Dominion Observatory staff members Miriam Burland and Malcolm Thomson directed the second largest group of observers. Usually occupying two, sometimes three, sites, in the Ottawa area, they could be counted upon to observe the major showers. Volunteers came from the Ottawa centre of the RASC, the country's second largest. Over the next five years, major showers would be observed from eight to ten locations, mostly in Ontario, but with sites as far flung as British Columbia and Newfoundland. Data were then sent to Millman for analysis. In January 1934, he began a regular column, "Meteor News", in the *Journal of the Royal Astronomical Society of Canada* to report on Canadian observations and on other items of interest in this growing field.

Figure 2: The David Dunlap Observatory in the 1930s (Jarrell Collection).

Science students were Millman's mainstay at the David Dunlap Observatory, and the list includes a number of people who subsequently became prominent in science, including Arthur Schawlow, later to share a Nobel Prize for his work on laser spectroscopy. Women made up about one-third of the observers at Toronto, and sometimes more than half in Ottawa. Where sufficient numbers were available, teams of six were used, but there were a few scattered observers working alone or in pairs.

Millman published the data on hourly counts in "Meteor News," usually trying to calculate averages based upon the average for the six-person group. These, he believed, were more accurate than counts provided by individual observers. This contrasted with the American Meteor Society's reliance upon individual counts. In addition to counts, Millman insisted upon as accurate an estimate of magnitude as possible. This assumed, of course, relatively experienced amateurs, although Millman could not always expect to obtain them. As he noted:

> The organization of visual meteor observing generally depended on the recruitment of a large number of heterogeneous, but enthusiastic volunteers. The police sometimes added to the sky-watchers' problems, as they were inclined to question the propriety, and even the sanity of mixed groups which spent all night in freezing temperatures in unsheltered fields, emitting frequent cries of "Time"! (Millman and McKinley, 1967: 280-281).

Each observer was given a map with a stereographic projection of the sky. Millman's emphasis was upon getting the path plotted and estimating the brightness within half a magnitude if possible.

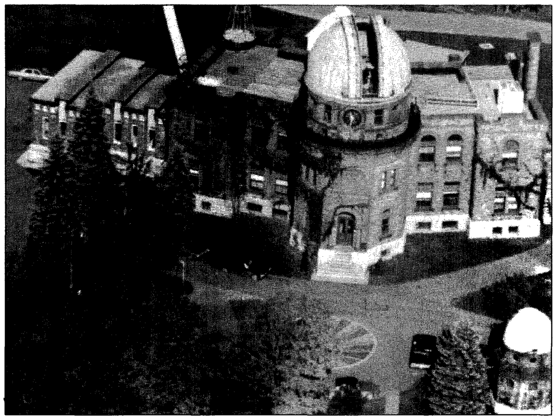

Figure 3: The Dominion Observatory, Ottawa, in the early 1950s (Jarrell Collection).

Once Canada entered the Second World War in 1939, it was no longer 'business as usual' for the Astronomy Department. "Meteor News" appeared in the *Journal* through 1940, then lapsed, with the last instalment in February 1941. In that year, Millman enlisted in the Royal Canadian Air Force (RCAF), initially teaching aerial navigation, but later working in Operational Research in London, England. He ended the War as Scientific Adviser to the Chief of Air Staff.

Reluctant to return to the University of Toronto due to the low salaries there, he considered remaining in the RCAF but received an invitation from the Dominion Astronomer, R.M. Stewart, to take a post at the Dominion Observatory (Figure 3). He resigned his commission and took up the Ottawa post as Head of the Stellar Physics Division in July 1946 knowing that Carlyle Beals was soon to lead the Observatory. Millman had earlier worked with Beals at the DAO and respected him highly. During the 1930s and 1940s, the Stellar Physics Division had produced solar and stellar spectra with obsolete equipment. Given retirements in the Division, Millman had a free hand to promote his own research programme.

3 NEW TECHNOLOGIES AND NEW DIRECTIONS: THE SUPER-SCHMIDT TELESCOPES

Before joining the Dominion Observatory, Millman was involved in discussions with Harvard, MIT and the US Navy about the possibilities of meteor photography with pairs of Super-Schmidt cameras. Once Beals became Director in Ottawa, Millman persuaded him to join the programme and in due course, two small observatories were built in Alberta. In March 1946, Millman was in Cambridge, Massachusetts, to talk with other specialists, notably Harvard's Professor Fred L. Whipple, who had just arrived at Harvard when Millman was in residence. In 1943, Whipple published a paper arguing that by photographing meteors entering the Earth's atmosphere and determining their velocities and altitudes, one could analyse the density of the upper atmosphere. Such data, although useful scientifically, might also have military applications. Harvard would develop special cameras for a research programme, MIT agreed to analyse the data, and Millman offered Canadian assistance in meteor spectroscopy. US Navy representatives at the meeting promised to underwrite the costs of the American portion of the project. The scheme involved using pairs of high-quality cameras, spaced over a baseline of several kilometres, which could photograph meteor trails simultaneously. The measurement and reduction of the data from the photographic plates could then provide information on the meteors' paths.

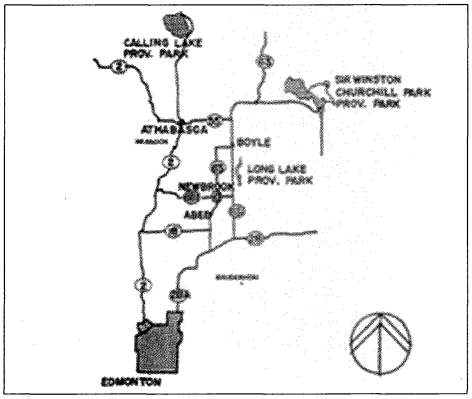

Figure 4: Map showing Central Alberta meteor observing localities (courtesy: The Hammond Consulting Group Ltd.).

In May 1946, the Chief of the US Navy's Bureau of Ordnance invited the Canadian Government to participate. Canada agreed to commit the Dominion Observatory to the project as a partner with Harvard. Millman came on staff two months later and planning began. Harvard intended to locate two pairs of cameras in New Mexico, while Canada agreed to purchase one pair. Millman then needed a site. He required uncluttered horizons and clear nights, but he also wanted to be far enough north of the American sites to have a good spread of latitude. On the other hand, he did not want to have too much interference from the aurora borealis. The prairies seemed ideal, and after some searching, he chose as his first site, Meanook, near Athabasca, Alberta (Figure 4). A federal geomagnetic station had been located there since 1916 and offered a secure base. For a second camera location, Millman chose the hamlet of Newbrook, forty-two kilometres to the southeast (Figure 4). The sites must have been selected by late 1947. In the following year, Beals (1948) reported that:

> This investigation is being carried out in co-operation with the R.C.A.F., the U.S. Bureau of Naval Ordinance [sic] and Harvard University. It is undertaken primarily as a joint defence project and has as its object the study of the upper atmosphere in its relation to the velocities of high speed projectiles. It is also expected that it will lead to much useful general information concerning the nature of meteors ... [part of sentence missing] the structure of the atmosphere supplementing the work at Ottawa with more extensive data obtained with more powerful equipment.

Because of the defence implications, the RCAF was to provide $3,000 for the construction of the two Alberta stations. However, $18,000 for the two new cameras would come out of the Observatory's funds.

By the spring of 1948, Beals believed that construction of the two stations was imminent. Millman would travel west and work with Meanook's officer-in-charge, H.E. Cook, in supervising the erection of simple frame buildings to house the new telescopes. At the same time, the Observatory purchased 0.8 hectares of land in Newbrook. Unfortunately, the prime contractor, the Perkin-Elmer Corporation, experienced difficulties in producing the cameras, so the project went on hold. The five-year experimental 'Defence Project' was to have begun in 1946, but by the time the Observatory's estimates for 1949/1950 went to the Minister there was still no progress in sight. The cameras in question, known as Super-Schmidts, were designed by Harvard's J.G. Baker as its contribution. The units were very sophisticated for the time. They were massive wide-angle telescopes, each with a spherical primary mirror and a hemispherical, transparent corrector shell. Ideally, they could record meteors much fainter and more quickly than the cameras then in use, theoretically up to 200 times more efficiently. But no optical firm could supply the hemispherical shells. With Navy prodding, the US Bureau of Standards undertook development of the lenses. Finally, by the summer of 1951, the first Harvard unit was shipped to New Mexico. Canada's pair was not ready until the spring of 1952. After Millman inspected them in Connecticut, the cameras—each weighing 2.2 tonnes—were flown to Alberta by the RCAF. Millman made the first exposure at Newbrook in August (Millman, 1959; Hodgson, 1994).

In choosing sites in Alberta for the meteor stations, Millman was primarily interested in having observations made as far north as practically possible, in this case, about 54°. By having a wide latitude spread, more sky could be covered. The Harvard sites in New Mexico were at approximate latitude 32° North. It soon became apparent that the Canadian locations were much less suitable than the American ones. Being so far north, the extended summer twilight meant that much of June and July was useless for observation. In fact, the Alberta observers took their holidays during this period or devoted their time to routine maintenance. While longer winter nights might have compensated, the cloudiness of north-central Alberta, combined with extreme cold, routinely dropping to –30° C or lower, curtailed the work. Alberta also experienced far more auroral activity than New Mexico. Although aurorae interfered with meteor studies, they did favour the National Research Council of Canada's (NRC) auroral studies. During the International Geophysical Year (IGY) in 1957-1958, Millman's staff placed an all-sky auroral camera at Meanook and made visual aurora observations at Newbrook (Meek, 1959). By the time the IGY ended, the American meteor photography programme was essentially complete and its cameras turned to artificial satellite tracking.

The Harvard programme had had a good head start. Regular work with the Super-Schmidts did not commence in Alberta until 1954, but astronomical and meteorological limitations meant that the Canadians could not compete in observational efficiency. Statistics at the end of 1957 tell the tale: the New Mexican observers averaged 130 good photographic nights a year compared with the Canadians' 40. From 1954 to 1957, the Alberta observers managed 1,800 pairs of exposures, from which 165 pairs recorded meteor trails. This was approximately 20% of the American rate.

The work could be frustrating, and the conditions required that those in charge be resourceful and tough. Harvard hired non-scientific staff to undertake the photography, but the Dominion Observatory insisted upon men with scientific training, usually single men paid relatively low salaries. As it happened, two of the first three initial observers were married.

The first Newbrook observer, Arthur A. Griffin (Figure 5), was a Belleville, Ontario, native who graduated from Toronto in 1951 with an honours B.A. in astronomy. Millman had spotted him a year earlier when Griffin was a student assistant at the David Dunlap Observatory. When Griffin and his new bride arrived in Newbrook there was no residence, and they spent some months in a hotel before refitting an uninsulated shack with no plumbing. A small residence was ready in late 1952. Depending on weather conditions and time of year, the unpaved roads to Edmonton and to Meanook were either dust, mud or ice. Still, the Griffins were able to raise a family in the small, welcoming community. Meanook was even more remote, and the observers' isolation was also scientific. They were a long way from other astronomers, although visitors—like Millman, or his associate, Ian Halliday—occasionally passed through. Even Beals made an appearance. To break the monotony, the observers visited one another, drove into Edmonton as often as possible, and were in direct contact via two-way FM radios.

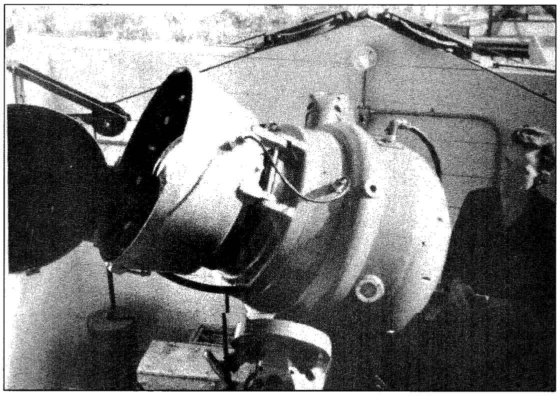

Figure 5: Arthur Griffin and the Super Schmidt at Newbrook (after Millman and McKinley, 1963: Plate 2).

As Griffin recalls (personal communication, 1992), the observers dealt with isolation by keeping busy. There was always activity. New instruments arrived, photographic plates had to be fetched and shipped out, cameras adjusted and repairs made. Observing could be arduous. A typical night began about 11.00 pm and lasted until dawn. The Super-Schmidt cameras were not easy to handle and their shelters had roll-off roofs, giving observers almost no protection against wind and cold. Several cameras were out-of-doors, and observers had to hustle back and forth between the observatory and the yard. The men had to work rapidly. Different parts of the sky were targeted for each night. Before 11.00 pm, depending upon sky conditions the Meanook and Newbrook observers had to decide whether or not to work, exchanging notes by radio. If they did decide to observe, they then made a succession of 12-minute exposures of the agreed-upon patches of sky every 15 minutes. The large cameras had to be opened in the middle to change plates for each exposure. Clouds, a bright Moon or a temperature below –35° C would halt the night's work. However, during an important meteor shower, even clouds had to be tolerated and the observers might remain at their posts all night to 'shoot' through breaks in the

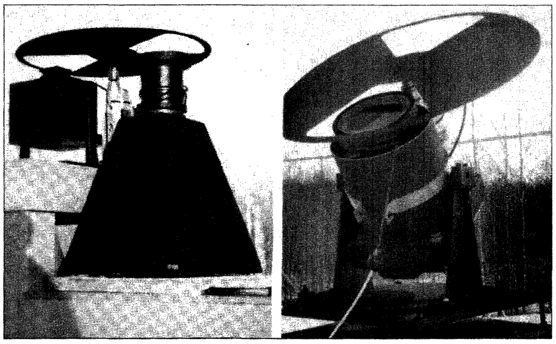

Figure 6: Rotating shutter spectrographs (after *Journal of the Royal Astronomical Society of Canada*, 52, 174, August 1958).

cloud cover. In addition to photographic work, they also made visual observations and noted meteor trails on maps provided by Ottawa. At least for visual work, they could observe through a glass skylight from inside the unheated observatory.

The film was processed at Meanook. Because of the unique design of the Super-Schmidt cameras, the circular film had to be curved. It was formed by heat in a special moulding machine at Meanook. The curved-film exposures were then projected onto flat, glass photographic plates. During the 1950s, these were shipped to Harvard (via Ottawa) for measurement and analysis.

The original impulse for building the stations was to obtain data on the Earth's upper atmosphere, but by the mid-1950s it was apparent that rockets could provide superior information. But Millman's programme was more ambitious: he wanted the fullest data possible on meteors, whether from direct photography, radar or spectroscopy (which was his own specialty). The radar and visual work, initiated at the NRC's Radio Field Station in Ottawa in 1947, moved south of the city in 1956 to the new Springhill Observatory, which acted as the centre for IGY operations. However, much of the photographic and spectrographic work remained in Alberta. The Dominion Observatory and the NRC supplied a wide range of cameras to Newbrook and Meanook. During the 1950s, the two stations used some seventeen different spectrographic cameras with transmission gratings and rotating shutters (e.g. see Figure 6). These, not the Super-Schmidts, were the real heart of the scientific work. This was no easy matter: it could require 100 hours' observing to obtain one good meteor spectrum. Halliday utilized the data in Ottawa for a series of important papers in which he identified chemical lines in meteor spectra, including the auroral green line (see Halliday, 1960).

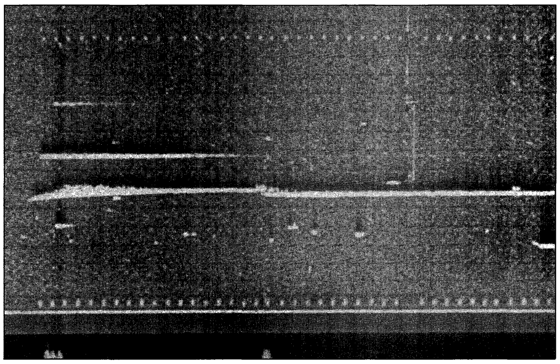

Figure 7: Radar echoes photographed from a cathode ray tube (after *Sky and Telescope* 8, 5, March 1949).

By the time of the IGY, Newbrook and Meanook likely had the world's greatest concentration of meteor cameras. A 1956 survey of world activity (Halliday, 1956) showed that 45% of all meteor spectra known were due to Canadian observers. During the IGY, and the follow-up International Geophysical Cooperation (1958-1959), the routine in Alberta continued, with additional duties to record meteorological data and observe aurorae—photographically at Meanook and visually at Newbrook. One break in routine occurred on 4 October 1957, when the Soviet Union launched the world's first artificial satellite, Sputnik 1. Its initial orbit was too far north for American observatories to photograph its passage, so after telephone calls from American officials to Ottawa, and from Ottawa to Newbrook, Griffin was able to obtain the first photograph of Sputnik from North America on 9 October. From June 1958, satellite tracking of the first two Soviet satellites was hastily added to the Alberta programme, and was initiated at six other stations. Measured positions were passed to the three World Data Centers for satellite observations established during the IGY. At Meanook and Newbrook, the work lasted for several months, normally requiring early evening photography when the satellites caught the reflection of the setting Sun. Nearly daily, Soviet space officials telegraphed orbital data to Newbrook; after plates were measured, the data were passed back. In an area with a concentration of Ukrainian families, this direct contact with Soviet science created a stir. Satellite tracking was an annoyance, however, and the Dominion Observatory soon dropped it.

4 NEW TECHNOLOGIES AND NEW DIRECTIONS: METEOR RADAR

Meteor work might well have concentrated entirely on photographic and spectroscopic studies but for a meeting between Millman and D.W.R. McKinley of the NRC. McKinley was a member of the NRC's radar research programme during the War. He had earlier, as a physics graduate student at Toronto, lived close to the David Dunlap Observatory, where he and his sister participated in Millman's observational sessions. He and Millman had met again, during the War, when Millman sought out radar information for the Royal Canadian Air Force. In the late fall of 1946, Edward Appleton lectured at the NRC on recent British radar astronomy work, noting J.S. Hey's and G.S. Stewart's observations of meteor echoes (Hey, 1973, 19-23). Millman had, in fact, visited them at Richmond Park in the spring of 1945, corroborating their belief that they were detecting meteors. Both Millman and McKinley attended Appleton's Ottawa lecture and afterwards, Millman suggested to McKinley that the Dominion Observatory and the NRC collaborate on a three-way programme of radar, visual and photographic meteor observations. McKinley would handle the radar work, and Millman the photographic observations. For the visual work, Millman brought in his Observatory colleague, Miriam Burland, a veteran of the pre-War observing parties. Work began with the Perseid shower in August 1947 at the NRC's Radio Field Station, just south of Ottawa. Radar recorded more than three times as many meteors as the visual observers, but Millman and McKinley found a correlation between the longer-lived radar echoes and the brightest visual meteors (see Figure 7). The first published data appeared in *Nature* in 1948 (Millman et al., 1948). Radar operations employed war surplus pulse radar units operating at 32.7 MHz with home-movie cameras to record the video output. Millman and McKinley were one of three teams studying meteors with radar: C.D. Ellyett and J.G. Davies (1948) observed with pulse radar at Manchester, while at Stanford, L.A. Manning, O.G. Villard and A.M. Peterson (1952) experimented with continuous wave transmission.

A photograph taken in the summer of 1948 at the NRC's Radio Field Station shows a typical visual observing group (Figure 8). At the top are McKinley and Millman. A fabric enclosure protected the observers somewhat from the wind, but they were still exposed, lying on cots. In 1948, Millman and McKinley decided to estimate altitudes of brighter meteors by combining radar with visual observations, utilising the Radio Field Station and two new outstations near Ottawa (Figure 9). Altitudes were then calculated by combining three radar ranges, or one radar range with one visual plot, or two or three visual plots. The next step came in 1949, with the introduction of continuous wave radar to study meteor velocities. By 1950, nearly 12,000 meteor velocities had been recorded and McKinley (1951) was able to show statistically that most meteors were of Solar System, not interstellar, origin.

After an eleven-year hiatus, Millman's column, "Meteor News", recommenced in the *Journal* of the RASC in 1952. With the success of the Ottawa programme, and McKinley's move up the ranks in the NRC's Radio and Electrical Engineering Division, he suggested that Millman transfer from the Dominion Observatory to the NRC as Head of the Upper Atmosphere Research Section within his Division. This Millman did in January 1955, just as planning for the International Geophysical Year was beginning. As the NRC expected to undertake a major effort for the IGY, and the Radio Field Station was being engulfed by development, Millman and McKinley argued for a new site for visual, photographic and radar observations.

Their plea was answered in the construction of the Springhill Meteor Observatory (Figure 10), 32km south of Ottawa (Millman, 1957). Operations began in the summer of 1957, in time for the beginning of the IGY meteor programme. Although the Observatory was an NRC site, the visual work continued to be coordinated with the Dominion Observatory.

Visual observing at Springhill was a far cry from the open fields at the Dunlap Observatory in the late 1930s. Observers worked on the roof of a small building to give them a good view of the horizon. Eight observers, rather than six, were employed at a time, with the timekeeper in the centre (Figure 11). For protection from the elements, observers were encased in wooden 'coffins' so that only their heads and shoulders were outside. Heat from an oil furnace below was piped into the coffins and timekeeper's station in cold weather. Observers lay upon platforms with a raised back and a foam mattress and each was equipped with a map and a pen that held a flashlight, a rheostat to control the illumination and a button that connected to the radar recording device. When a meteor was observed, the button was pressed and a match could be made of a visual and radar record. During the IGY, joint visual and radar observations were made during the seventy-one World Days plus ten days at the peaks of showers.

Figure 8: Meteor observing group at the Radio Field Station ca. 1950. Standing at the rear (left to right) are McKinley and Millman (courtesy: National Research Council of Canada).

During the late 1940s and early 1950s, RASC observers continued to send meteor observations to Millman. The Montreal Centre was particularly active

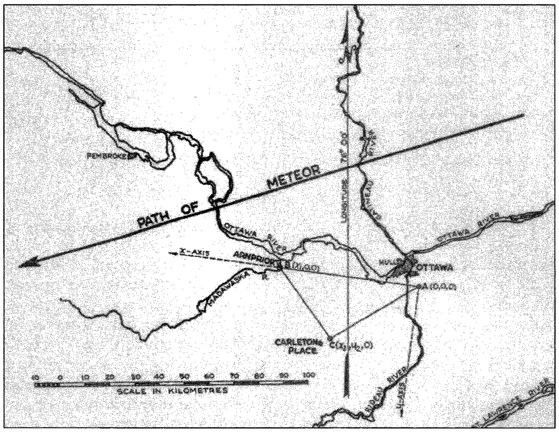

Figure 9: Map of meteor observing sites in the Ottawa area (after *Canadian Journal of Research*, A27, 54, May 1949).

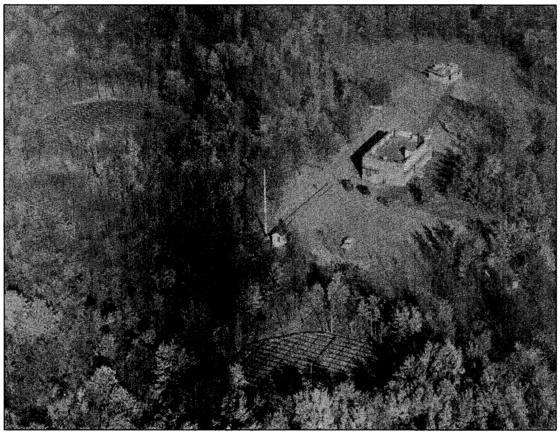

Figure 10: Springhill Meteor Observatory (after *Bulletin of the Radio and Electrical Engineering Division*, National Research Council of Canada, 7(4), Plate 1, 1957).

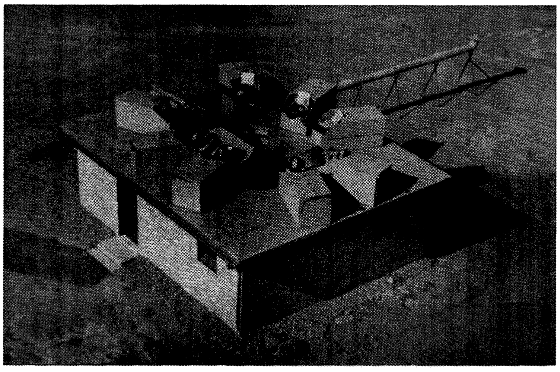

Figure 11: Meteor observers at Springhill in their 'coffins' (after *Bulletin of the Radio and Electrical Engineering Division*, National Research Council of Canada, 7(4), Plate 2, 1957).

from 1946 onwards, joined in the early 1950s by the Regina Astronomical Society, which coordinated observers across Saskatchewan. By the mid-1950s, other groups in Winnipeg, Fredericton, Deep River and Ottawa could be counted upon. For the 1956 Perseids, for example, the Regina group organised eighty-two observers across the Province. Millman did not direct any of these groups, but acted as the clearing house for observations, which he published in "Meteor News". Amateur participation was to be an important part of the NRC's IGY programme. Millman announced in the *Journal* that he would send out instructions and pads of maps to amateurs anywhere who would send data back to the NRC. Response was excellent and he soon had new recruits for his 'army'. As usual, he emphasised group averages and careful magnitude estimates over ten-minute intervals during shower periods and on World Days. Many of the RASC observers joined in, but the response from the United States was even greater. By February 1958, he reported data from 367 observers located in Canada, USA, Puerto Rico, Jamaica, England and Switzerland. Within a few months, reports came in from Italy, Brazil, Japan, India, New Zealand, the Philippines and South Africa. By the time the IGY ended, he reported that some 93,000 meteor observations had been entered onto IBM punch cards.

Some institutions decided to carry on the collection of data after the IGY, and the NRC visual meteor programme was one of these. From 1957 until the end of the programme in 1967, Millman received observations of some 277,000 meteors, mostly from Canadian and American observers. After the IGY, operations slowed at Springhill. Teams of twelve observers were normally used for visual and camera operations, and since they had to drive out from the city and then observe all night, it only proved efficient to work at times of meteor showers. Still, the data were impresssive: between 1947 and 1969, the NRC's volunteers observed 41,000 meteors at the Radio Field Station and at Springhill.

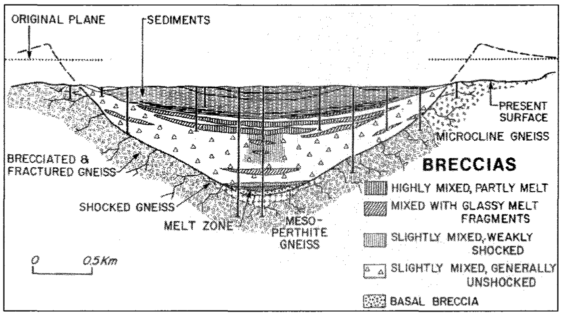

Figure 12: Cross-section of the Brent Crater made by the Geological Survey of Canada (courtesy: Geological Survey of Canada).

5 FROM METEORS TO METEORITES

Millman and his colleagues had always concentrated upon meteors, recording them visually, spectrographically and by radar. One consequence of Millman's move to the Dominion Observatory was his influence upon Beals, who was a spectroscopist, trained by Alfred Fowler in London, and a leading specialist on Wolf-Rayet stars. A successful twenty-year career at the Dominion Astrophysical Observatory made him a good candidate for Dominion Astronomer when R.M. Stewart retired in 1946. He was expected to shake up the staid Observatory, which he did, but not without ruffling feathers in Ottawa. Supporting Millman's work—which was quite unlike anything done previously at the Observatory—was one instance of his innovation. After accepting the Directorship, Beals ceased to observe and spent his time through into the early 1950s cleaning up work from his Victoria days and writing research papers.

The work of Beals and his colleagues on impact structures focussed upon the consequences of meteorite falls not on the meteorites *per se*, but their interest in the area was serendipitous. A few terrestrial craters, including the Barringer Crater in Arizona, were known or suspected, but until the late 1940s, most geologists assumed they—just like their lunar analogues—were of volcanic origin. Work by Robert Dietz, Ralph Baldwin, Harold Urey and Gerard Kuiper from 1946 to 1954 strengthened the alternative view that such structures were caused by impacts (see Hoyt, 1987). Baldwin (1949) found that if the diameters and depths of lunar, terrestrial and bomb craters were graphed logarithmically, a smooth curve (the so-called 'Baldwin curve') resulted. Millman brought Baldwin's book to Beals' attention. By chance, two suspicious circular features were noted on aerial photographs in 1950 (New Quebec Crater, in northern Quebec) and 1951 (Brent Crater, in central Ontario). In the former instance, Royal Ontario Museum geologist V.B. Meen examined the site. Millman obtained detailed aerial photographs from the Royal Canadian Air Force in 1953 and analysed the structure to see if it fitted the Baldwin curve. In the same period, J.M. Harrison from the Geological Survey of Canada, undertook a more detailed study of the geology. The Brent crater (Figure 12) had been spotted by a private aerial photography company. Millman and two scientists from the Geological Survey explored the site in July 1951.

In 1955, Beals inaugurated a systematic study of aerial photographs. Systematic research on suspected impact structures required accurate mapping along with geological, magnetic, gravity and seismological studies, followed up by diamond drilling. The Dominion Observatory's involvement, with Beals' blessing, had several advantages: it had a long history and expertise in gravity, magnetic and seismological research and it was a Division of the Department of Mines and Technical Surveys (which also controlled the Geological Survey of Canada). Over the following twenty-five dar, electro-optical devices, telescopes and infrasound. This group now operates a five-station all-sky camera network in southwestern Ontario.

Meteorite recovery, through the Prairie Meteorite Search, was launched by Alan Hildebrand at Calgary and is now a cooperative venture between Calgary, Regina and Western Ontario Universities. Brown, Hildebrand and their groups were central to the study of the Tagish Lake fall in 2000 (Brown et al., 2000).

With a good flow of graduate students into the area, it appears that Canadian meteor science will survive and thrive.

8 CONCLUSION

Canadian meteor science went from nothing to international stature and back to virtual non-existence in sixty years. Before the 1930s, it was not a prominent area of professional astronomy anywhere, with only a few isolated workers, although meteor observing appealed to many amateur astronomers. Peter Millman was attracted to the area because of an unsolved problem: the nature of meteoric spectra. His unflagging leadership naturally attracted others, most notably Ian Halliday and C.S. Beals. During the 1940s and 1950s, several research problems in meteor science became tractable thanks to new technologies: better cameras, films, spectrographs and radar. Millman and McKinley and their Dominion Observatory colleagues turned visual observing into an art. A mountain of data was collected, especially during the IGY, from dedicated observing sites in Alberta and at the Springhill Observatory. The value of the Canadian work was noted, in one sense, by the inclusion of review papers by Millman and McKinley (1963) and Beals et al. (1963) in the five-volume series, *The Solar System*, edited by Barbara M. Middlehurst and Gerard P. Kuiper.

Yet, the research programme had its limits. Many of the interesting questions about meteor streams, shower radiants, speeds, heights, ionization, etc., were answered. When Millman retired, he could no longer defend the maintenance of existing programmes. Shifts in interest came with new researchers in the NRC and budgetary crises. While Springhill, Meanook and Newbrook could have continued to operate, the probability that important new data would be produced was very low. Even the expansion of astronomy programmes in Canadian universities during the 1960s and 1970s brought almost no new blood into this area—the research action was elsewhere.

Canadian meteoritics, in the form of studies of impact structures, came a decade after Millman's first work. This was a natural area for Canadians, with a long tradition of geology and mapping. Even here, the broad-brush work was essentially complete by the 1980s, and interest shifted to the recovery and analysis of meteorites. Again, Canadian advantages—a vast prairies region with unhindered horizons and snow cover much of the year—and expertise in photographic technology, led to the successful MORP programme. By the 1990s, astronomers had an increasingly clear idea of the origins of meteorites, both in terms of their birth places in the Solar System and their compositions. But astronomy at the NRC increasingly focused upon radio astronomy and upon expensive, cooperative optical programmes offshore. With no champion and no new staff, meteor science was cut. Ironically, it was one of the cheapest operations.

Peter Millman saw the winding down of meteor studies with some sadness, but as he related to me in 1989, science always moves on. His first publication on meteors appeared when he was twenty-four; his last was penned when he was eighty-four. He had the satisfaction of knowing that some important questions about the nature and origins of meteors had been answered, and that his work had been an important factor.

9 ACKNOWLEDGEMENTS

I wish to thank Peter Millman and Arthur A. Griffin for providing information relevant to this study, and two anonymous referees for their helpful comments.

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Journal of Astronomical History and Heritage, 12(3), 235-239 (2009).

AN ASTRONOMICAL INVESTIGATION OF THE SEVENTEEN HUNDRED YEAR OLD NEKRESI FIRE TEMPLE IN THE EASTERN PART OF GEORGIA

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Abstract: The Nekresi Fire Temple is a second to third century A.D. archaeological site in eastern Georgia that was excavated by archaeologists towards the end of the twentieth century. In 2004 we carried out an archaeo-astronomical investigation of this site, which indicated that it was used for astronomical observations. We now suggest that this structure should be renamed the 'Nekresi Sun Temple'.

Keywords: Georgian astronomy, Nekresi Temple, solar observations

1 INTRODUCTION

The cosmological ideas of ancient populations are reflected in different aspects of their cultural heritage, including architecture, artifacts, folklore and written records. Prehistoric monuments, legends and myths tell us how the ancient people reacted to the regularity and the recurrence of celestial phenomena and the diversity and the brightness of different heavenly bodies. Cosmological ideas and activities often were closely connected with religious notions, and rituals and ceremonies played an important role in the accumulation of knowledge about the Sun, the Moon and the stars. Ancient peoples often used this knowledge and experience to orientate themselves in time and in space. Some knowledge was materialized, manifesting itself in stone instruments, temples and sanctuaries, in architectural complexes serving ritual purposes, where the gods were worshipped and astronomical observations were made. These simple 'astronomical observatories' have been discovered in many different countries (see Aveni, 1997; Heggie, 1981; Iwaniszewski, 1994; Ruggles, 1999).

One such nation is Georgia, an ancient country beside the Black Sea. Over the centuries, the Georgian people created and developed their own language, literature, music and architecture (Bround, 1994). Various sciences also flourished, including astronomy and mathematics. Simonia (2001) and Simonia and Simonia (2005) have outlined the main stages in the development of the ancient Georgian astronomical 'world view' between the sixteenth century BC and the eighteenth century AD, and the ethnocosmological symbolism of certain Bronze Age artifacts. In particular, they have shown that the ancient Georgians had a deep interest in heavenly bodies and astronomical phenomena, as reflected in different artifacts and remnants of stone buildings found during archaeological excavations (see Sanikidze, 2002).

In the final decade of the twentieth century an expedition from the National Museum of Georgia carried out archaeological excavations at Kakheti, in eastern Georgia, where the ruins of the ancient town of Nekresi were discovered (Chilashvili, 2000).[1] Among the ruins at Nekresi was a complex building that was identified as a temple. In this paper we discuss the archaeological features of the Nekresi Fire Temple and then examine its astronomical significance.

2 THE INITIAL ARCHAEOLOGICAL INVESTIGATION OF THE NEKRESI TEMPLE

The first structure at Nekresi investigated by the archaeologists was the stone foundation of a cult building, which was identified as the 'Nekresi Fire Temple'. The aim of the archaeological excavation was to determine the structural peculiarities of this ancient temple and to preserve what remained of it. The temple was located in a field at the foot of Nazvrevi Hill (Figure 1), and Chilashvili (ibid.) noted that on the Hill itself was another temple-like structure which may have been associated with the Nekresi Fire Temple.

The walls and foundations of the Nekresi Fire Temple consisted of mortared cobble-stones and broken stones (Figure 2), but in the upper layer of the construction flat bricks were encountered. The design of the temple was complex. In the center was an almost square building of 76m², around which were four buildings forming the shape of a cross (see Figure 3).

During the archaeological excavations an approximately square area of clay, measuring 4.5m² and containing traces of fire, was discovered in the southwestern corner of the central building (hence the name, 'Nekresi Fire Temple'). Elsewhere, the floor of the central building consisted of brickwork. The eastern building had an entrance in the eastern wall, and on both sides of this extension was a corridor and storerooms. Likewise, the western building had an entrance in the western wall. The length of this western building was 9.5m, and the walls were 1.5m thick. The eastern and western buildings were almost equal in area, and only differed in the details of their construction. The northern and southern buildings leading off the central building were also surrounded by corridors and storerooms. The central building, the four buildings to the north, south, east and west, and their associated corridors and storerooms were all enclosed by a wall, the entire complex measuring ~50m × 50m.

Figure 1: View of the excavated Nekresi Temple from Nazvrevi Hill.

The following facts seem to be important: the walls of the temple complex were constructed of large stones and mortar, the thickness of the walls averaging 1.5m; the width of the doorways was, on average, also 1.5m; and access to any of the rooms in the complex was possible via doors in the external corridors.

During the excavations ceramics in the form of small red and white sherds and fragments of jugs were found, and these and other artifacts dated to the second, third and fourth centuries AD. Radiocarbon dating of charcoal from the entrance doorway to the temple revealed that the complex was destroyed in the fifth century AD.

On the basis of the accumulated evidence, Chilashvili (ibid.) concluded that this archaeological site is the remains of a temple where rituals associated with fire-worship were performed, and he dubbed it the 'Nekresi Fire Temple'. The main 'area of attraction' was the centrally-positioned square building with its altar, which served as a sanctuary for the fire-worshippers during their ceremonies.

Figure 2: View across the archaeological site showing the stone construction of the walls.

Near the Fire Temple Chilashvili discovered other ruins and artifacts of various ages, some of which we also assigned cult functions associated with the worship of the Sun. He noted that these buildings seemed to be aligned with the point of sunrise on the day of the summer solstice, and that they deviated to the north from the direction to the east by about 30º. He also noted that there is a tendency for the older buildings to be more oriented to the north. It is important to stress, however, that all of these conclusions were based upon estimated orientations not surveyed measurements. On this basis, the Nekresi Fire Temple was clearly an excellent candidate for a detailed archaeoastronomical investigation.

3 THE ASTRONOMICAL ROLE OF THE NEKRESI FIRE TEMPLE

In the autumn of 2004 we began studying the archaeoastronomical parameters of the Nekresi Fire Temple. These investigations were carried out in three stages: fieldwork, followed by the processing of the observational data, and finally the theoretical interpretation of the complex.

The fieldwork included:

1. Visual examination of the Nekresi Fire Temple in order to determine the architectural and geometrical peculiarities of the construction.
2. Determination of the exact geographic coordinates and orientation of main structural elements of the Temple.
3. Noting the characteristics of the surrounding landscape, including the height of hills and their azimuths.
4. Observation of sunrise from the main structural elements of the Temple.

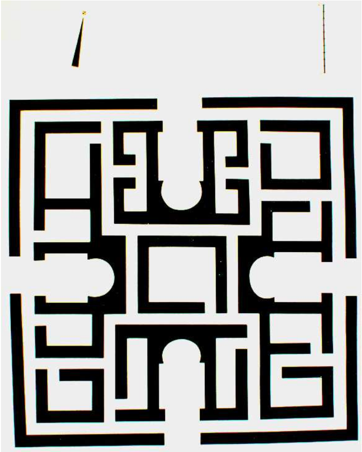

Figure 3: Plan of the Nekresi Fire Temple (after Chilashvili, 2000).

During the field work we used clinometers, an electronic compass, GPS, digital cameras and other instruments, and we took a series of photographs of the Temple and the surrounding landscape in order to create a photo-catalogue.[2]

The visual examination of the temple confirmed the complexity of its construction and its multifunctional purpose, including the ritual associations. The approximate mirror symmetry of the main structural elements—the four rooms off the central room—in our opinion, suggest that regular observations of heavenly bodies and phenomena (such as sunrise and sunset, the heliacal rising of stars and the culmination of the Moon) could have been carried out from these rooms (Figure 4). Our measurements of the orientation of the northeastern (NE), southeastern (SE), northwestern (NW) and southwestern (SW) points of these structural elements and of the central room are listed in Tables 1 and 2. The orientation of structural elements of con-

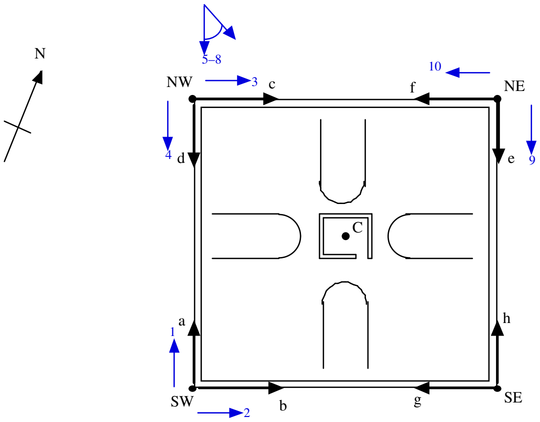

Figure 4: Plan of the Nekresi Fire Temple showing points surveyed during the 2004 expedition.

struction was determined as well, and some features of the surrounding landscape which may have served as orientation points for those observing from the Temple were also recorded. It should also be noted that the hills surrounding the Nekresi Fire Temple have not been thoroughly studied archaeologically, although artifacts and buildings of various ages have been discovered on some of them. Accordingly, the azimuths, heights and distances to various landscape elements were measured.

We also observed the sunrise from the interior of the eastern room and from the central sanctuary. Our observations showed that the first rays of the rising Sun only illuminated some areas of these two rooms, then a little later, the whole Fire Temple was fully sunlit. The peculiarities of illumination of the Fire Temple at the moment of sunrise are connected with the natural landscape in the easterly direction. One cannot exclude the possibility that this landscape may have undergone natural change (e.g. through erosion) over the last thousand years or so. It should also be noted that the landscape (i.e. hills and hillocks) surrounding the Fire Temple does not allow the observer standing in the Temple to fix the moment of sunrise above the horizon.

During the field-work we determined that the Fire Temple is aligned approximately in the direction of the solstice. For an observer standing in the Fire Temple on 22 June the Sun rises over the highest point of eastern part of the visible horizon, while on 22 December the Sun rises over the top of a small hill. It may mean that the summer and winter solstice were important astronomical phenomena for Georgians living in the period of antiquity. Thus, the Fire Temple was aligned such that twice a year, during cult ceremonies, the Sun was seen rising over designated points on the horizon. Only twice a year would the first rays of the rising Sun fall upon some feature in the sanctuary, indicating the beginning of the season for harvesting or sowing the crops. Thus, observation of the rising Sun on the days of the solstice had very important practical significance for the ancient Georgians, by helping them to orient in time and by allowing them to divide the year into two parts. This is the primary astronomical importance of the Nekresi Fire Temple, although this result warrants further investigation.

The next step in the research project was to analyze the data obtained during the fieldwork, which led to some new conclusions.

Using the measured geographical coordinates of certain structural elements of the Fire Temple, as well as data about the sizes of these elements we determined the orientation of the various rooms in the complex. Our calculations showed that two of the rooms off the central sanctuary were oriented towards the northeast and the southeast, and should be known as the northeastern and southeastern rooms, respectively. In particular, it was determined that the northeastern room was aligned with a point on the horizon with the geodetic azimuth of A' = 32° 40′. Meanwhile, the southeastern room was approximately aligned with the point of sunrise on the day of the mid-winter solstice. We believe that this is further evidence of the astronomical functionality of the Nekresi Fire Temple, which should be renamed the 'Nekresi Sun Temple'.

We believe that the ancient Georgians observed the winter solstice from the southeastern room, and that throughout the year they also observed the rising and setting of certain bright stars from the northeastern, northwestern and southwestern rooms. The orientation of the Nekresi Sun Temple indicates that for the ancient Georgians the key zero point in determining time was the winter solstice, since this was the precursor for the sowing of new crops.

Other heavenly bodies and phenomena, including circumpolar stars, the heliacal rising of certain stars, the culmination of the Moon, eclipses of the Sun, etc., could also have been observed from the rooms in the Sun Temple. On the basis of ethnographic analogies (e.g. see Simonia et al., 2008), we suggest that inside the Temple religion and astronomical observations were combined in order to allow a regular 'interaction' between human beings and celestial bodies. The ancient people prayed and conducted astronomical observations believing that their gods would help them personally and the country in general, that the order of the world would remain the same as usual—that a cold season would be followed by a warm season, that the sowing of crops would be followed by the plentiful harvest, and so on. The regularity of the motion of heavenly bodies and of various astronomical phenomena was caused by peculiarities of the ancient belief system and practical necessity associated with agriculture, the cultivation of grapes, and the like.

4 DISCUSSION

At the beginning of 2008, Professor Clive Ruggles, President of IAU Commission 41, prepared and circulated a document titled "Ancient and Historical Properties Relating to Astronomy". The section on Candidate Properties in Europe includes the following entry:

> Georgia: Nekresi Fire Temple. This pre-Christian temple, dating to the II – III century AD, takes the form of a rectangular building measuring c. 50 × 50m, with various rooms and corridors surrounding a central space where there is evidence of intensive fire. The temple is approximately aligned with the direction of sunrise on the day of the summer solstice, demonstrating a link between pre-Christian cultic beliefs and astronomical observations.

Table 1: The orientation of different parts of the Nekresi Sun Temple, as determined during the 2004 field expedition (for identification of the different parts see Figure 4).

	UTM (WGS84 datum) measured by GPS				Conversion using GRIDLA	
Point	Zone	Grid easting	Grid northing	Error	Latitude N	Longitude E
NW	38	05 630 16	46 464 68	(4m)	41º 58′ 14″	45º 45′ 38″
NE	38	05 630 62	46 464 84	(6m)	41º 58′ 15″	45º 45′ 40″
C	38	05 630 42	46 464 56	(3m)	41º 58′ 14″	45º 45′ 39″
SW	38	05 630 26	46 464 29	(3m)	41º 58′ 13″	45º 45′ 39″
SE	38	05 630 74	46 464 40	(6m)	41º 58′ 14″	45º 45′ 41″

The archaeoastronomical findings presented in Section 3, above, warrant further investigation, but the Nekresi Sun Temple also requires additional study from the archaeological point of view. This applies in particular to the central sanctuary and the northeastern and southeastern rooms. Looking further afield, within a radius of 1.5 km from the center of the Sun Temple and in the directions of horizon points with a geodetic azimuth of 30º 40′ and an astronomical azimuth of −57º 20′ we can expect to find archaeological artifacts that are associated 'genetically' with the Sun Temple, and we cannot exclude the possibility that the Nekresi Sun Temple is, in fact, merely the center of a larger religious-astronomical complex. Such a point of view seems appropriate given the fact that a structure with probable religious and astronomical significance was discovered some kilometers from the Nekresi Sun Temple but was destroyed during building operations.

5 CONCLUDING REMARKS

In this paper, we describe the most important aspects revealed by the archaeological excavation of a seventeen hundred year old temple site in Eastern Georgia. We also describe the results of our initial archaeoastronomical investigation of this site, and show that this temple was oriented towards the summer and winter solstices. On the basis of archaeological and ethnographic evidence we know that the worship of the Sun was an important element in ancient Georgian culture, and we conclude that during the second and third centuries AD the temple at Nekresi was used for solar and other astronomical observations. We suggest that instead of being known as the 'Nekresi Fire Temple' a more appropriate name would be the 'Nekresi Sun Temple'.

We hope that future archaeoastronomical investigations at the Nekresi Sun Temple will reveal interesting new evidence on the ways in which the ancient Georgians developed their astronomical 'world view'.

6 NOTES

1. For information about the ancient city of Nekresi see Kaukhchishvili, 1959: 29.
2. This photo-catalogue has been stored in electronic form, and the various images can be used for future scientific investigations or to illustrate lectures. Copies of individual images can be obtained from the first author of this paper.

Table 2: Azimuths of different parts of the Nekresi Sun Temple.

Direction	Mag az measured (°)	True az deduced (°)
a	340.0	345.5
b	69.5	75.0
c	70.5	75.5
d	160.5	165.0
e*	*158.0*	*163.5*
f	249.5	255.0
g	248.5	254.0

7 ACKNOWLEDGEMENT

The authors express their gratitude to the anonymous reviewers for their valuable comments, and to Wayne Orchiston for helpful discussions.

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Journal of Astronomical History and Heritage, 12, 240-248 (2009).

HOW THE FIRST DWARF PLANET BECAME THE ASTEROID CERES

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Abstract: The discovery on 1 January 1801 of an object between Mars and Jupiter was the most remarkable astronomical discovery since the planet Uranus had been found in 1781. Its discoverer, Giuseppe Piazzi at Palermo Observatory in Sicily, was quick to name it Ceres Ferdinandea. But the discovery was considered so important that it sparked national rivalries. In Germany, the much anticipated planet had been dubbed Hera sixteen years previously, and other Germans quickly gave it their own names. Some leading French astronomers soundly rejected Ceres Ferdinandea, preferring to call it Piazzi, while others in Paris accepted the name Ceres, while at the same time objecting to Ferdinandea. Once another 'planet' dubbed Pallas was discovered in 1802, William Herschel realised that astronomers were dealing with a new class of object. He was uncertain what name should be employed however, so he canvassed his friends and colleagues for suggestions. Not content with the often ludicrous ideas put forward, he coined the word asteroid. This paper reveals these dual nomenclature issues through previously-unpublished private letters, an Italian journal, and the much more sedate language used in printed journals.

Key words: asteroids, minor planets, planets

1 INTRODUCTION

Until 1781 the Solar System, consisting of six planets revolving around a central star, seemed as immutable as the fixed stars themselves. On 13 March in that year William Herschel (Figure 1) discovered a seventh planet. Herschel, himself, was unsure what to call his epochal discovery, but he was quite certain what it should not be called:

> In the fabulous ages of ancient times the appellations of Mercury, Venus, Mars, Jupiter and Saturn were given to the Planets, as being the names of their principal heroes and divinities. In the present more philosophical era, it would hardly be allowable to have recourse to the same method, and call on Juno, Pallas, Apollo or Minerva, for a name to our new heavenly body. (Herschel, 1783).

Figure 1: Sir William Herschel, 1738–1822 (courtesy Wikipedia).

The nomenclature issue arose soon after the discovery. In a letter written in November 1781, Joseph Banks (Figure 2) urged Herschel in November 1781 to name it quickly, otherwise "… our nimble neighbours, the French, will certainly save us the trouble of baptizing it." It was the German astronomer Johann Bode who dubbed it Uranus, but Herschel gave it the name Georgium Sidus. For many decades it was usually called in England 'the Georgian planet' as a tribute to King George III of England. Continental astronomers opted for the classical name, despite Herschel's opinions on the matter. Thus the stage was set for future controversy: should another new planet be named by its discoverer, and what should the astronomical community do if another royal patron is duly honoured?

That another planet could be lurking in the Solar System had been the subject of speculation for many years before Herschel's discovery. Johann Titius first expounded the 'law' of planetary distance in 1766, and his text was incorporated into books by Johann Bode (Figure 3) in the 1770s, a publicity coup that has usually given him the credit for the promotion of 'Bode's Law' (see Cunningham, 2001: 19). When the Italian astronomer Giuseppe Piazzi (Figure 4) found a new celestial body on the first day of the nineteenth century (see Cunningham, 2001; Foderà Serio et al., 2002) it was soon regarded by most astronomers throughout Europe as a new planet, and one that neatly fitted into the predictions of Bode's Law. The stage had indeed been set, now the curtain was about to rise.

2 THE CONTROVERSY IN GERMANY

The name given to the object discovered on 1 January 1801 generated huge controversy in Europe, and the debate raged throughout 1801 and into 1802.

On 7 May 1801 Piazzi wrote a letter to Barnaba Oriani in which he stated his intention to name his discovery Cerere Ferdinandea, the Italian version of Ceres Ferdinandea. This was reiterated in his first monograph on the discovery, *Results of the Observations of the New Star Discovered the* 1^{st} *of January*

1801 at the Royal Observatory of Palermo.[1] Piazzi also made his choice known directly to Johann Bode, Director of the Berlin Observatory in a letter dated 1 August 1801:

> I embrace you heartily that you have first announced my new planet, to which I would like bestowed the name Ceres Ferdinandea. (quoted in Bode, 1801).

Piazzi chose Ceres as the patron goddess of Sicily in the ancient Roman pantheon, and Ferdinandea in honour of Piazzi's patron King Ferdinand of Naples and Sicily.

The debate opened at once, but was initially confined to a squabble between German astronomers. First off the mark was Bode. As he related in a paper written in September 1801, it was in May that he wrote to Baron Franz Xaver von Zach in Gotha:

> I would like to suggest the name Juno (Hera, in Greek), as I already informed Baron von Zach in Gotha in May. We must remain with mythology for the sake of analogy and to avoid flattery, and because the planets found over Jupiter carry the name of his ancestors and those standing closer to the Sun the names of his spouse and children. (Bode, 1801).

In 1801, Zach wrote to his close friend Oriani in Milan about the machinations of Bode, who is likened to a farm animal by the haughty French astronomers:

> Bode wrote me confidentially that he had already thought about a name for the new planet and that it should be Junon (ed: Junon is the French name for Juno). But since I have been talking about this planet for 16 years now and been hoping to find it working on my zodiacal catalogue, the Duke [Ernst II; Figure 5] has already jokingly baptised this new hidden planet Hera or γρα, which means Junon in Greek. Thus I did not mention anything of Bode's nice idea in my journal since he told me the secret, I only said that 16 years ago the Duke of Saxe-Gotha gave this planet between Mars and Jupiter the name Hera and that it absolutely and necessarily must be Hera and not Juno. Here is the demonstration: **1**. the new planet cannot be called Juno since this name is already consecrated to Venus. Pliny *Hist. Nat*. Lib. II chap. VI said: Below the Sun walks the great star some call Venus … others call it, however, Juno. L. Apuleius said at the beginning of *de Mundo*: Juno, which esteems to be the star of Venus, is ranked as the fifth. St. Augustine *De Civitate Dei* Lib. VIII c. 15 calls Venus Stellam Junonis. Hence it is against the rules to give this name to the new planet. **2**. It must be Hera because Hera is the mother of Vulcan who resides in Sicily. (ed: it was believed Vulcan, the god of fire, had his smithy under the volcano Mt. Etna). This city of Hera is also named Hybla Minor, and it is of this which Cicero talks in *ad Atticum* II.2. and in Pausanias in Elis Lib. VI c.6, and which comes up in the Antonine Itinerary (ed: a register of stations and roads in the Roman Empire); this will conserve, perpetuate and bequeath at the same time the discovery made by a Sicilian astronomer in Sicily to posterity. **3**. It must be the Greek name Hera and not the Latin Juno, because Herschel's planet also has a Greek name – Uranus, it should be Coelus in Latin, but it is very good, all the ancient planets will have Latin names, the modern Greek ones, this distinguishes them at a glance, so if a new planet beyond Uranus will be discovered, it needs a Greek name. And here is my poor Baudet (as La Lande called him writing to Gotha) fleeced of the honour to be the parent of the new planet, as well of the honour to have recognised the planet and to have said it was the one between Mars and Jupiter for it belongs to two fine Italians and not to a heavy German like Baudet. (ed: in French, 'baudet' means donkey). (Zach, 1801a; his underlining and bolding).

Figure 2: Sir Joseph Banks, 1743–1820 (courtesy Wikipedia).

The ink was scarcely dry on this letter before Zach became aware of other contenders for the nomenclature crown, as he wrote in the July issue of his journal *Monatliche Correspondenz* (*The Monthly Correspondence*), which was the world's first astronomical journal:

> That a new planet would be conferred several new names was to be expected. In the Leipziger Allgem. Literar. Anzeiger no. 72, an unnamed source suggested the name Vulkan. He believed it would not be improper to give the god who forged the weapons of Achilles a place in the sky next to the god of war [Mars], the husband of Venus next to her lover. Vulkan would also not be able to complain that the honour was paid to him too late and that such an inconspicuous planet had been given his name, since he himself, due to a small mistake on the foot, is not fleet of foot or otherwise of splendid form. Vulkan, as the son of Jupiter, belongs to the family and has, in this respect, a well-founded claim to the honour intended for him. Doctor and Professor [Heinrich] Reimarus in Hamburg is of the opinion that it should be called Cupido. Because it was once established that planets be named according to the gods of dis, he would therefore be (counting from Venus down-

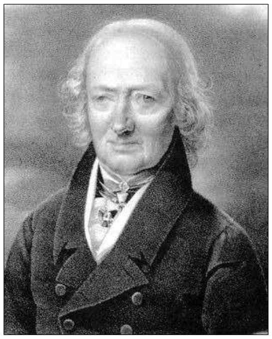

Figure 3: Johann Elert Bode, 1747–1826 (courtesy Wikipedia).

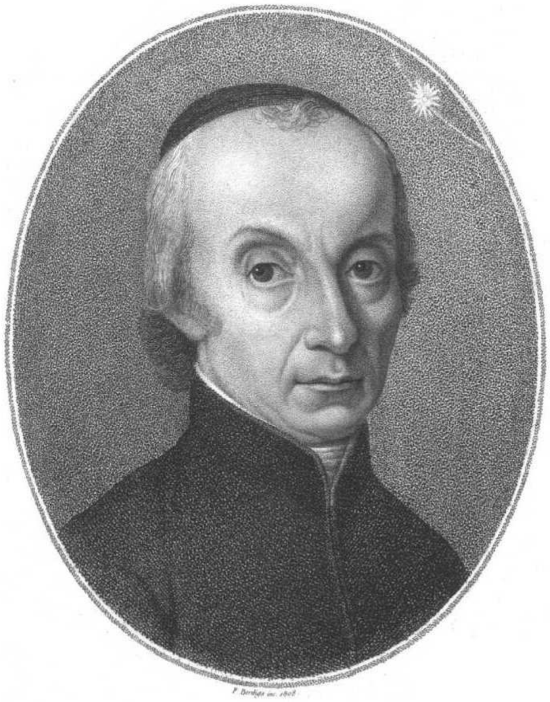

Figure 4: Giuseppe Piazzi, 1746–1826, the discoverer of Ceres (courtesy Wikipedia).

> ward) the next from Mars, a lover of Venus. Others believe the name Cupido is fitting because the name is associated with the idea of blindness. The new planet appears only as a magnitude eight star and cannot be seen with the naked eye. But should the planet be confirmed, the question of a name will be decided by the majority, and perhaps even by chance. It is also possible that a general consensus will never come to be, as was the case with Uranus. [MC, July 1801: 56]. A known chemist [Martin Klaproth] wants to christen the new planet Titan after his newly discovered and named metal [titanium], because he had given shortly after the discovery of Uranus the element discovered by him the name uranium. (cf. Bode, 1802b).

Figure 5: Ernst II, Duke of Saxe-Gotha-Altenburg, 1745–1804 (courtesy Wikipedia).

Oriani (1801) warned Piazzi of the naming situation in Germany:

> I must tell you that the name Hera or Juno has been given universally by all of Germany, for which it will be very difficult now to rename it Ceres.

Piazzi (1801) was scathing in his response:

> If the Germans think they have the right to name somebody else's discoveries they can keep calling the new star the way they want, for we will always call it Cerere. I will be very glad if you and your colleagues will do the same.

By the time Ceres had been recovered in December 1801 (by Zach) and January 1802 (by Olbers), Bode caved in to the pressure:

> I accept with much pleasure the name Ceres Ferdinandea. You discovered it in Taurus, and it has been found again in Virgo, the Ceres of ancient times. These two constellations are the symbol of Agriculture. The chance is very singular. (Bode, 1802a).

3 THE CONTROVERSY IN FRANCE

Even before Ceres had been recovered, the French weighed in with their own views. We gain a unique insight into Joseph-Jerome Lalande (who held the Chair of Astronomy in the Collège de France) and the search for Ceres through a diary that was kept by L.V. Brugnatelli of Pavia. In 1801 he set out from Italy for Paris with the physicist and electrical pioneer Alessandro Volta, who had been invited there by Napoleon. The new object and its name were the topic of a memoir that Lalande presented at the opening ceremony at the Collège de France on 21 November 1801 in the presence of the Interior Minister. Brugnatelli (1801) writes:

> Lalande invited us to the opening of the French College. His (Lalande's) memoir begins with the discovery of the new planet made by Piazzi about which he (Lalande) doesn't raise any doubt anymore. He said that this discovery had been made on the first of January. Lalande spoke about the name that was given to the new planet discovered by our Italian. Piazzi would call it 'Ferdinandum sidus', Bode and other astronomers named it Juno or Hera. For me (said Lalande) I always call it -Piazzi- and I think that most astronomers agree.

Early in 1802 Napoleon Bonaparte, who always took a keen interest in scientific matters, made his views known, through a letter Zach (1802a) wrote Oriani:

> Senator [Pierre-Simon] Laplace writes me that Bonaparte would like the new planet to be called "Junon." Lalande wants to call it "Piazzi." As for me, I will continue to call it Ceres while begging Mr. Piazzi to dispense with "Ferdinandea," which is a bit long.

In his annual paper "History of astronomy" for 1802, Lalande leads off the list of accomplishments of the year 1801 with Piazzi's discovery, including his opinion on a suitable name:

> As he hopes that this star will be acknowledged to be a planet, he has given it the name of Ceres Ferdinandea, in honour of the king of Naples; and Bode wishes it to be called Juno: as for my part, I shall call it Piazzi, as I gave the name Herschel to the planet discovered in 1781. The pagan deities are no longer interesting; and adulation pleases only the person who is the object of it.

Lalande amplified his opinion on the subject in a letter to Zach, the contents of which were then passed on in a letter to Carl Gauss:

> La Lande really wrote: "Soon we will have all satisfaction. And the name Juno is being used. The senator La Place uses it exclusively." Méchain plays the diplomat and is still manoeuvring. He neither writes Juno nor Ceres, but only "the new planet"; it is ridiculous to see how anxiously and world-wisely he tries to avoid the *nomen proprium* (proper name). La Lande who is French, too, with all his heart but still a respectable and honest soul with his own head, is different as he writes: "To me, it will always be Piazzi and nothing else, if someone wants to steal his treasure, I do not want to be part of this injustice". That is great! But incompatible with the court and an affront to Bonaparte, who calls him (Lalande) his grandpa. (Zach, 1802b, his underlining and italics).

Within the next few weeks, Pierre Méchain (Figure 6) had softened his stance. In a letter to William Herschel, Méchain (1802) first uses the phrase "planete de Piazzi", then the name Ceres a few lines later.

All of this was contained in private correspondence. When Zach went public with the controversy in his journal, *The Monthly Correspondence*, he presented a stoic face, likening it to a religious schism:

> La Lande, true to his principle wants to name it Piazzi – just as he insists to call Uranus George's planet or Herschel. Some time ago he wrote regarding this matter: "I will never consent to rip off of this small planet the name of my student Piazzi and replace it by Ceres, who is nothing to me. The rural deities were something in former times but are nothing today. The names had a meaning once but none today." Senator La Place wrote in his latest letter: "Bonaparte, to whom I talked about the new planet some days ago, and who has despite all his other obligations a vivid interest in science and especially astronomy and its progress, prefers the name Juno to Ceres, and I agree with him. It is only natural to place Juno close to Jupiter. The German astronomers were the first to give it the name of this Greek goddess, but it certainly is better to give it a Latin name." Well, again a schism in the church of astronomy, just as with Uranus. (Zach, 1802c).

Piazzi (1802b) was determined to have his way, and wrote in very strong terms to Zach in late April 1802.

> I've noted in one of your memoirs in your journal the desire of a few to give this new planet the name Juno instead of Ceres. I trust that these astronomers, who are peaceful people, will never consent to having their deities called the name of a goddess as anxious, jealous and vindictive as Juno. Jupiter finally chased her from the sky as he had threatened a number of times; in her place he had Ceres appear, who has so much more right to the homage of mankind, and whom he hid very close to himself, loving her passionately ... These questions should always be treated light-heartedly.

4 THE AFFIX FERDINANDEA

By the middle of 1802 the name Ceres had been adopted by everyone except Laplace and Lalande. But what of Ferdinandea? Piazzi had added this name to honour his patron, Ferdinand (Figure 7), who was King of Sicily as Ferdinand III and King of Naples as Ferdinand IV (Ferdinand I, King of the Two Sicilies from 1816-1825). Piazzi was strident in his claims, the raw emotion that the controversy had generated within him literally overflowing the page:

Figure 6: Pierre Méchain, 1744–1804 (courtesy Wikipedia).

> Being the first in the discovery of this new planet, I thought to have the full right to name it in the most convenient way to me, like something I own. Thankful to my master, thankful to the Sicilian nation, willing to maintain a certain coherence with the other planetary names, it looked right to me to name it Ceres Ferdinandea. I will always use the name Ceres Ferdinandea, nor by giving it another name will I suffer to be reproached for ingratitude towards Sicily and its King, who with so much zeal, protects the sciences and arts, and without whose favour, perhaps we may never have arrived at this discovery. It is not adulation, but tribute, right and fair homage. (Piazzi, 1802a).

The double-barrelled name found few friends, as we learn in a letter from Wilhelm Olbers (1801) to Zach:

> I like the name Ceres since it reminds one of Sicily. Piazzi has certainly earned the right to name the new

Figure 7: Piazzi's patron, King Ferdinand III of Sicily, 1751–1825 (courtesy Wikipedia).

> planet. But the affix Ferdinandea will meet with as little luck as Herschel's George's planet.

Olbers was correct, but at least it met with a polite reception from the British Astronomer Royal, Nevil Maskelyne:

> You had the right to name the planet, which you discovered, and you paid due homage to your King, patron of the Arts and Sciences and founder of your observatory. I will call, and it will be called in England, Ceres Ferdinandea. (Maskelyne, 1802).

Despite his lofty proclamation, the affix Ferdinandea was never used in England by Herschel in his published papers on Ceres. Zach (1801b) used 'Ceres Ferdinandea' in private correspondence and in his Journal:

> Since Piazzi has baptised his own child and named it Ceres Ferdinandea, which is entirely within his right as the discoverer, and since all of his correspondents have been asked to use this designation, we on our part also subscribe to this fitting designation with genuine and therefore greater pleasure, because the King of Naples, being an eager protector and patron of astronomy, as well as the magnanimous founder of a new, splendid observatory, indisputably deserves our gratitude, since he not only started to build an observatory, but completed it; not only bought the most valuable and splendid English instruments and instead of keeping them in boxes and crates in junk rooms, put them where they belong, and entrusted these splendid instruments not to unskilled and lazy hands, but rather to a scholar of recognised merit and skilfulness, and placed him in a position to promote his work and observations to print at the expense of the king. Since then, in such a short time, the most helpful and brilliant fruits have come from the Palermo Observatory, the learned world has been given several volumes of the most valuable observations, and this temple of Sicilian Urania has been immortalised, with its founder and priest, for millennia through the remarkable discovery with the coming new century. Piazzi therefore says in his discourse, and rightly so, that Ferdinand IV has more of a right a place in the heavens than some other protectors of astronomy.

Piazzi could hardly have asked for a more ringing endorsement, but this resolution did not last long, as the final appearance of Ferdinandea in the title of a paper in the *The Monthly Corresponedence* appeared in March 1803. In Russia, N. Fuss wrote several short papers in Russian about Piazzi's discovery, but the affix Ferdinandea was never used (e.g. see Fuss, 1802). However, the name Piazzi continued to be used for a while, and even appears on a map of the Solar System (circa 1802; see Figure 8) and on a French-made orrery (circa 1809; see Figure 9).

5 SELECTION OF THE TERM ASTEROID

On 28 March 1802, only two months after Ceres has been recovered, Olbers discovered a second small 'planet' which he named Pallas. Just as the controversy had settled down about the proper name for Piazzi's discovery, William Herschel began a controversy that has continued to this day. Herschel had visited Paris in 1801, where he met Laplace and Napoleon, but he did not concern himself—as the French did—with the naming of the new planets individually. His concern was their collective appellation, and for this his choice was 'asteroids'.

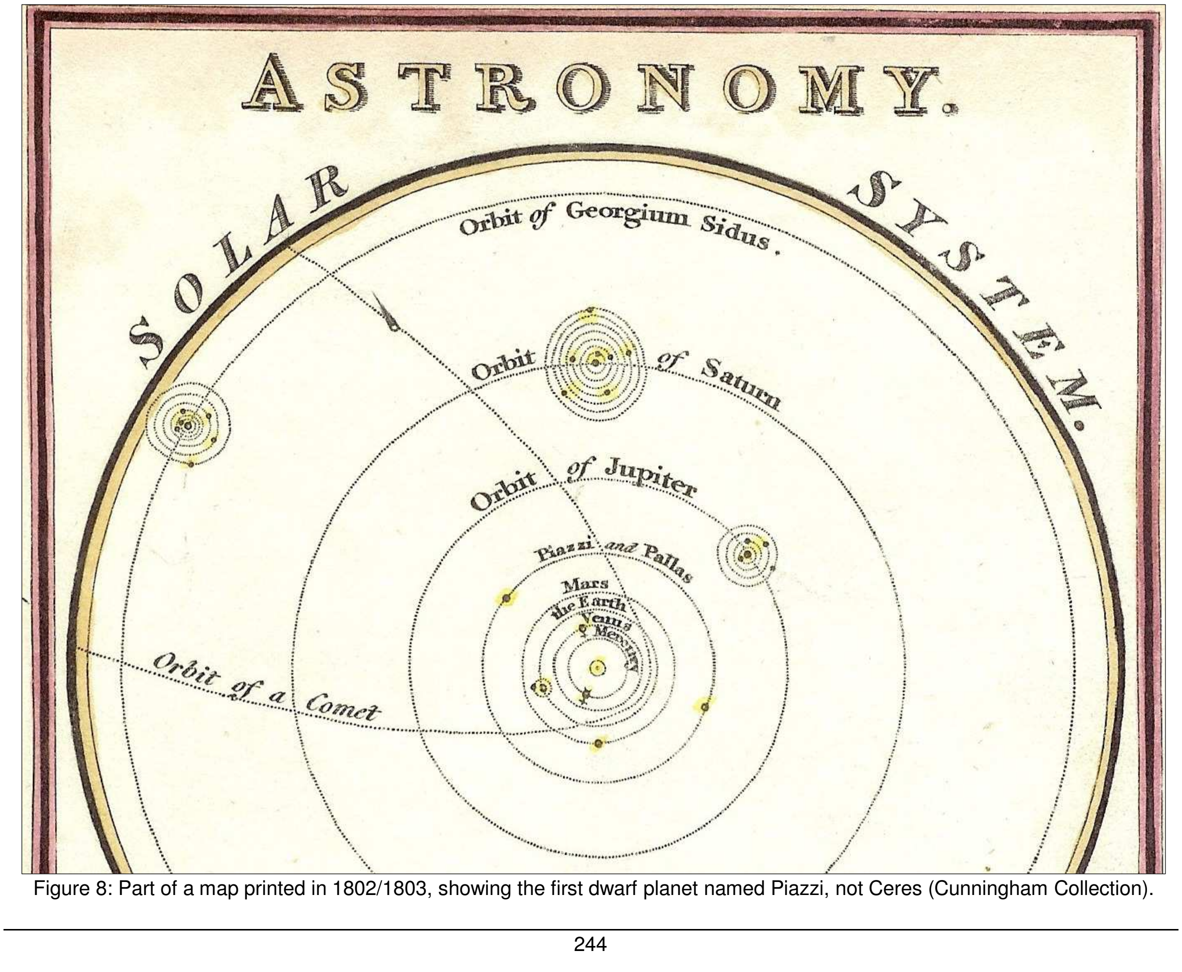

Figure 8: Part of a map printed in 1802/1803, showing the first dwarf planet named Piazzi, not Ceres (Cunningham Collection).

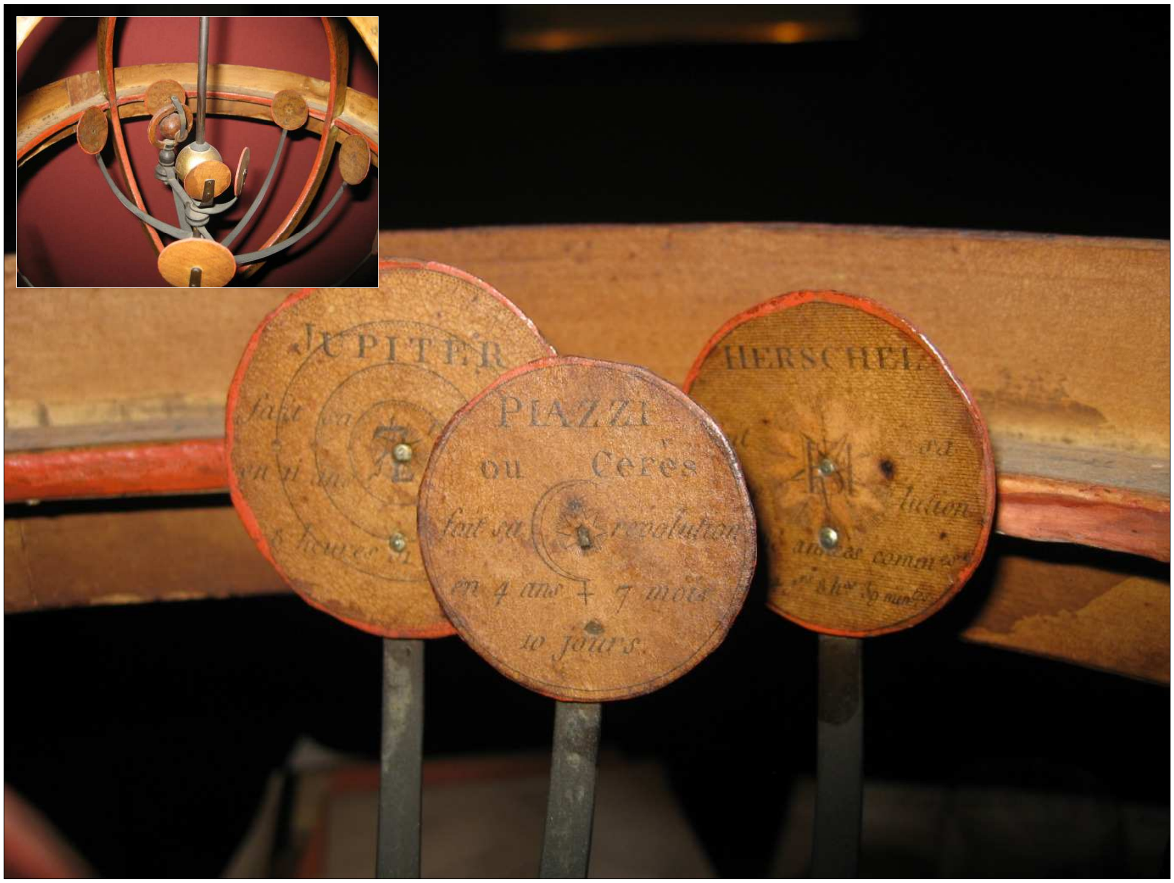

Figure 9: Close up of part of the French orrery in the inset, showing a roundel named both Piazzi and Ceres (Photograph: C. Cunningham).

We must look into Herschel's private letters to discover how he arrived at the terminology that is widely used today. His letter to Sir Joseph Banks, President of the Royal Society, is a crucial piece of information. It was written just three months after the discovery of Pallas:

> The names you have done me the favour to send I have carefully examined, and beg leave to give you my remarks on them. The title of them, "Names for the new Planet," shows immediately that none of them can possibly be used for the new species of bodies which we have to christen: for they are not planets.
>
> If Mr. [William] Watson were to have a definition of the thing we want a name for, he might possibly find a better one than that of asteroids, which is not exactly the thing we want, though still the most unexceptionable [sic] of any that have been offered by my learned friends. Will you do me the favour to consult him once more upon the subject, and mention to him that the bodies to be named are neither fixed stars, planets, nor comets, but have a great resemblance to all the three? With this view before him he will probably succeed in an appropriate appellation. (Herschel, 1802c).

In this extraordinarily frank letter, Herschel admits that the term asteroids is not optimal—merely the best of an unremarkable suite of options. Unfortunately the names suggested by Banks do not appear in the extant letters.

The search for a new name began two months earlier, when Herschel (1802a) turned to his friend Sir William Watson for help. In writing this, he was certainly well aware that Newton (1687), wrote an analysis of the motion of comets in the third book of the *Principia*, in which he shows that comets "… are a sort of planet." He wrote:

> I have now to request a favour of you, which is to help me to a new name. In order to give you what will be necessary I must enter into a sort of history. You know already that we have two newly discovered celestial bodies. Now by what I shall tell you of them it appears to me much more poor in language to call them planets than if we were to call a razor a knife, a cleaver a hatchet, etc. They certainly move round the Sun; so do comets. It is true they move in ellipses; so we know do some comets also. But the difference is this: they are extremely small, beyond all comparison less than planets; move in oblique orbits, so that, if we continue to call that the ecliptic in which we find them, we may perhaps, should one or two more of them be discovered still more oblique, have no ecliptic left; the whole heavens being converted into ecliptic, which would be absurd. I surmise [again] that in them to hurt one another by attraction, or to disturb the planets, may possibly be running through the great vacancies, left perhaps for them, between the other planets, especially Mars and Jupiter. But should there be only two, surely we can find a name for them. The diameter of the largest of them is not 400 miles, perhaps much less. Now as we already have Planets, Comets, Satellites, pray help me to another dignified name as soon as possible. If I could in any way express the condition of a nimble, small, interloper going obliquely through the majestic orbits of the great bodies of the Solar System it would be just what is required. But pray, if you can, help me soon. I am writing a paper in which if possible

> I would propose a name, but as it should go to London by next Thursday I am hardly willing to press you so much for haste. However you will give it a thought, and if two or three names could be proposed it would give me some choice. Greek derivation such as planet from πλαναω[2] would probably be best.

Watson received Herschel's letter the next day and responded after a day of thought:

> I received much gratification at the perusal of your letters — the discovery of a new species of heavenly bodies is truly surprising, and I agree with you that a new name ought to be given such bodies. The best name I can think of is Planetel as a diminutive of Planet, just as Pickerel or Cockerel (used by Shakespeare) is of a Pike and a Cock. The sportsmen too call a young stag stagerel. You may also use as the diminutive the word Planeret, as baronet is of the word Baron — so we say islet tartlet tablet cygnet, the respective diminutives of island, tart, table, tablet, Cygne the French for Swan. But as these are made by the mere addition of et, except tartlet, the word should be Planetet, and that does not sound well. Diminutives are also formed by adding -kin as manikin, lambkin, so you may say Planetkin — or better Erratikin — being the diminutive of Erratic. I should like Planetine (pronounced Planeteen) best of all, but I find no example of that way of diminishing in English. The diminutives formed by adding -ling such as duckling will not have place here — we cannot say Planetling. So upon the whole the word Planetel is the least objectionable. Perhaps you may be more happy in your research after a new name.
>
> Since I wrote the above I reflected that after the Romans we make diminutives by adding –ule such as spherule, a little sphere. So Planetule may be a little Planet.

Herschel rejected all these suggestions, and came up with his own appellation within a month. In the modern equivalent of a multiple-address email, Herschel announced his choice of the term asteroid to every notable Continental astronomer with a stake in the subject. On 22 May 1802 he wrote to Gauss, Méchain, Lalande, Laplace, Bode, Zach, Olbers, Karl Seyffer, Johann Schroeter and Piazzi. He first makes clear that both Ceres and Pallas are "… a new species of celestial bodies …", and then he gives his specific rationale for choosing the term asteroid. Here, by way of example, is what he wrote to Gauss (Herschel, 1802b; his underlining):

> These new stars are mixed with the small fixed stars of the heavens and resemble them so much that even with a good telescope they cannot be distinguished from them. From this their asteroidal or starlike appearance I take my name, and call these new celestial bodies Asteroids.

What was Herschel trying to do with this letter? By targeting all the leading astronomers, he was trying to build a consensus, but his reputation as something of a rebel, combined with his apparent 'proclamation' of the term asteroid, foiled this approach and generated great controversy (see Cunningham, 1984; 1991; 2006; Hughes and Marsden, 2007). He likely could have quenched the firestorm that arose over his choice if he had accepted the suggestion of 'planetoid' made to him by Piazzi in a letter dated 4 July 1802. Piazzi (1802d) chose not to make his nomenclature choice public, and Herschel did not back away from his decision.

To understand the actual meaning of the word Herschel chose, we must look at its Greek etymology:

> Greek has two words for "star": aster, which gives astero- in compound words, and astron, which gives astro- in compounds. The first means an individual star (usually a conspicuous one), whereas the second word is normally used in the plural to refer to "the stars" in general. This distinction is generally observed in compound words, whether by luck or design: thus asterisk means "a little star", and asteroids "like a star", whereas astrology, astrometry, astronomy and astrophysics all refer to study of "the stars" in general. (Fitch, 1987, his underlining).

In ancient Greek we find πλανήτης (*planētēs*), a variant of πλάνης (*planēs*, 'wanderer, planet'). The planets were called by the Greeks *asteres planetai* (wandering stars) or *planetai* (wanderers). The Latin term used in place of the Greek was *stellae errantes* (wandering stars); but Late Latin borrowed the Greek term in the plural form, *planetae*, while the singular was *planeta*. The English word planet comes directly from the Latin *planeta*.

The gender precedent had been set at the beginning when these two new objects were given female names, in contradistinction to that of names given to planets, which were male—except for Venus. There was a recent French trend to use the word *planete* as a feminine noun, "… contrary to analogy and to etymology, considering them as immediately derived from the Greek … " in the words of the English amateur astronomer Capel Lofft (1798). By giving the name 'asteroid' to Ceres and Pallas, Herschel effectively countered this trend—the precedent to name the asteroids after female deities was one that would be followed into the twentieth century. Although the feminization of names (by adding an -a or -ia at the end of a word) continued until the mid-twentieth century, some names of asteroids were deliberately made masculine (starting notably with Eros in 1898 and then Achilles in 1906), if they were not in the main belt. The application of male names to new planets was followed with the selection of the names Neptune and Pluto. In the twenty-first century, Pluto joined Ceres in the select group of Solar System objects known as dwarf planets, generating yet another nomenclature controversy that has spread around the world (see Tyson, 2009).

6 EARLY USE OF THE TERM ASTEROID

Use of the term asteroid began to spread in the 1820s. In America it was mentioned by Blair (1821) in a natural philosophy book for the general reader: "Ceres, Pallas, Juno and Vesta are very small bodies, and called by Dr. Herschel *asteroids*." Hughes and Marsden (2007) quote from several astronomy books of the 1820s that mention the word, but a measure of how it truly reached popular culture can be gleaned from a satirical swipe at Ireland published in the review of a 'silly book' in the widely-read *London Magazine*. After noting that potatoes, a staple of the Irish diet, are 'anti-intellectual', the reviewer writes:

> It seems hard to be "blown up sky-high" into an Asteroid, for a mistake in diet. And it is still far from certain that Ireland would fare better by becoming an Asteroid, for some of the little planets, the moon for example, are in want of bare necessaries. (Notes on the various sciences, 1825).

In the professional realm, the term asteroid only came into regular use in the U.S.A. later in the nineteenth century when Benjamin Apthorp Gould (1848) employed it:

> By the common consent of astronomers, they have received the name of "asteroids," a name proposed by the elder Herschel, in consequence of a theory of his own. The word asteroid, in its present signification, may be defined as "a small planetary body, which revolves around the sun between the orbits of Mars and of Jupiter."

It was Gould's consistent use of 'asteroid' in the *Astronomical Journal* (which he founded in 1849) that strongly influenced the use of the word in the United States (though not in other countries). A British book of the same year uses the word asteroid interchangeably with meteor and shooting star (Thomson, 1849).

7 CONCLUDING REMARKS

For the first time this paper comprehensively traces the birth and evolution of the name 'Ceres Ferdinandea' from sources in English, German, French, Italian and Russian. It also traces the birth of the term 'asteroid', and makes the point that feminine names could be applied solely to this separate category of objects, leaving male names for any future (major) planets and unusual asteroids.

Despite his stature as the discoverer of the planet Uranus, the views of William Herschel were soundly rejected time and again by Continental astronomers. The very name he denounced for his own planetary discovery—Juno—became the name fought over so fiercely twenty years later as a contender for Piazzi's discovery. Herschel's attempt to honour his royal patron was rejected, and Piazzi's similar attempt to honour *his* royal patron was widely ignored and quickly fell into disuse. Finally, Herschel's use of the term asteroid met with widespread disapproval by his contemporaries, with the exception of Olbers. The term planetoid was coined by Piazzi (1802c), and first used in a letter by him to Oriani dated 2 July 1802. The word, which was first used in print by Henry Brougham (1803), achieved some currency but never rose to the level reached by yet another term, 'minor planet'. This was introduced in 1835 for the 1837 issue of *The Nautical Almanac and Astronomical Ephemeris.* The term was introduced in *Monthly Notices of the Royal Astronomical Society* in 1853. Its use became official in the U.K. from the 1850s onwards, as well as in Germany ('klein Planet') and France ('petite planète') and other European countries around the same time. It was therefore natural that the IAU would use the term, and it did so as soon as it was itself established in 1919. Commission 20 was concerned with petites planètes or minor planets, in the two official languages, right from the start, with no mention of asteroids until 2006. When the IAU established a center to keep track of these bodies in 1947, it thus became The Minor Planet Center.

It was in 2006 that the IAU defined the new category of 'dwarf planets' which consists of Ceres, Pluto and the distant objects Eris, Makemake, and Haumea. There is a reluctance to apply the term asteroids to objects in the transneptunian region, although 'planetoids' or 'minor planets' are still acceptable there. So Ceres, entering its adolescence as a dwarf planet, can look back on more than two centuries and marvel at all the fuss that was caused by its birth as the first asteroid. One can only imagine what it will be called when it reaches adulthood.

8 NOTES

1. The completion of this monograph can be dated to 25 August 1801, since Piazzi mailed a copy on that date to Oriani.
2. The word written in Greek, *planao*, is the verb of "to wander."

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Journal of Astronomical History and Heritage, 12 (3), 249-253 (2009).

THE IAU HISTORIC RADIO ASTRONOMY WORKING GROUP. 3: PROGRESS REPORT (2006-2009)

This Progress Report follows the publication of two earlier Progress Reports (Orchiston, et al., 2004; 2005) and a Triennial Report of the Working Group for 2003-2006 (Orchiston, et al., 2006), all of which appeared in the *Journal of Astronomical History and Heritage*.

1 Role of the Working Group

This WG was formed at the 2003 General Assembly of the IAU as a joint initiative of Commissions 40 (Radio Astronomy) and 41 (History of Astronomy), in order to:

- assemble a master list of surviving historically-significant radio telescopes and associated instrumentation found worldwide;
- document the technical specifications and scientific achievements of these instruments;
- maintain an on-going bibliography of publiccations on the history of radio astronomy; and
- monitor other developments relating to the history of radio astronomy (including the deaths of pioneering radio astronomers).

The membership list of the WG contains the names of about one hundred astronomers who are active in the history of radio astronomy field or sympathetic to it.

2 National Masterlists of Surviving Historically-Significant Radio Telescopes

WG members actively worked on national master lists for Australia, France, Germany, India, the Netherlands, the United Kingdom and the USA, and a number of research papers were prepared documenting individual instruments or instruments and research associated with specific radio astronomy field stations.

3 The Destruction of Historically-Significant Radio Telescopes

Despite intensive lobbying by members of the WG and others, Stanford University proceeded to demolish the five 60-ft antennas at their field station off Highway 280 (California). However, the concrete pillars were spared that contain the engraved names of well-known optical astronomers and radio astronomers.

4 The WG Project on Early French Radio Astronomy

Immediately following the 2006 Prague IAU General Assembly the Chairman of the WG went to Paris to launch a collaborative project aimed at documenting, in English, the main developments in French radio astronomy that occurred up to and including 1961. Since this initial visit, four further research visits have been made to Paris Observatory, and the following colleagues have participated in the collaboration: Jacques Arsac, Émile-Jacques Blum, André Boischot, Suzanne Débarbat, Jean Delannoy, Mukul Kundu, James Lequeux, Monique Pick and Jean-Louis Steinberg. To date, four research papers have been published (Debarbat et al, 2007; Orchiston and Steinberg, 2007; Orchiston et al., 2007; and Orchiston et al., 2009—see details, the listing in Section 6, below). Two further papers, completing this series, will be published in March 2010.

5 Research on the History of Radio Astronomy

Colleagues who actively researched aspects of radio astronomical history during 2005-2009 included: *the late Émile-Jacques Blum* (France), *André Boischot* (France), *the late Ron Bracewell* (USA), *Wim Brouw* (The Netherlands), *Geoffrey Burbidge* (USA), *Bernard Burke* (USA), *Ron Burman* (Australia), *Jessica Chapman* (Australia), *Marshall Cohen* (USA), *Nan Dieter Conklin* (USA), *R.D. Dagkesamanskii* (Russia), *Rod Davies* (United Kingdom), *Suzanne Débarbat* (France), *Jean Delannoy* (France), *John Dickel* (USA), *Martin George* (Australia), *Miller Goss* (USA), *Dave Green* (United Kingdom), *Alastair Gunn* (United Kingdom), *Dave Jauncey* (Australia), *Ken Kellermann* (USA), *A.A. Konovalenko* (Ukraine), *Mukul Kundu* (USA), *the late Arcady Kuzmin* (Russia), *James Lequeux* (France), *Bruce McAdam* (Australia), *Dick McGee* (Australia), *Don Mathewson* (Australia), *Leon Matveenko* (Russia), *A.V. Megn* (Ukraine), *Doug Milne* (Australia), *Wayne Orchiston* (Australia), *Yuri Parijskij* (Russia), *Monique Pick* (France), *V. Radhakrishnan* (India), *Peter Robertson* (Australia), *Bruce Slee* (Australia), *F. Graham Smith* (UK), *Peter Stark* (USA), *Jean-Louis Steinberg* (France), *Ronald Stewart* (Australia), *Richard Strom* (The Netherlands), *Woody Sullivan III* (USA), *Govind Swarup* (India), *Dick Thompson* (USA), *I.B. Vavilova* (Ukraine), *the late Edward Waluska* (USA), *Wang Shouguan* (China), *Harry Wendt* (Australia), *John Whiteoak* (Australia), *Richard Wielebinski* (Germany) and *Hugo Van Woerden* (The Netherlands).

6 Further Publications on the History of Radio Astronomy

Since the last list was published (Orchiston et al., 2005) we have noted the following books and papers about the history of radio astronomy or that contain a significant historical component:

Bignall, H.E., de Bruyn, A.G., and Jauncey, D.L., 2005. The variable extragalactic radio universe. In Gurvits, et al., 157-176.

Booth, R.S., 2005. Galactic masers. In Gurvits, et al., 297-316.

Bracewell, R., 2005. Radio astronomy at Stanford. *Journal of Astronomical History and Heritage*, 8, 75-86.

Burbidge, G., 2007. Attempts by a theorist to work with Martin Ryle in the Cavendish, 1953-1955. *Astronomische Nachrichten*, 328, 432-433.

Burke, B.F., 2005. Early years of radio astronomy in the U.S. In Gurvits, et al., 27-56.

Conklin, N.D., 2006. *Two Paths to Heaven's Gate*. Green Bank, National Radio Astronomy Observatory.

Cohen, M.H., 2007. A history of OVRO: Part II. *California Institute of Technology Engineering and Science*, LXX(3), 33-43.

Cohen, M.H., 2009. Genesis of the 1000-foot Arecibo Dish. *Journal of Astronomical History and Heritage*, 12(2), 141-152.

Dagkesamanskii, R.D., 2007. The Pushchino Radio Observatory: origin and first decade's history. *Astronomische*

Nachrichten, 328, 395-404.

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

Davies, R.D., 2007. The search for the elusive Zeeman effect in HI. *Astronomische Nachrichten*, 328, 436-442.

Davies, R.D., 2009. Recollections of two and a half years with 'Chris' Christiansen. *Journal of Astronomical History and Heritage*, 12, 4-10.

Débarbat, S., Lequeux, J., and Orchiston, W., 2007. Highlighting the history of French radio astronomy. 1: Nordmann's attempt to observe solar radio emission in 1901. *Journal of Astronomical History and Heritage*, 10, 3-10.

Dickel, J.R., 2006a. What are supernovae and supernova remnants? In Chen, K.-Y., Orchiston, W., Soonthornthum, B., and Strom, R. (eds.). *Proceedings of the Fifth International Conference on Oriental Astronomy*. Chiang Mai, Chiang Mai University. Pp. 37-42.

Dickel, J.R., 2006b. The structure and expansion of the remnants of historical supernovae. In Chen, K.-Y., Orchiston, W., Soonthornthum, B., and Strom, R. (eds.). *Proceedings of the Fifth International Conference on Oriental Astronomy*. Chiang Mai, Chiang Mai University. Pp. 57-63.

Gayland, M.J., and Nicolson, G.D., 2007. Forty years of radio astronomy at Hartebeesthoek. *African Skies*, 11, 49-52.

Goss, M., and McGee, R.F., 2009. *Under the Radar – The First Woman in Radio Astronomy: Ruby Payne-Scott.* Springer.

Graham-Smith, F., 2005. The early history of radio astronomy in Europe. In Gurvits, et al., 1-13.

Gunn, A.G., 2005. Jodrell Bank and the pursuit of cosmic rays. In Gurvits, et al., 15-26.

Gurvits, L.I., Frey, S., and Rawlings, S., 2005. *JENAM 2003. Radio Astronomy from Karl Jansky to Microjansky*. PA deCourtaboeuf, EDP Sciences.

Hirabayashi, H., 2005. Next generation space VLBI. In Gurvits, et al., 465-478.

Kassim, N.E., Perez, M.R., Junor, W., and Henning, P.A., 2005. *From Clark Lake to the Long Wavelength Array: Bill Erickson's Radio Science*. San Francisco, Astronomical Society of the Pacific (ASP Conference Series, Volume 345).

Konovalenko, A.A., and Stepkin, S.V., 2005. Radio recombination lines. In Gurvits, et al., 271-295.

Kuzmin, A.D., 2007. Detection of the polarized radio emission from the Crab Nebula. *Astronomische Nachrichten*, 328, 434-435.

Lockman, F.J., Ghigo, F.D., and Balser, D.S., 2007. *But it was Fun. The First Forty Years of Radio Astronomy at Green Bank*. Green Bank, National Radio Astronomy Observatory.

McAdam, B., 2008. Molonglo Observatory: building the Cross and MOST. *Journal of Astronomical History and Heritage*, 11, 63-70.

Matveenko, L.I., 2007. Early VLBI in the USSR. *Astronomische Nachrichten*, 328, 411-419.

Milne, D.K., and Whiteoak, J.B., 2005. The impact of F.F. Gardner on our early research with the Parkes Radio Telescope. *Journal of Astronomical History and Heritage*, 8, 33-38.

Orchiston, W., 2005. Sixty years in radio astronomy: a tribute to Bruce Slee. *Journal of Astronomical History and Heritage*, 8, 3-10.

Orchiston, W., and Mathewson, D.S., 2009. Chris Christiansen and the Chris Cross. *Journal of Astronomical History and Heritage*, 12, 11-32.

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Orchiston, W., Lequeux, J., Steinberg, J.-L., and Delannoy, J., 2007. Highlighting the history of French radio astronomy. 3: The Würzburg antennas at Marcoussis, Meudon and Nançay. *Journal of Astronomical History and Heritage*, 10, 221-245.

Orchiston, W., Steinberg, J.-L., Kundu, M., Arsac, J., Blum, É-J., and Boischot, A., 2009. Highlighting the history of French radio astronomy. 4: Early solar research at the École Normale Supérieure, Marcoussis and Nançay. *Journal of Astronomical History and Heritage*, 12, 175-188.

Orchiston, W., Bracewell, R., Davies, R., Denisse, J.-F., Goss, M., Gunn, A., Kellermann, K., McGee, D., Morimoto, M., Slee, B., Slysh, S., Strom, R., Sullivan, W., Swarup, G., Van Woerden, H., Wall, J., and Wielebinski, R., 2005. The IAU Historic Radio Astronomy Working Group. 2: Progress Report. *Journal of Astronomical History and Heritage*, 8, 65-69.

Parijskij, Y.N., 2007. The big Pulkovo Radio Telescope and Pulkovo radio astronomy. *Astronomische Nachrichten*, 328, 405-410.

Radhakrishnan, V., 2006. Olof Rydbeck and early Swedish radio astronomy: a personal perspective. *Journal of Astronomical History and Heritage*, 9, 139-144.

Roos, M., and de Kroon, P.-R., 2009. A 45 minute film titled "Spiral Galaxy – De Melkweg Ontrafeld" available on DVD (see: http://www.spiralgalaxy.nl/)

Slee, B., 2005. Early Australian measurements of angular structure in discrete radio sources. *Journal of Astronomical History and Heritage*, 8, 97-106.

Smith, F.G., 2007. Early Cambridge radio astronomy. *Astronomische Nachrichten*, 328, 426-431.

Steinberg, J.-L., 2001. The scientific career of a team leader. *Planetary and Space Science*, 49, 511-522.

Steinberg, J.-L., 2004a. Radioastronomie & interférométrie. *L'Astronomie*, 118, 622-625.

Steinberg, J.-L., 2004b. La création de la Station de Nançay. *L'Astronomie*, 118, 626-631.

Strom, R.G., 2007. Ir A.H. de Voogt: life and career of a radio pioneer. *Astronomische Nachrichten*, 328, 443-446.

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Swarup, G., 2006. From Potts Hill (Australia) to Pune (India): the journey of a radio astronomer. *Journal of Astronomical History and Heritage*, 9, 21-33.

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Wielebinksi, R., 2007. Fifty years of the Stockert Radio Telescope and what came afterwards. *Astronomische Nachrichten*, 328, 388-394.
Wilson, T.L., and Batrla, W., 2005. Radio astrochemistry. In Gurvits, et al., 331-345.
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Woerden, H. van, and Strom, R., 2007. Dwingeloo – the golden radio telescope. *Astronomische Nachrichten*, 328, 376-387.
Zarka, P., 2004. Le réseau décamétrique de Nançay. *L'Astronomie*, 118, 17-20.

7 The Prague IAU General Assembly

At the August 2006 General Assembly of the IAU the WG Committee held a Business Meeting, a one-day Science Meeting devoted to "The History of European Radio Astronomy" and a half-day Science Meeting on "Radio Astronomy Fifty Years Ago: From Field Stations to 'Big Science'".

7.1 "The History of European Radio Astronomy"

This meeting was held on Thursday 17 August, during Sessions 1, 2 and 3, and included the presentation of the 2006 Grote Reber Medal to Bernie Mills. The following papers were presented:

- The Dwingeloo 25-meter Dish Celebrates its Golden Jubilee (Hugo van Woerden)
- Fifty Years of the Pushino Radio Astronomy Observatory (R.D. Dagkesamanskiy)
- Attempts by Theorists to Work with Martin Ryle in the Cavendish, 1954-1956 (G. Burbidge)
- Early VLBI in the USSR (Leonid Matveyenko)
- The Pulkovo (BRP 1956) Giant Radio Telescope (Yuri Parijskij)
- A.H. de Voogt, Radio Amateur, Engineer and Astronomy Pioneer (Richard Strom)
- Fifty Years of the Stockert 25-m Radio Telescope and What Came Afterwards (Richard Wielebinski)
- The Search for the Elusive Zeeman Effect (Rod Davies)

These papers were subsequently published in a special issue of *Astronomische Nachrichten*, edited by Richard Wielebinski, Ken Kellermann and Wayne Orchiston.

7.2 "Radio Astronomy Fifty Years Ago: From Field Stations to 'Big Science'"

This meeting was held on Wednesday 23 August, during Sessions 3 and 4, and the following papers were presented:

- The Beginnings of the U.S. National Radio Astronomy Observatory (Ken Kellermann and E.N. Bouton)
- The 218-ft Jodrell Bank Transit Telescope and its Contribution to Radio Astronomy (Andrew Quinn, Alastair Gunn and Wayne Orchiston)
- A True Radio Astronomy Pioneer: Cornell H. Mayer (1921-2005) (V. Radhakrishnan)
- Solar Radio Astronomy at Fort Davis, Stanford and Kalyan, 1956-1966: Personal Reminiscences (Govind Swarup)
- The Contribution of the Ex-Georges Heights Experimental Radar Antenna to Australian Radio Astronomy" (Wayne Orchiston and Harry Wendt)
- The Development of Low Frequency Radio Astronomy in Tasmania (Martin George and Wayne Orchiston)

There were also two poster papers:

- The Contribution of the Potts Hill Field Station to International Radio Astronomy (Harry Wendt and Wayne Orchiston)
- Owens Valley Radio Observatory, QSOs and Palomar (Edward Waluska and Marshall Cohen)

8 ICOA-6 Conference

In 2008 the Sixth International Conference on Oriental Astronomy was held at James Cook University in Townsville, Australia, and the program included four sessions on the history of radio astronomy, where the following papers were presented:

- Quasi-Stellar Objects, The Owens Valley Radio Observatory, and the Changing Nature of the Caltech-Carnegie Nexus (Edward Waluska)
- The World's First Radiospectrograph—Penrith 1949 (Ron Stewart, Harry Wendt, Wayne Orchiston and Bruce Slee)
- Cygnus A in Historical Perspective: Unravelling the Enigma of the first 'Radio Star' (Edward Waluska, Wayne Orchiston, Bruce Slee and Harry Wendt)
- The Contribution of the Division of Radiophysics Potts Hill and Murraybank Field Stations to International Radio Astronomy (Harry Wendt)
- A Retrospective View of Australian Solar Radio Astronomy—Part 1 (1945-1960) (Ron Stewart, Harry Wendt, Wayne Orchiston and Bruce Slee)
- From String and Sealing Wax to Serious Science: The First Ten Years of Australian H-line Research (1951-1961) (Harry Wendt, Wayne Orchiston and Bruce Slee)
- The Sun Sets on a Brilliant Mind: John Paul Wild (1923-2008), Solar Radio Astronomer Extraordin-

aire (Ron Stewart, Wayne Orchiston and Bruce Slee)
- The Contribution of W.N. Christiansen to Radio Astronomy: 1948-1960 (Harry Wendt, Wayne Orchiston and Bruce Slee)

Most of these papers will appear in the Proceedings, which will be published by Springer in 2010.

9 The Rio IAU General Assembly

At the August 2009 General Assembly of the IAU the WG Committee held a Business Meeting, a half-day Science Meeting devoted to "The Development of Aperture Synthesis Imaging in Radio Astronomy" and a quarter-day Science Meeting on "Recent Research".

9.1 Business Meeting

At this meeting the new Committee listed at the end of this report was appointed. We particularly welcome new members, James Lequeux, Norio Kaifu and Yuri Ilyasov representing France, Japan and Russia respectively.

The Report of the WG included in the Division's Triennial Report was summarised, and the program of work for the WG during the next triennium (2009-2012) was outlined and discussed. Apart from a continuation of the existing program, key new initiatives included the following studies:

- Christiansen & Dutch radio astronomy (Brouw & Casse)
- Arthur Covington & Goth Hill (Broten & Wall)
- Culgoora Circular Array—non-solar work (Slee)
- Fleurs Synthesis Telescope (Goss)
- Ft. Davis Radio Astronomy field station (Thompson, Hughes, Maxwell & Swarup)
- Key developments in Japanese radio astronomy
- 'Le Grand Radiotelescope' at Nançay (Lequeux, Steinberg & Orchiston)
- Mills & the Mills Cross (Slee, Orchiston & Wendt)
- Radio astronomy at the University of Maryland (Kundu et al.)

9.2 "The Development of Aperture Synthesis Imaging in Radio Astronomy"

This meeting was held on Wednesday 5 August during Sessions 3 and 4, and included the presentation of the 2009 Grote Reber Medal to Barry Clark. The following papers were presented during this meeting:

- Aperture Synthesis 1946; a Proposal by Pawsey and Payne-Scott (Miller Goss)
- Why Synthesis Imaging Works in Radio Astronomy (V. Radhakrishnan)
- Early Developments in Australia (Bob Frater)
- Cambridge and Australia, Similarities and Differences (Ron Ekers)
- Synthesis Imaging from the Clark Clean Algorithm Onward (Tim Cornwall)
- The Impact of Computing to Synthesis Imaging (Barry Clark)

9.3 "Recent Research"

This meeting was also held on Wednesday 5 August, but during Session 2. The following papers were presented:

- The History of Radio Astronomical Studies of Supernova Remnants (John Dickel)
- Highlighting the History of Australian Radio Astronomy: The CSIRO Division of Radiophysics Potts Hill Field Station, 1948-1962 (Harry Wendt, Wayne Orchiston and Bruce Slee)
- Science with the Molonglo Cross: Publications 1960-1984 (Bruce McAdam)
- Highlighting the History of Australian Radio Astronomy: The CSIRO Division of Radiophysics Dapto Field Station, 1952-1965 (Ron Stewart, Wayne Orchiston and Bruce Slee)

The following poster papers were also displayed during this meeting:

- Early Australian Optical and Radio Observations of Centaurus A (Peter Robertson, Bruce Slee and Wayne Orchiston)
- Highlighting the History of Australian Radio Astronomy: Grote Reber's Low Frequency Research at Kempton, Tasmania, in 1956-1957 (Martin George, Wayne Orchiston and Bruce Slee)
- Highlighting the History of Australian Radio Astronomy: The CSIRO Division of Radiophysics Murraybank Field Station, 1956-1961 (Harry Wendt, Wayne Orchiston and Bruce Slee)
- Highlighting the History of Australian Radio Astronomy: The CSIRO Division of Radiophysics Penrith Field Station, 1948-1951 (Ron Stewart, Wayne Orchiston and Bruce Slee)

10 The End of an Era

With sadness WG members noted the passing of the following pioneering radio astronomers since the 2006 IAU General Assembly: Émile-Jacques Blum, Ron Bracewell, W.N. ('Chris') Christiansen, Fred Haddock, Arcady Kuzmin, Slava Slysh, and J. Paul Wild.

11 Graduate Studies in the History of Radio Astronomy

A notable recent development has been the introduction of an off-campus part-time Ph.D. program in history of astronomy at James Cook University (JCU), Townsville, Australia. Since its inception in 2005, the following six students have researched aspects of early Australian and U.S. radio astronomy:

- Martin George (Australia) "The History of Low Frequency Radio Astronomy in Tasmania"
- Peter Robertson (Australia) "John Bolton and the Enigma of the 'Radio Stars'"
- Peter Stark (USA) "Early Pulsar Research and the Roles of the Molonglo Radio Telescope, Parkes Radio Telescope and Culgoora Circular Array"
- Ron Stewart (Australia) "Contribution of the Division of Radiophysics Penrith and Dapto Field Stations to International Solar Radio Astronomy"
- Edward Waluska (USA) "Quasi-Stellar Objects, the Owens Valley Radio Telescope, and the Changing Nature of the Caltech-Carnegie Nexus"
- Harry Wendt (Australia) "Contribution of the Division of Radiophysics Potts Hill and Murraybank Field Stations to International Radio Astronomy"

Wayne Orchiston, Bruce Slee, Richard Strom and Richard Wielebinski are supervising these research projects; for this purpose, Slee, Strom and Wielebinski have all been appointed Adjunct Professors by James Cook University.

We are pleased to report that in 2008 Harry Wendt became the first of these students to complete his thesis, and in March 2009 was awarded a Ph.D. Edward Waluska also completed the first draft of his thesis in 2008 but sadly he died after a long battle with cancer before completing the necessary revisions. Wayne Orchiston and Richard Strom are looking at the possibility of making these revisions and submitting the thesis so that a posthumous Ph.D. can be awarded. In August 2009 Ron Stewart completed his thesis, and it is currently with the examiners.

In addition to the foregoing doctoral program, Alastair Gunn (Jodrell Bank) and Wayne Orchiston supervised the following Masters research project:

- Andrew Quinn (UK) "The 218-ft Jodrell Bank Transit Telescope and its Contribution to Radio Astronomy"

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Ken Kellermann, Chair (USA)
Wayne Orchiston, Vice-Chair (Australia)
Rod Davies (United Kingdom)
James Lequeux (France)
Norio Kaifu (Japan)
Yuri Ilyasov (Russia)
Govind Swarup (India)
Hugo Van Woerden (The Netherlands)
Jasper Wall (Canada)
Richard Wielebinski (Germany)

10 November 2009

Journal of Astronomical History and Heritage, 12(3), 254 (2009).

IAU TRANSITS OF VENUS WORKING GROUP. TRIENNIAL REPORT (2006-2009)

1 INTRODUCTION

The previous Transits of Venus Working Group report #5, covering the time mid-2003 to mid-2006, was published by Steven J. Dick in the *Journal of Astronomical History and Heritage*, Volume 9, page 205 (2006), where the preceding reports are also listed. The present report #6, covers the time up to mid-2009, and was prepared for a presentation at the August 2009 IAU General Assembly in Rio de Janeiro.

In 2008, Steve Dick handed over the Chair of the Working Group to the undersigned. As may be expected, activities between the transits of 2004 and 2012 are presently at a low level, and no significant events connected with the 2012 transit are presently known.

2 PUBLICATIONS IN THE PAST TRIENNIUM

A list of publications that have appeared since 2006, with some additional earlier references, is given in Section 4. A web bibliography (with links to original publications) is kept more or less up-to-date by R. van Gent (see Section 3), and another one, covering modern books and pamphlets up to the time of the 2004 transit, was published by Duerbeck (2004).

3 WEB LINKS

Web sites dedicated to historical Venus transits are:

Robert van Gent's *Transit of Venus Bibliography*:
http://www.phys.uu.nl/~vgent/venus/venustransitbib.htm
(see Section 2).

Steven van Roode's *Historical Observations of the Transit of Venus* (with reports, photos and engravings, coordinates, maps of sites of the seventeenth to nineteenth century observers, as well as photos of commemorative plaques:
http://www.transitofvenus.nl/history.html

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Any relevant information on past or future activities is gratefully acknowledged (mail to:
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Hilmar W. Duerbeck (Chairman)

Journal of Astronomical History and Heritage, 12(3), 255-256 (2009).

BOOK REVIEWS

Nebel und Sternhaufen – Geschichte ihrer Entdeckung, Beobachtung und Katalogisierung, by Wolfgang Steinicke (Books on Demand GmbH, Norderstedt 2009), pp. 676, 350 illustrations. ISBN 978-3-8370-8350-7 (hard cover), €59.90, 21.6 × 14.8 mm.

This is the text of a thesis submitted to Hamburg University by the historian of astronomy and deep-sky observer Wolfgang Steinicke. He is well known for his web page on the NGC/IC catalogues, and the present book *Nebulae and Clusters - the History of Their Discovery*, *Observation*, *and Cataloguing* presents his in-depth research on the genesis of John Louis Emil Dreyer's *New General Catalogue* and its supplemental *Index Catalogues*.

While there are many books dealing with Messier's catalogue—K. Glyn Jones' book *Messier's Nebulae and Clusters* (1991) is especially relevant for historically-minded readers—there is nothing equivalent for the NGC and its IC supplements, yet they contain >100 times more objects and are the concerted effort of many astronomers. Dreyer compiled his catalogue from many sources, without giving precise references. Steinicke's immense task was to reconstruct the genesis of the NGC, and he presents the various discoverers through short biographies, describes their instruments, and determines their success rate (i.e. the number of verified nebulae that were announced by a given observer for the first time). Only for 34 objects was the author unable to uncover the history of discovery, due to the fact that Dreyer also used private communications, and most of his correspondence has not been recovered.

The reading of this book brings forth a panorama of professional and amateur astronomical activities in the second half of the nineteenth century. Many excerpts from research papers, letters and observing books are quoted. Besides the Herschels, the activities of Lord Rosse and his collaborators, Wilhelm Tempel, Edward Swift and Edward E. Barnard, are extensively described, but not a single contributor—even when his success rate was extremely modest—was neglected. The final 100 pages deal with special aspects of nebular observations, the relation between drawings and photography, the discovery of spiral pattern, and the controversy about the existence of the nebulae surrounding the Pleiades.

The small print text allowed Steinicke to include an enormous amount of information—about five times that of a normal book. The author has provided an indispensable work on the genesis of one of the most important celestial catalogues, and it can be recommended to any serious deep-sky observer and historian of astronomy. An English edition of this book will be published by Cambridge University Press in the near future.

Another product of Steinicke's analysis, the creation of an historical NGC, with a catalog of its objects and documentation of their often complex history of discovery will be provided on the web at the following site: http://www.ngcicdetectives.org/

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Eastern Astrolabes, Historic Scientific Instruments of the Adler Planetarium & Astronomy Museum. Volume II, by David Pingree (Chicago, Adler Planetarium & Astronomy Museum, 2009), pp. xxii+268, ISBN 1-891220-02-0, US$75:00, 285 × 224 mm.

This is the second volume of the *Historic Scientific Instruments of the Adler Planetarium & Astronomy Museum* (see Figure 1); the first volume, by R. Webster (2007), was about their *Western Astrolabes*.

The astrolabe is a very important astronomical instrument of the Medieval Period, and there are several good books about it, including Morrison's *The Astrolabe* (2007), which I reviewed earlier in the year in this Journal (see Volume 12, page 85).

The author of *Eastern Astrolabes* …, David Pingree (1933–2005), is a former Professor from Brown University, and was a very prominent figure in the study of ancient astronomy, and particularly Indian astronomy (see Burnett et al., 2004). His bibliographical study (Pingree, 1970-) of Sanskrit works on astronomy and mathematics is highly appreciated, even though his interpretation of Indian astronomy was sometimes controversial (e.g. see Ohashi, 2002; van der Waerden, 1980).

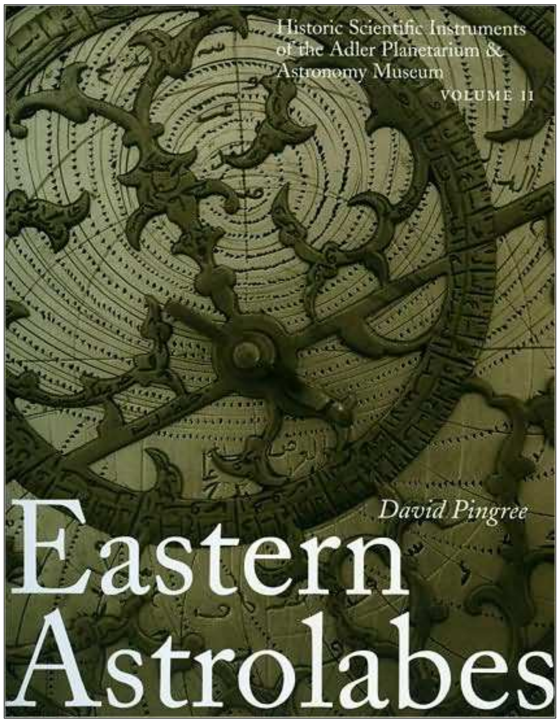

Figure 1: The front cover of Eastern Astrolabes.

The present volume is an annotated catalogue of the Eastern astrolabes in the Adler Planetarium & Astronomy Museum in Chicago, and it contains several clear pictures and a detailed commentary. The main part of this book consists of the following catalogues:
(a) Maghribi [an Arabic word meaning 'western' which roughly corresponds to the Islamic World in Spain (formerly) and western North Africa] Astrolabes.
(b) Mashriqi [an Arabic word meaning 'eastern' which roughly corresponds to the Islamic World in the Middle East, West Asia and South Asia] Astrolabes.
(c) Sanskrit Astrolabes.
(d) Other [Astronomical] Instruments.

Besides images of the front and back, each component of the astrolabes is shown in high-resolution pictures. The photographs are so clear that inscriptions in Arabic, Sanskrit, etc., can easily be read. The English commentary is detailed, and star-names, city-names, etc., which are inscribed on the astrolabes, are well identified. In additional, a thorough list of references is given for several instruments, which will be useful for future researchers.

As this volume is intended to be an annotated catalogue of the astrolabes, the general theory of the astrolabe is not explained here. So readers who are not familiar with the

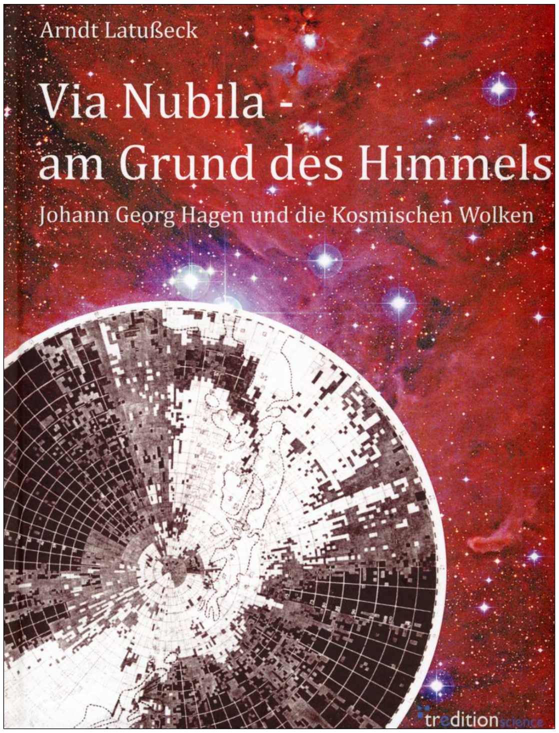

Figure 2: Front cover of Latußeck's book.

astrolabe are advised to read a theoretical book, such as Morrison (2007), first, and then study the actual examples included in *Eastern Astrolabes*. For those readers who can read Arabic or Sanskrit, this volume is a veritable 'goldmine' for their own detailed investigations.

Although the title of this volume is the *Eastern Astrolabes*, several other astronomical instruments, such as quadrants, qibla [direction of the sacred Kaaba in Mecca] indicators, sundials and celestial globes are also described. They will also interest researchers of classical astronomical instruments.

The admirable printing technology of this volume enables us to study the construction of the astrolabes in detail, even if we cannot access the actual instruments. According to the Introduction in this volume, some researchers are preparing catalogues of the astrolabes in other areas, so we can expect that the study of the astrolabe will be developed further.

This is a masterpiece from a 'giant' researcher of the twentieth century. Now, Pingree's disciples are also quite active in the field of the history of mathematics in India (see Hayashi et al., 1997; Plofker, 2009).

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***Via Nubila - am Grunde des Himmels. Johann Georg Hagen und die Kosmischen Wolken,* by Arndt Latußeck (tredition GmbH, Hamburg 2009), pp. 577, 84 illustrations (some in colour). ISBN 978-3-86850-472-9 (hardcover), €59.00, 22.7 x 17.2 mm.**

This is the text of a thesis submitted by the historian of astronomy and deep-sky observer Arndt Latußeck to Hamburg University. The author will be known to readers of this journal through his related publication "William Herschel's fifty-two fields of extensive diffused nebulosity" (*JAH*^{2}, 11, 235, 2008). The cosmic clouds are one of the most elusive observational phenomena in the sky. Their discoverer, Austrian-born Jesuit astronomer Johann Georg Hagen (1847–1930), started in 1910 a visual study of all nebulae listed in Dreyer's NGC, which resulted in a *Preparatory Catalogue for a Durchmusterung of Nebulae*. As a by-product of these observations, he often preceived a background of faintly luminous 'cosmic clouds', which seemed to occur more frequently towards the galactic poles. He often encountered harsh criticism, because these clouds could not be registered on photographic plates, and seen only by a few astronomers. Hagen noted that William Herschel had seen some of these areas "… affected with milky luminosity …", and Barnard had been able to photograph dark clouds in and near the Milky Way.

The book *Via Nubila - At the Bottom of the Sky. Johann Georg Hagen and the Cosmic Clouds* (see Figure 2) describes Hagen's life and character, and the history of the discovery of and research into 'Hagen's clouds' up to the present. While Hagen sought support in England (without success), the US (with some success) and continental Europe (with some resonance, especially in German-speaking countries), the case was not settled at the time of his death. It was Friedrich Becker who carried out the final observations and published Hagen's *Rassegna delle Nebulose Oscure*. Dorothea Klumpke, the widow of the English astrophotographer, Isaac Roberts, published photographs of Herschel's fields, and offered rewards to those who would conduct research on cosmic clouds. The French amateur, Marcel de Kerolyr, tried to prove their existence by photographic material, and the Vienna Observatory Director Kasimir Graff observed such clouds visually in the Ori-Tau region. However, in the early 1950s, Becker in collaboration with Joseph Meurers, was able to prove on the basis of artificial star fields that most of Hagen's findings were due to contrast phenomena in star-rich and star-poor regions. Nevertheless, in some cases there were also correlations with galactic cirrus, and the case is not completely settled.

The author has thoroughly researched the existing material, not only published sources, but also extensive archival material, observing books and correspondence, kept at the Vatican Observatory, at the estate of Friedrich Becker, and other institutions. The present book constitutes an exhaustive study of one of the most controversial observing phenomena in twentieth century astronomy. It is an admirably complete case study and makes fascinating reading—unfortunately only for those who are still familiar with what was the 'lingua franca of science' in the early twentieth century.

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Journal of Astronomical History and Heritage, 12(3), 257-258 (2009).

JOURNAL OF ASTRONOMICAL HISTORY AND HERITAGE
ISSN 1440-2807

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