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COVER PHOTOGRAPH

Frank Loud (1852–1927), seen here in an oil painting by J.I. McClymont, pursued astronomy in Colorado Springs, Colorado from 1877 until his retirement in 1907. His contributions to the growth of astronomy on the American frontier are described in Steve Ruskin's article on pages 115–124.

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A HISTORY OF RADIO ASTRONOMY POLARISATION MEASUREMENTS

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Abstract: While intensity of electromagnetic radiation (radio, infrared, light, or X-ray) gives us primary information about the distribution of the baryonic matter in the Universe, polarisation is a parameter that enables us to investigate many additional details. Polarisation at radio frequencies gives us details of emission processes since the non-thermal synchrotron process dominates at low radio frequencies in emission regions. In addition, polarised radio sources can be used as probes of the intervening interstellar medium through which the radio waves are propagated. Faraday rotation effects are observed and in conjunction with known thermal emission can be used to determine magnetic fields. The Zeeman effect, a direct method of determining magnetic fields, depends on the observation of the circular polarisation components of a spectral line. In this paper I describe the early polarisation observations of radio sources, but in addition I follow the developments through to the present day.

Keywords: radio astronomy, polarisation

1 INTRODUCTION

The beginnings of radio polarisation studies date back to the publications of James Clerk Maxwell (1831–1879) who in his famous equations had to account for the polarisation of electromagnetic waves. Subsequent work by Heinrich Hertz (1857–1894) showed that polarisation is a basic consideration in the transmission of electromagnetic waves from a transmitter to a receiver. The 'Hertzian Dipole' is still a basic radiating antenna element used in antenna theory. Hertz showed that dipoles had to be aligned to receive transmitted radio waves while 90° misalignment led to no detectable signal. Later, radio engineers were at the forefront in defining polarisation: the Institute of Radio Engineers in 1942, followed by the Institute of Electrical and Electronic Engineers in 1969. Only in 1973 did the International Astronomical Union publish its definitions.

The early observations of radio emission by Jansky (1905–1950) and Reber (1911–2002) at first eluded interpretation. Whipple and Greenstein (1937: 181) discussed the "… interstellar radio disturbances …" and concluded that there was "… failure of black-body radiation to account for Jansky's observations quantitatively." Henyey and Keenan (1940) gave an account of the intensities expected from (radio) free-free emission of hydrogen and argued that they did agree with the quoted intensity values of the Reber (1940) observations, possibly within a factor of two. Here it must be noted that the methods of intensity calculations were problematical at that time, with engineers discussing with physicists and astronomers how intensity was to be defined. Reber (1944) followed up his earlier publication with the first radio map of our Galaxy. Writing also in 1944, Unsöld (1946) argued that Reber's intensity values could be explained by thermal emission if the interstellar gas had a temperature of 100,000K.

Radio observations of the Sun made as early as 1939 but published only after 1945 (e.g. Hey, 1946; Reber, 1946; Schott, 1947), usually at metre wavelengths, implied effective temperatures of around millions of degrees. The intensities were lower at higher frequencies, which again suggested the failure of the thermal interpretation. The solar community was the first to search for an alternative interpretation. Kiepenheuer (1946) discussed the emission of electrons in a magnetic field as a source of solar radio waves. This discussion was continued by Unsöld (1947) who agreed that in addition to thermal radio waves from the Sun 'Ultra-strahlung' must be present during eruptions. A review of the possible interpretation of cosmic radio waves was given by Reber and Greenstein (1947), who hinted at a non-thermal spectrum for solar emission. In a much-forgotten paper Moxon (1946) actually presented results of observations of our Galaxy at three frequencies, clearly deriving a non-thermal spectrum. Elder et al. (1948) and Schwinger (1949) studied the emission in synchrotron generators, and they coined the term 'synchrotron radiation', which was produced by energetic electrons in magnetic fields. This radiation, as observed when the accelerated electrons entered the Earth's magnetic field, was polarised.

The earliest reports about the polarisation of radio emission came from observers studying the Sun (e.g. Martyn, 1946; Little and Payne-Scott, 1951; Payne-Scott and Little, 1951), negating the thermal free-free process. The next step in interpretation was taken by Alfvén and Herlofson (1950), who suggested that electrons in magnetic fields generated the radio emission exhibited by the newly-discovered 'radio stars'. Kiepenheuer (1950) extended this interpretation, pointing out that this emission process may also apply to the radio emission from our Galaxy. Finally Shklovsky (1953: 983) proposed "… that emission of the Crab Nebula at radio and optical bands is synchrotron radiation of relativistic electrons in the magnetic field." In the USSR, Dombrovskii (1954) made optical observations of the Crab Nebula and showed that the light was linearly polarised, concluding that it was synchrotron emission, as suggested by Shklovsky. This great idea changed the whole thinking about the origin of cosmic radio waves.

Linear polarisation of synchrotron emission in a uniform magnetic field (e.g. Westfold, 1959; see Figure 1) is seen normal to the magnetic field orienttation and can be as much as 75% of the total intensity. In addition, a small (relative to the linear polarisation) circular polarisation component is expected (e.g. Legg and Westfold, 1968). An extensive review of the synchrotron emission process was published by Ginzburg and Syrovatsky in 1965.

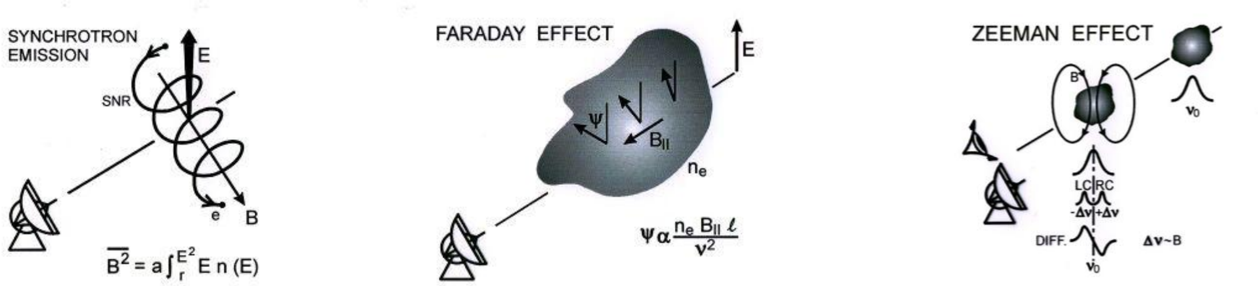

Figure 1: The basic effects of importance in radio astronomy polarisation studies. Left: Synchrotron emission; centre: Faraday rotation; and right: the Zeeman effect (after Wielebinski and Klein, 2010).

The search for radio polarisation concentrated on the Crab Nebula (also known as Taurus-A). The detection was preceded by numerous negative reports, albeit at long wavelengths, until success was finally achieved at short radio wavelengths. The depolarisation of the radio waves was expected to be strongest at low radio frequencies due to the Faraday effect in thermal regions. The detection of radio polarisation of the Crab Nebula was made at 3.15cm (Mayer et al., 1957), confirming depolarisation at longer wavelength. In a way, the Crab Nebula can be considered the 'Rosetta Stone' of radio astronomy as it allowed progress in our understanding of cosmic radio emission.

The detection of polarised radio waves from Jupiter followed (see Radhakrishnan and Roberts, 1960). In 1962 detections of diffuse radio polarisation in our Galaxy were made (Wielebinski et al., 1962; Westerhout et al., 1962), and ionospheric Faraday rotation of the detected linear polarisation was observed by Wielebinski and Shakeshaft (1962). Also, the radio galaxies Cygnus-A (Mayer et al., 1962a) and Centaurus-A (Bracewell et al., 1962) were observed to be polarised, confirming the synchrotron emission interpretation. These detections laid a foundation for the study of cosmic magnetic fields in radio sources. Linearly-polarised radio emission gives us information about the magnetic fields normal to the line of sight. Faraday rotation (see Figure 1) that is detectable, for example, in Centaurus-A (Cooper and Price, 1962) and in our Galaxy (Muller et al., 1963) occurs along the line of sight in thermal interstellar regions, adding another parameter to the study of magnetic fields. With these two pieces of information we can delineate the morphology of magnetic fields in three dimensions.

The Zeeman effect (see Figure 1) requires the observation of the difference between left and right circular polarisations that are produced in a magnetic field. The Zeeman effect at radio frequencies was predicted by Bolton and Wild (1957) to be observable in the HI line. The first reliable detection of the radio Zeeman effect was achieved by Verschuur (1968). Pulsars were discovered by Hewish et al. (1968) and immediately reports of their polarisation were made (see Lyne and Smith, 1968). In fact, the polarisation of pulsar signals was an important step in their interpretation in terms of rotating neutron stars. Meanwhile, the detection of Faraday rotation in clusters of galaxies implied the presence of magnetic fields in intergalactic space.

The study of polarisation is highly instrumentally dependent. Hence progress takes place in steps, in response to new technical possibilities. The development of new technologies, like digital polarimeters, and new analysis software, like rotation measure synthesis, led to new conclusions.

Synchrotron emission, which is polarised, is generated by relativistic electrons in magnetic fields. The *E*-vector is seen normal to the magnetic field orienttation. Maximal linear polarisation in a homogeneous magnetic field is 75%, but in practice only a much lower polarisation percentage is usually observed.

The Faraday effect rotates the *E*-vector in a thermal medium in a parallel magnetic field. The Rotation Measure (*RM*) is a parameter derived from multi-frequency polarisation observations:

$$RM = \psi \lambda^{-2} \quad \text{radians metre}^{-2} \qquad (1)$$

where ψ is the angle of Faraday rotation and λ is the wavelength.

The Zeeman effect is the splitting of a line by a magnetic field into two circularly-polarised components. The difference between left and right circular polarisation gives the magnitude of the magnetic field for a particular spectral line.

The Zeeman effect allows the determination of magnetic field intensity directly since each line species (HI; OH; H_2O) has its own typical difference between left and right circular polarisations (e.g. see Heiles and Crutcher, 2005). On the other hand, determination of the magnetic field intensity from radio continuum data is indirect. One important method is to assume equipartition between magnetic fields and cosmic rays (e.g. Beck and Krause, 2005). The observed Faraday rotation also can be used when the path length and electron density are known. With pulsar observations this technique is of particular importance since both the Rotation Measure and Dispersion Measure are determined—this is again a direct method of determining the magnetic field strength (e.g. see Lyne and Smith, 1969).

2 TECHNIQUES OF RADIO POLARISATION OBSERVATIONS

Radio polarisation observations were a driver for instrumental developments. For solar observations at metre wavelengths crossed dipole antennas were usually used (e.g. Little and Payne-Scott, 1951; Payne-Scott and Little, 1951). The next simplest observation mode is to place a linearly-polarised feed at the focus of a single parabolic dish radio telescope. The feed can be rotated or else the feed may remain fixed in the telescope and the Earth's rotation can be used. These methods were pioneered for example by Mayer et al. (1957) who used the 50-foot Naval Research Laboratory (NRL) dish. Instrumental effects were dominant and many improvements were necessary to make reliable radio polarisation measurements. A simple dipole-reflector feed in a parabolic reflector has an elliptical beam pattern (different beams in the *E* and *H* planes) and hence instrumental signals can look like real linear polarisation. In particular, the effects of ground radiation must be carefully calibrated.

The next step in the evolution of the polarimeter was to place two orthogonal dipoles as feeds of a parabolic radio telescope. By switching between the orthogonal dipoles and rotating the whole system more reliable polarisation values could be obtained. At higher frequencies waveguide feeds are used, but crossed dipoles are invariably needed to couple out the orthogonal polarisations. In such circular waveguide feeds an additional metal collar-like structure can be added to adjust the antenna feed (amplitude and phase distributions) for minimum instrumental polarisation. The collar-like structure was developed in Cambridge by Wielebinski (1963) resulting in successful polarisation detection. Considerable progress to obtain polarisation purity was attained by using corrugated multi-mode wave-guide structures (e.g. Minnett and Thomas, 1968). Such structures allow the superposition of several waveguide modes and hence give a designed phase-amplitude distribution that could be optimised for the best polarisation performance. Antennas pick up ground radiation that appears as if it was a polarised source. By tipping the antenna a correction for ground radiation is possible. Ferrite rotators have also been used instead of feed rotation at microwave wavelengths.

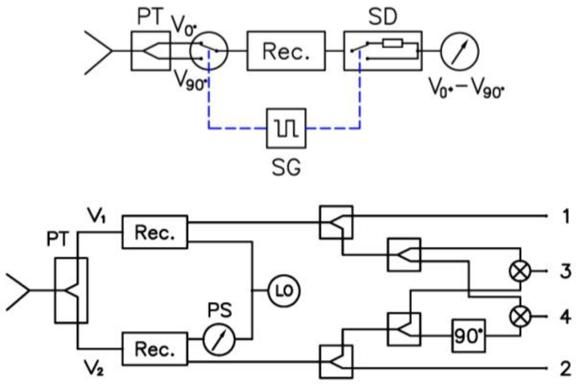

Figure 2 (upper): Block diagram of an analogue switching polarimeter. PT = polarisation transducer; Rec = receiver; SG = square wave generator; SD = synchronous detector.

Figure 2 (lower): Block diagram of an analogue correlating polarimeter. PT = polarisation transducer; Rec = receiver; LO = local oscillator; PS = phase switch; 90° phase shift; outputs 1 and 2 = total power; outputs 3 and 4 = linear polarisation of circular outputs at transducer (after Wielebinski and Klein, 2010).

Some indirect methods of polarisation measurement were also developed: for example taking the difference between a narrow bandwidth and a broad one, as the result of the Faraday effect, polarisation could be indicated (see Razin, 1956; 1958). However, this method cannot give exact information about the polarisation intensity or the polarisation angle. In the early days of radio astronomy, when low noise amplifiers were scarce, switching between the orthogonal dipoles was employed (e.g. Wielebinski, 1963; see Figure 2 upper diagram) with the receiving system being rotated in 45° steps. The use of two amplifier chains and a correlating polarimeter (e.g. Westerhout et al., 1962; see Figure 2 lower diagram) was the ultimate practice in later years.

Polarisation can be described in terms of the Stokes parameters (*I*, *Q*, *U*, *V*), where *I* is the total intensity, *Q* and *U* are the linear polarisation parameters and *V* is the circular polarisation parameter (see e.g. Tinbergen, 2005), and

$$I^2 \geq Q^2 + U^2 + V^2 \qquad (2)$$

The correlating polarimeter would analyse the incoming two channels and give the Stokes parameters (*I*, *Q*, *U*) if the inputs were from a circularly-polarised feed. If the two inputs were linearly polarised (which was simpler to manufacture) the outputs were (*I*, *Q*, *V*).

Analogue polarimeters have been constructed with bandwidths of up to 2 GHz, limited by the 90° phase-shifter characteristics (see Wielebinski et al., 2002). Also multi-channel analogue polarimeters are in use. The design of the feeds, polarisation transducer (following the feed) and the 90° phase shift in the receiver chain are crucial for successful polarisation observations.

Interferometers were used for polarisation observations from the early years of radio astronomy. Descriptions of the method of polarisation observations with interferometers can be found in Little and Payne-Scott (1951), Hanbury Brown et al. (1955), Morris et al. (1964a) and Conway and Kronberg (1969). A source would be observed with a sequence of feed dipoles in parallel and with the dipoles crossed. Rotation in steps of 45° would also be employed. There are some advantages to be had in reduction of the instrumental polarisation effects with an interferometer, but it requires good calibration. However, it must be noted that with interferometers source structure plays an important role: some spatial frequencies are lost due to the discrete antenna spacing, and they are more difficult to retrieve in polarisation than in total intensity. On the other hand, when observing compact sources the loss of the general background polarisation can be of advantage.

Aperture synthesis arrays have been adapted to map polarised radiation in extended sources (e.g. see Ryle et al., 1965; Weiler and Seielstad, 1971; Kronberg, 1972; Hargrave and Ryle, 1974) and in very long baseline interferometry (e.g. Cotton et al., 1984). Most recently, the advent of fast digital chips, in particular the FPGA chips, have allowed the construction of wide-band digital polarimeters.

A more detailed discussion of the techniques of polarisation measurement can be found in Tinbergen (2005) and in Wielebinski and Klein (2010).

3 EARLY RADIO POLARISATION OBSERVATIONS

Solar radio waves were detected as early as 1939 but publication came only later (e.g. Hey, 1946; Reber, 1944; Schott, 1947; Southworth, 1945) and indicated that in addition to the thermal quiet Sun a non-thermal component was present during solar eruptions. Radio polarisation of this solar emission was detected (e.g. Martyn, 1946; Little and Payne-Scott, 1951; Payne-Scott and Little, 1951) leading to the development of radio polarimeters (e.g. Hatanaka et al., 1955) for observations first at metre wavelengths and later at microwave frequencies (Akabane, 1958). In fact interferometers were used to study solar polarisation from the very beginning (see Cohen, 1958, and references therein). In this paper I will not describe the history of the polarisation observations of the Sun, as there are many details of the studies of the Sun that can be found in the literature (e.g. see Krüger, 1979; Kundu, 1982).

3.1 Radio Sources

In the early observations of 'radio stars' by Ryle and Smith (1948) it was noted that the emission had some similarities to solar radio radiation, and hence polarisation should be expected. Negative results of polarisation observations were first reported by Hanbury Brown et al. (1955) at metre wavelengths using a two-antenna interferometer at Jodrell Bank. At Cambridge, the long parabolic cylindrical reflectors and corner reflectors that were developed for the successful detection of radio sources were unsuitable for polarisation observations. Observations at 21cm by Westerhout (1956) using the 7.5-m 'Würzburg' dish failed to detect polarisation from selected radio sources. The next directed attempts to detect radio polarisation concentrated on the Crab Nebula. The break-through was made by Mayer et al. (1957), who used the 50-foot NRL dish at 3.15 cm to detect polarisation in the Crab Nebula, a supernova remnant (SNR). There was a steady evolution of the polarisation receivers for this historical single dish that became a leader in this field of research. Almost at the same time Kuz'min and Udal'tsov (1957) confirmed the Crab Nebula polarisation observations at 10cm. In this case a ferrite rotator was employed with a 31-m 'hole in the ground' dish. Both of these observations indicated that Faraday rotation was indeed depolarising the longer wavelength observations.

Radio emission from Jupiter was first detected by Burke and Franklin (1955) at 22.2 MHz. The emission was time variable and showed considerable circular polarisation (Franklin and Burke, 1956). This radio emission has since been interpreted to be a result of the cyclotron emission process. Later Sloanaker (1959) detected radio emission from Jupiter at 10cm. This emission was found to be linearly polarised by Radhakrishnan and Roberts (1960) at 960 MHz (λ31cm), suggesting that it was due to a non-thermal process. The polarised emission of Jupiter originated in outer regions of the planet's atmosphere, similar to the Earth's van Allen Belt, where rather strong magnetic fields are present. Two 90-foot antennas connected as an interferometer at the Owens Valley Radio Observatory (OVRO) of the California Institute of Technology were used for these observations. John Bolton, who was involved in the construction of the OVRO dishes, insisted on providing polarisation capabilities from the very beginning (see Roberts, 1994). This interferometer, with receiver instrumentation at various frequencies, specialised in polarisation observations of radio sources in the following years.

3.1.1 Extragalactic Radio Sources

Observations of polarisation from extragalactic radio sources (EGRS), at first called 'radio stars', proved to be more difficult. Earliest observations, admittedly at metre wavelengths, showed no polarisation. Observations by Hanbury Brown et al. (1955) made at 1.9m did not detect polarisation in Cygnus-A. These results can be understood today from the fact that Cygnus-A has a small-scale structure of polarisation vectors in the radio lobes and thus one needs good angular resolution to overcome the Faraday depolarisation effects. Finally, the 50-foot reflector at the NRL succeeded in detecting low linear polarisation in Cygnus-A at 3.15cm (Mayer et al., 1962a), but only the average polarisation from the whole source. The next major step in the measurement of radio galaxies came from the then newly-completed 64-m Parkes Radio Telescope: the first observations of Centaurus-A by Bracewell et al. (1962) at 11cm immediately detected polarisation. An advantage of the Parkes dish was the good angular resolution (at that time), coupled with the fact that Centaurus-A is a very large source (see Bracewell, 2002). Almost simultaneously, Mayer et al. (1962b) and Radhakrishnan et al. (1962) reported the detection of polarisation in Centaurus-A. The Parkes dish was subsequently used by Gardner and Whiteoak (1962) at 20cm to observe polarised emission in a number of extragalactic radio sources. It is debatable who was first to make a detection, but one thing is clear: John Bolton, who was back at Parkes from Caltech, pushed polarimetry to be an integral part of the capability of what was then the best single-dish radio telescope in the world. This work paved the way for a whole new field of research.

Faraday rotation (see Figure 1) was found in Centaurus-A by Cooper and Price (1962), by observing at several frequencies between 970 MHz and 3 GHz, thus adding another parameter for the study of magnetic fields. Since Centaurus-A is a source many degrees across, its *RM* could be determined for several regions. Faraday rotation takes place in a thermal medium with a magnetic field along the line of sight. This direction of investigation was followed up by Gardner and Whiteoak (1963) for a number of EGRS seen in different directions in the Galaxy. Sources near the Galactic Plane showed much higher values of *RM* (see Davies and Gardner, 1966) suggesting that polarised EGRS could be used as probes of the magnetic fields in our Galaxy. More recently, the origin of Faraday rotation has been discussed (see Farnsworth et al., 2011; Pshirkov et al., 2011), and although there are some questions of detail the general opinion remains that *RM* can be used to derive the structure of galactic magnetic fields.

The Caltech group continued to make polarisation observations using the OVRO Two-element Interferometer at different wavelengths: 21.2cm (Seielstad and Wilson, 1963), 10.6cm (Seielstad et al., 1963)

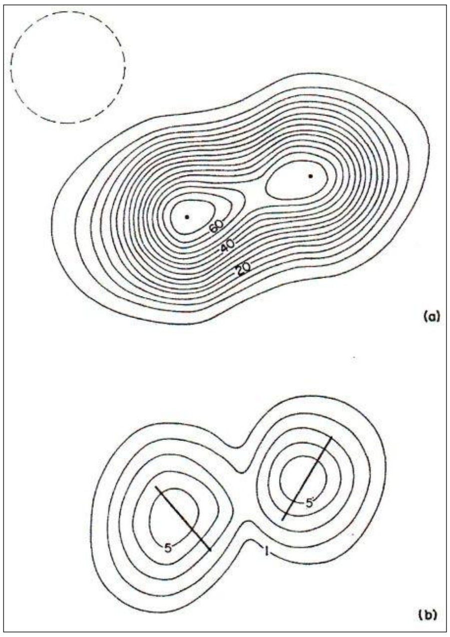

Figure 3: Early polarisation map of Cygnus-A at 1.55cm. Above: total intensity 1 unit = 0.18 K; below: polarised intensity 1 unit = 0.36 K, with the average polarisation *E*-vector (after Mayer and Hollinger, 1968).

and at 18cm (Morris et al., 1964c). With different interferometer spacings, Morris et al. (1964b) began to study the distribution of linear polarisation over the usually double sources. The realisation that the orientation of the linear polarisation vectors may be different in the two lobes was the major finding of this paper. It became clear that there is considerable structure in the EGRS with different orientations of polarisation vectors leading to depolarisation in single dish observations. A concise report on the methods used at Caltech is found in Morris et al. (1964a) and in references therein. It must be noted that the use of an interferometer (at Caltech) gave more accurate values of source polarisation since the overall diffuse polarisation was rejected, especially at the lowest frequencies. Observing at Parkes, Gardner and Davies (1966) produced a catalogue of polarisation of sources at wavelengths between 11.3 and 74cm. This catalogue was used by Davies and Gardner (1966) to confirm the earlier suggestion that the observed Faraday rotation did in fact originate in the magnetic fields and thermal regions of our Galaxy. Observations of linear polarisation were extended to 3.12cm by Berge and Seielstad (1969) using the OVRO Interferometer.

Another group that advanced the study of the polarisation of EGRS was at the Jodrell Bank Observatory (Kronberg and Conway, 1967), where a combination of the Mark I (250-foot) and Mark II (125-foot × 83-foot) radio telescopes made it the most powerful interferometer for studies of weak sources. This instrument was subsequently used by Conway and Kronberg (1969) to measure the distribution of polarisation in radio sources. A catalogue of the polarisation of EGRS at 610 MHz (Kronberg and Conway, 1970) followed. Further multi-frequency source polarisation observations were presented in Conway et al. (1972).

The National Radio Astronomy Observatory (henceforth NRAO) in Green Bank became involved in polarisation observations upon the completion of the 140-ft Radio Telescope. Discrete EGRS were observed by Sastry et al. (1967) at 6cm. Using the 140-ft dish at 1.55cm Mayer and Hollinger (1968; see Figure 3) finally solved the mystery of the low polarisation of Cygnus-A: the two lobes showed different polarisation orientations, and hence beam depolarisation gave the previously-observed low values. In addition, there were considerable *RM* gradients (Dreher et al., 1987) that led to depolarisation at lower radio frequencies. At first the 140-ft dish was in the forefront of polarisation observations. Then the successful implementation of aperture synthesis by Ryle and Neville (1962) in Cambridge led to its application in mapping polarisation in extended radio sources. Ryle et al. (1965) then published an early map of Cygnus-A. The two-dimensional distribution of polarisation in two EGRS was presented by Kronberg (1972) using Jodrell Bank Interferometer data.

The presence of circular polarisation in EGRS was under discussion from the theoretical point of view (e.g. Legg and Westfold, 1968). As a result, numerous observational attempts were made, albeit unsuccessfully. It was clear that any circularly-polarised component was very low. The first claims of successful detections came from the Nançay Radio Telescope by Biraud and Veron (1968) and Biraud (1969), with surprisingly high values. These claims were questioned (e.g. see Seielstad, 1969) or much lower limits were set (Gilbert and Conway, 1970).

Ryle et al. (1975; 1976) put a lower limit on the circular polarisation of several radio sources. Successful very low levels of circular polarisation were finally re-

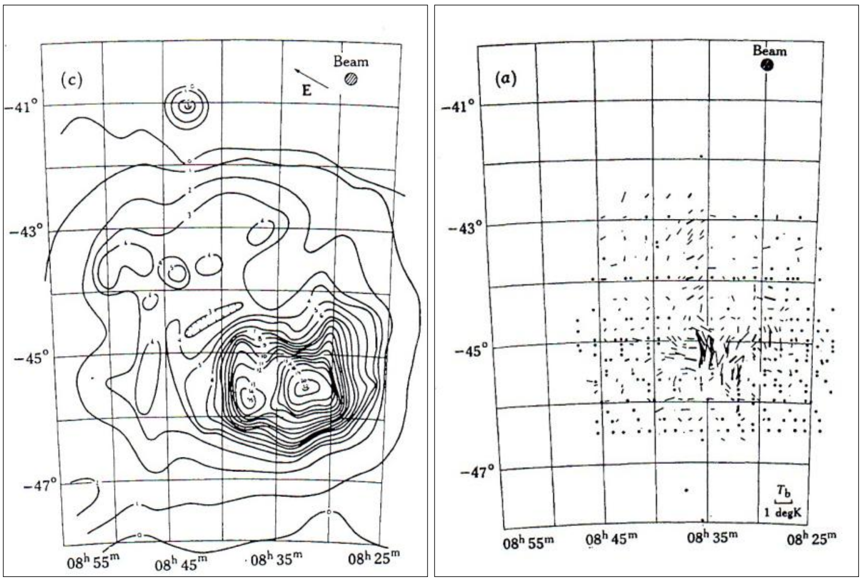

Figure 4: Early maps of the SNR Vela-X at 1410 MHz. Far left: total intensity; left: polarisation *E*-vectors (after Milne, 1968).

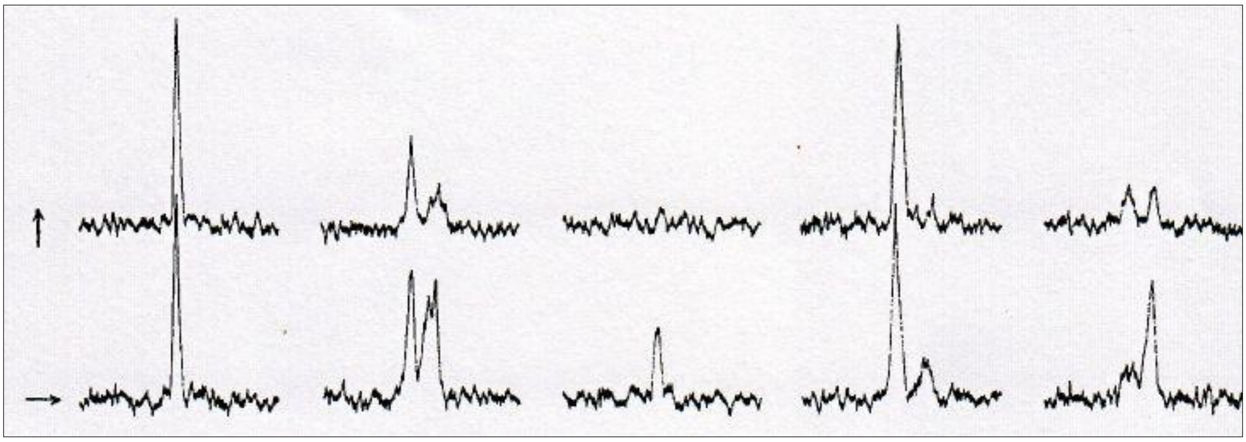

Figure 5: Polarisation of single pulses of PSR 0950+08 observed at 151 MHz with orthogonal dipoles as shown on the left (after Lyne and Smith, 1968).

ported by Conway et al. (1971), Roberts et al. (1975) and Weiler and Wilson (1977).

3.1.2 Supernova Remnants

As already discussed, the Crab Nebula, the prototype supernova remnant, was the first radio source to be detected in polarisation. It was clear from theoretical considerations that polarisation identified a SNR. However, since SNRs are less intensive than radio galaxies and the polarisation is usually a smaller fraction of the total intensity, their polarisation studies needed considerable instrumental development. In fact, at first a radio source was considered to be a SNR if found in the Galactic Plane and if it had a steep non-thermal spectrum. Using this method Milne (1970) identified 97 supernova remnants. Later flat-spectrum plerionic centre-filled sources were identified as supernova remnants, and here the presence of polarisation played a major role in their interpretation. The second SNR to be mapped in polarisation was Cassiopeia-A (Mayer and Hollinger, 1968). Cassiopeia-A (a young SNR) has a very well-developed shell structure but with a radial magnetic field. Older SNRs are invariably observed with a tangential magnetic field (e.g. Dickel and Milne, 1976). The Parkes Radio Telescope was used by Milne (1968; see Figure 4) to map the Vela-X SNR in polarisation at three frequencies. The first aperture synthesis observations of Cassiopeia-A were made by Ryle et al. (1965). Later Seielstad and Weiler (1968) published one-dimensional strip scans over four SNRs. The next development was the publication of synthesis maps by Weiler and Seielstad (1971) of two supernova remnants.

3.1.3 Pulsars

Pulsars were first discovered by Hewish et al. (1968), and have a high degree of polarisation, especially at low radio frequencies (e.g. Lyne and Smith, 1968; see Figure 5). At first linear polarisation was observed but later circular polarisation of pulsars was detected as well. Observations of polarisation by Radhakrishan and Cooke (1969) were crucial in establishing the rotating neutron star model for pulsars. Pulsars have in some ways an opposite evolution of polarisation when compared to radio sources: in radio sources polarisation usually increases at higher frequencies because of a reduced depolarisation by the Faraday effect. In pulsars there is a fall off in polarisation at higher radio frequencies (e.g. Manchester, 1971; Seiradakis and Wielebinski, 2004). This unusual feature of pulsars, attributed to the emission mechanism, is not yet well understood. The polarisation of pulsars is so stable that it can be used to calibrate the polarisation characteristics of a radio telescope (see Xilouris, 1991).

3.2 Polarisation of the Galactic Background (Foreground)

Radio astronomers began quite early to search for the radio polarisation of galactic emission. The first published report was by Razin (1956; 1958), who observed at 207 MHz (1.45m) and 91 MHz (3.3m) with low resolution antennas and claimed that he detected linear polarisation at these low radio frequencies. The observations were made by taking the difference between a narrow and broadband signal, and expecting the Faraday effect to depolarise the signal in the broadband channel. In view of later observations this detection claim must be questioned as other observers, working at similar radio frequencies, did not confirm this result. In Cambridge Thomson (1957), using a 160 MHz receiver, switched between orthogonal feed dipoles on a 7.5-m Würzburg dish. In Australia Pawsey and Harting (1960) also failed to detect any polarised signal at 215 MHz. Moving to higher frequencies (408 MHz), Pauliny-Toth et al. (1961) searched in the direction of the Galactic Spur at l = 30° but again failed to detect polarisation. The breakthrough came in 1961 with Wielebinski et al. (1962; Figure 6) working in Cambridge and Westerhout et al. (1962) in Dwingeloo

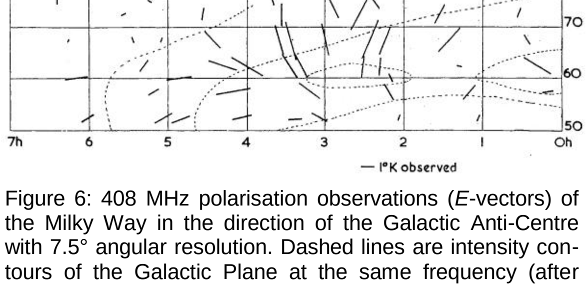

Figure 6: 408 MHz polarisation observations (E-vectors) of the Milky Way in the direction of the Galactic Anti-Centre with 7.5° angular resolution. Dashed lines are intensity contours of the Galactic Plane at the same frequency (after Wielebinski et al., 1962).

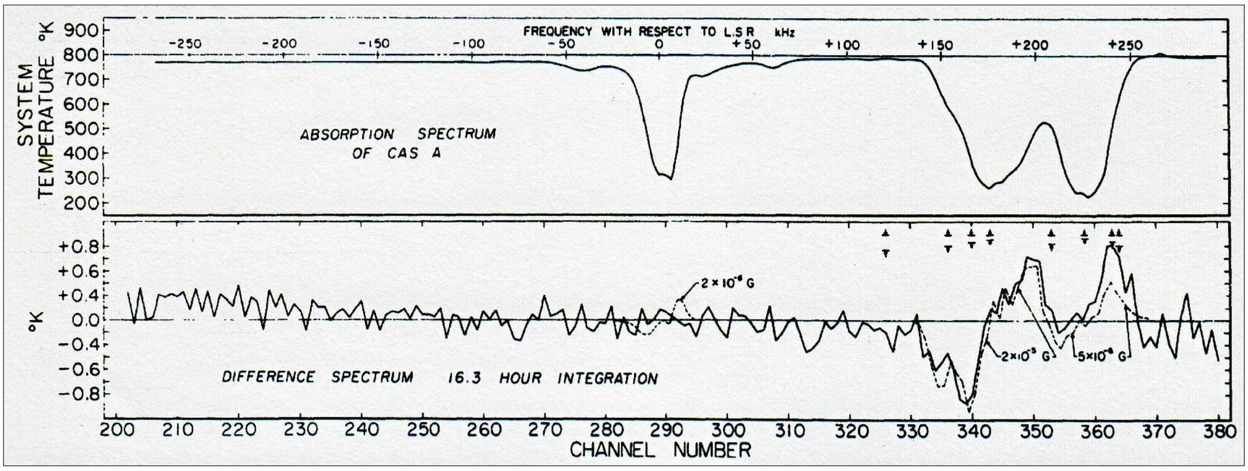

Figure 7: The first detection of the Zeeman effect by Verschuur (1968). The top trace shows the HI absorption spectrum in the direction of Cassiopeia A; the bottom trace shows the difference in left and right circular polarisations giving the typical S-like signature of a Zeeman effect detection.

making real detections at 408 MHz. Polarisation was found in many areas but in particular in the 'fan region' at l = 140°, b = 10°. The orientation of the observed polarisation vectors implied alignment of the magnetic field along the Galactic Plane. This result was in good agreement with the optical polarisation observations in this region. In addition, at l = 30° vertical vectors were observed suggesting that the North Polar Spur was a magnetic phenomenon. Both of these research groups were successful only after a considerable upgrade of the observing systems, with particular care given to reducing the instrumental polarisation. In Cambridge I made a new 'top hat' feed, put the receiving system on the rotating tube (which resulted in no more cable twists), and in the end I added a circulator to reduce the reflections between the Adler tube parametric amplifier and the antenna feed. In fact I was sure that I detected polarisation in 1961 but Martin Ryle insisted on additional proof of the reality of these observations. This was made by Wielebinski and Shakeshaft (1962) with ionospheric Faraday rotation studies that confirmed the reality of the galactic polarisation. Galactic Faraday rotation was detected by Muller et al. (1963) by observing the 'fan region' at 610 MHz.

A northern sky survey at 408 MHz by Wielebinski and Shakeshaft (1964) showed widespread linear polarisation. Southern sky polarisation observations were made with the Parkes Radio Telescope by Mathewson and Milne (1965) at 408 MHz and by Mathewson et al. (1967) at 620 and 408 MHz thus completing a data set for all-sky. After these initial detections the measurement of galactic polarisation became routine, especially at higher radio frequencies around 1420 MHz (e.g. Bingham, 1966). This development paved the way for the study of galactic magnetic fields.

A review of the state of our knowledge about the early polarisation results of observations of cosmic radio waves was given by Gardner and Whiteoak (1966).

3.3 The Zeeman Effect

The method par excellence for measuring magnetic fields is the Zeeman effect that depends on polarisation. A line is split by a magnetic field into two circularly-polarised components, in addition to the basic line frequency (see Figure 1c). The measurement of the frequency difference gives the magnetic field strength (e.g. Verschuur, 1968). The first detection of magnetic fields in sunspots used the Zeeman effect at optical wavelength (Hale, 1908).

In 1957 Bolton and Wild suggested that interstellar magnetic fields could be traced by observing the HI line and noting the existence of the Zeeman effect. In practice it was difficult to get a positive detection as the radio telescope had to provide a very clean circular polarisation in order to detect the Zeeman effect. After several unsuccessful attempts to measure the radio Zeeman effect (e.g. see Davies et al., 1963), the first detection was finally achieved by Verschuur (1968; Figure 7) using the NRAO 140-ft dish at Green Bank. At first all efforts were concentrated on the HI line. These observations showed that the magnetic field intensities in HI clouds were ~100 µGauss. These values were far greater than in the diffuse magnetic field in the spiral arms of our Galaxy where magnetic fields of only 3 to 10 µGauss had been deduced from radio continuum polarisation observations. Later Zeeman effect measurements in OH or H_2O molecular clouds showed even higher magnetic field strengths than in HI clouds. There are many problems in achieving the necessary polarisation purity for making successful Zeeman effect observations with radio telescopes. The differences in the opposite circular polarisations are minute and most feeds have a 'beam squint', a deadly effect for observers.

4 THE ERA OF NEW RADIO TELESCOPES WITH POLARISATION CAPABILITIES

The advent of new large radio telescopes that became operational in the 1970s (the Cambridge Ryle 5-km Radio Telescope, the Westerbork Synthesis Radio Telescope and the Effelsberg 100-m dish) opened up new possibilities to make high-class polarisation observations. These instruments allowed observations to be made with good angular resolution in the cm-wavelength range. The 100-m single dish was of particular value in many of the new polarisation observations since it was very sensitive to weak diffuse emissions. The aperture synthesis arrays were capable of high angular resolution observations and

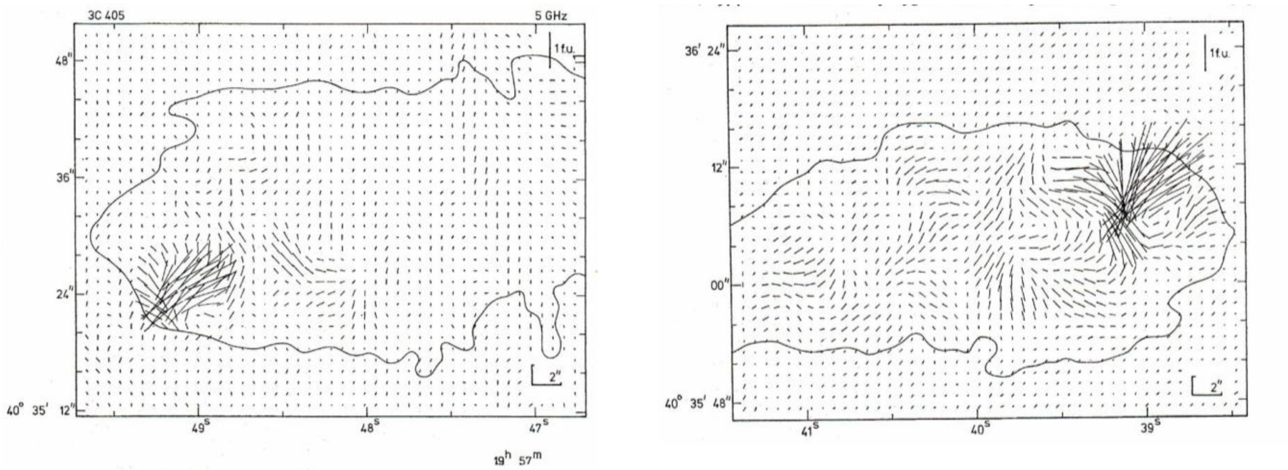

Figure 8: High resolution polarisation maps of the lobes of Cygnus-A observed at 5 GHz. The *E*-vectors are shown (after Hargrave and Ryle 1974; cf. Figure 3).

hence most suitable for compact source studies. Finally, a combination of both types of instruments gave the best data on extended objects.

The Very Large Array was inaugurated in 1980 and made a huge impact on our knowledge of the polarisation of radio sources. In particular the combination of VLA and large single dish data became of great importance in studying the polarisation of extended objects. The radio sources in the southern skies had to wait until the Australia Telescope Compact Array was completed in 1988 to see a similar dramatic development. These instruments dominate the research field up to the present day due to continued improvements, especially for polarisation measurements. In the following pages I will single out major contributions to a very rapidly-developing research field. It is not possible to make a detailed listing of all the polarisation observations made in the past 40 years. While in the 1960s the number of researchers involved in studies of radio polarisation numbered a dozen or so, a conference on magnetic fields or radio galaxies can now draw over 300 participants.

4.1 Radio Galaxies

The study of radio galaxies has made huge progress with the immense capabilities of aperture synthesis radio telescopes. A study of Cygnus-A by Hargrave and Ryle (1974, see Figure 8) using the 5-km Ryle Radio Telescope in Cambridge showed the details of the polarisation of the radio lobes of this source at 5 GHz. In a follow-up publication Hargrave and Ryle (1976) mapped Cygnus-A at 15 GHz but in total intensity only, as the steep spectrum of the emission precluded detection of polarisation. Using the Effelsberg 100-m Radio Telescope Baker et al. (1975) could map Cygnus-A in polarisation at 14 GHz but at low angular resolution. The NRAO interferometer at Green Bank also became an important source of polarisation data (e.g. Wardle and Kronberg, 1974; Kronberg and Wardle, 1977). Most of the results up to this time related to the linear polarisation.

The start of observations with the Westerbork Synthesis Radio Telescope led to a huge volume of new data on the polarisation of radio sources. For example, Miley (1973) studied the polarisation of head-tail galaxies. Westerbork studies of sources at 21cm and 6cm were used by Högbom and Carlson (1974) and Högbom (1979) to determine the spectra as well as polarisation across the sources. Multi-frequency studies have been published on many sources. The delineation of "… the largest sources in the Universe …" by Willis et al. (1974: 625) led to increased interest in polarisation studies in a bid to understand the jet-like phenomenon in radio galaxies. Multi-frequency observations were made of these large objects (e.g. see Willis and Strom, 1978; Strom and Willis, 1980). However, care has to be taken when comparing interferometer data at several frequencies: the spatial components must be compatible. Interferometers lose the large-spacing information, which can lead to misinterpretation of spectral and polarisation results.

In order to allow spectral investigations as well as robust polarisation determinations high frequency observations with the Effelsberg 100-m Radio Telescope were used (e.g. Baker et al., 1974; Stoffel and Wielebinski, 1978; Klein and Wielebinski, 1979).

The inauguration of the Very Large Array in 1980 opened up new and powerful instrumentation for mapping of polarisation. While it is difficult to single out individual papers, I would like to refer to the studies of Owen et al. (1980), Bridle et al. (1980), Perley et al. (1980), Fomalont et al. (1980) and Rudnick et al. (1985). One of the important early directions was the study of the magnetic fields in the jets of radio galaxies. With the four array configurations the aperture synthesis could be optimised for source size. One interesting development was the combination of the VLA and the 100-m Radio Telescope data for studies of radio galaxies (e.g. Kronberg et al., 1986). The general statement that can be made is: every radio galaxy shows synchrotron emission, and in cases where there is sufficient angular resolution and sensitivity polarised emission is observed. Hence all radio galaxies, out to the most distant ones at z ~ 6.0, have magnetic fields.

The development of Very Long Baseline Interferometry (VLBI) started with total intensity observations but later moved to polarisation mapping (e.g. Cotton et al., 1982; 1984). The combination of polarisation maps of jets made with the VLA and maps made with VLBI gave important information for the interpretation of emission processes in Active Galactic Nuclei (AGN).

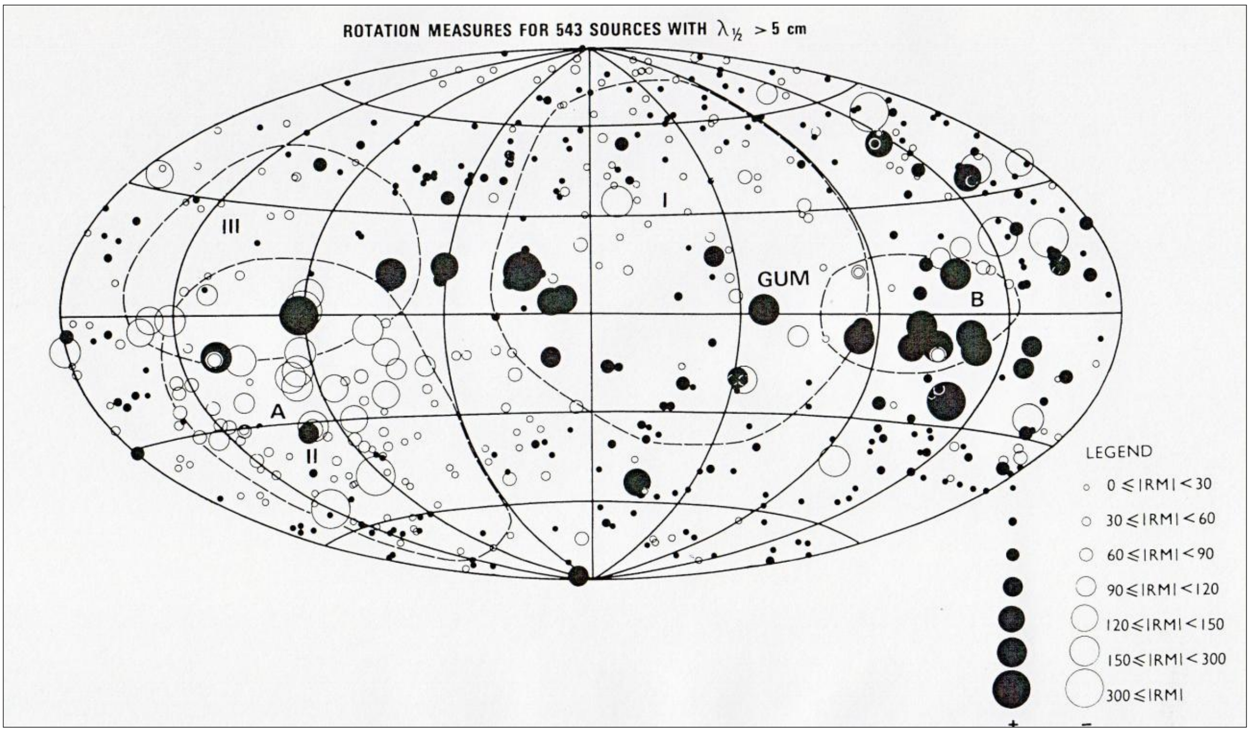

Figure 9: All-sky *RM* diagram (after Simard-Normandin and Kronberg, 1980).

4.2 Discrete Radio Sources as Probes of the Galactic Interstellar Medium

Following the early detections described in Section 2.1 a whole armada of researchers launched campaigns to catalogue EGRS polarisation at many wavelengths. The aim, in addition to understanding the emission mechanism, was to use the polarised sources as probes, since they emit electromagnetic waves that pass through the galactic (thermal) interstellar medium (ISM) and intergalactic space on the way to our radio telescopes. The discussion about the emission mechanism required studies at higher angular resolution of the sources themselves. The average *RM* of sources was attributed to the galactic ISM and has hence been used to derive a model of the galactic magnetic field. An example of a much-cited source catalogue, used for magnetic field studies, is the paper by Simard-Normandin and Kronberg (1980, see Figure 9). In this paper the *RM* of 543 sources distributed over the whole sky was compiled. Also, Tabara and Inoue (1980) compiled a catalogue of polarisation observations of over 1500 sources. However, the polarisation distribution in a source cannot be neglected. Using observations with different angular resolutions at different frequencies has led often to mistakes in the derived *RM* values. Using interferometry a clear source polarisation was obtained rejecting the polarised background but at a scale of the synthesised beam. A careful survey of 1600 selected sources in the northern sky with the Effelsberg Radio Telescope increased the data on point source polarisation to 2400 EGRS (Wielebinski et al., 2008).

A major step was recently achieved by Taylor et al. (2009) who re-analysed the 1.4 GHz NRAO VLA Sky Survey. The *RM* has been determined for 37,543 sources in the northern sky. The southern hemisphere was badly neglected and awaited a similar study, but this deficiency was rectified very recently by Carretti and Schnitzeler (2012).

The interpretation of these *RM*s suggests the presence of large areas with similar magnetic field orientations in the galactic halo, with some predominantly positive, and some negative, field directions. The earlier all-sky studies of *RM* did not include many sources along the Galactic Plane. This has been remedied recently with dedicated surveys by Brown et al. (2003; 2007) and van Eck et al. (2011). Along the Galactic Plane, where the spiral arms are causing the rotation, we see many sudden reversals. The values of *RM* increase towards the Galactic Centre. EGRS observations towards the Galactic Centre itself by Roy et al. (2008) suggest a field reversal around the Centre. These combined data (also with pulsar *RM* data) are a basis for modelling the magnetic fields in our Galaxy. From the data of van Eck et al. (2011) only one medium-scale reversal towards the Sagittarius spiral arm seems to be present.

Pulsars give complementary information to that obtained from studies of EGRS. For many years pulsars were more important as probes of galactic magnetic fields since they are clustered in the plane of our Galaxy, however the recent data on EGRS along the Plane (see above) has reduced this advantage. In addition, pulsars offer the possibility of investigating the distance of the object once the Rotation Measure and the Dispersion Measure have been determined. Lyne and Smith (1989) listed the *RM* of 185 pulsars, deriving the value of the local magnetic field as <B> ~ 3μGauss. Observations of pulsars also suggested that field reversals occur in our Galaxy. This study was followed up by Han and Qiao (1994) and Qiao et al. (1995), leading to models of the galactic magnetic field with a bi-symmetric field structure. Independent investigations by Vallée (1996) and Han, Manchester and Qiao (1999) continued the discussion about the nature of the galactic magnetic field. The effect of HII regions in front of pulsars was investigated by Mitra et al. (2003), who showed that this can lead to a field reversal. Also the previously-postulated field reversal beyond the Perseus spiral arm was disproved.

New observational *RM* data (Han et al., 2002; 2006; Noutsos et al., 2008) continued the discussion about the controversial nature of galactic magnetic fields. An investigation of the alternative interpretations, based on pulsar *RM*, by Men et al. (2008) could not give a clear answer about the nature of the galactic magnetic field. A combination of pulsar *RM*, the EGRS data and radio continuum polarisation is necessary to tackle this difficult question. As mentioned above, one medium-scale reversal has now been confirmed in our Galaxy. Many small-scale reversals are observed that may be caused by the local situation in the thermal clouds. It is of interest to note here that the *RM* values and field orientations derived using pulsars and EGRS towards the Galactic Centre are very similar. Since hardly any pulsars are observed beyond the Galactic Centre this would suggest that the *RM* of both types of sources occurs in foreground regions, with strong magnetic fields and high thermal electron density.

4.3 Diffuse (Galactic) Radio Emission

After the pioneering surveys made in the 1960s the mapping of the Galaxy in polarisation was virtually discontinued. It was only continued in Dwingeloo by Brouw and Spoelstra (1976) who mapped a large area of the northern sky at several frequencies between 408 MHz and 1400 MHz. Using the Dwingeloo data Spoelstra (1984) derived the *RM*, in particular for the 'fan region' at $l = 140°$, $b = 10°$. These values of *RM* were very low—a result of deriving the *RM* values with under-sampled low angular resolution data. A revival of polarisation mapping of the galactic emission came with the survey by Junkes et al. (1987) of the Galactic Plane at 11cm. In Effelsberg numerous surveys of a wide strip of the Galactic Plane were made at 21cm and 11cm. In Australia Duncan et al. (1997) mapped the southern Galactic Plane at 13cm with the Parkes Radio Telescope. These surveys turned out to be of great importance in discovering new supernova remnants. A review of recent galactic polarisation surveys is given in Reich (2006). The Galactic Centre was found to be highly polarised (e.g. Seiradakis et al., 1985; Reich, 2003) implying emission by mono-energetic electrons. A major step in polarisation studies of our Galaxy came from Wieringa et al. (1993; see Figure 10) who made a 325 MHz polarisation map with the Westerbork Radio Telescope, which showed that there is considerable structure in polarisation at low radio frequencies. This rapid variation of polarisation structure was found at high (4 arc minute) angular resolution.

The discovery of a large-scale interstellar Faraday rotation feature, a Faraday screen, by Gray et al. (1998) revived interest in the galactic radio continuum emission. This direction of work was taken up in Effelsberg with deep polarisation maps at 21cm with 9 arc minute resolution (e.g. Uyaniker et al., 1999), a part of a Medium Latitude Survey of the Galactic Plane. Numerous galactic Faraday screens were discovered. Also the Australia Telescope Compact Array was used by Gaensler et al. (2001) to map a section of the Galactic Plane at arc-minute resolution, deriving *RM* values for this area. The values derived were very much higher than was originally deduced by Spoelstra (1984), showing that the structure of the interstellar medium (ISM) is an important parameter. These maps also showed strong Faraday effects at higher angular resolution. On the other hand it became clear that there must be a reliable definition of the zero levels of the polarisation maps. The display of polarisation data changed with the advent of colour monitors and the data display showed black 'canals' of zero polarisation intensity (see Figure 11). The 'canals' are due to polarisation intensity going to zero as a result of small-scale Faraday rotation and may disappear or change once the correct zero level has been established. Details of the procedures used to establish the correct zero level can be found in Sun et al. (2007).

For the setting of the zero level, needed to understand the polarisation distribution, all-sky polarisation information was required. To achieve this goal the northern sky was mapped in 21cm polarisation

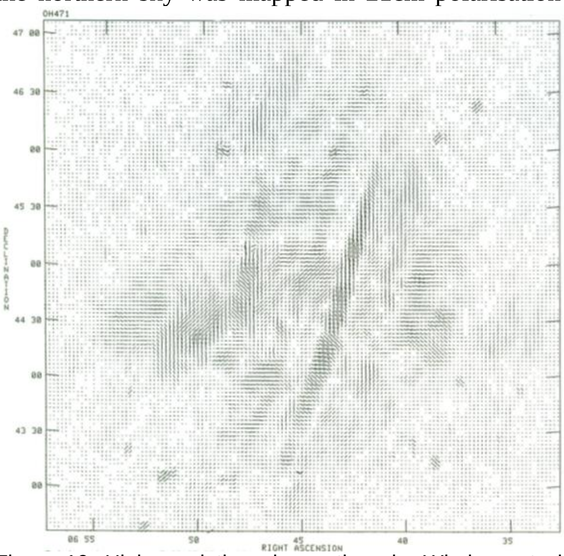

Figure 10: High resolution observations by Wieringa et al. (1993) showing polarisation (*E*-vectors) structure at 325 MHz with 4 arc minute resolution.

by Wolleben et al. (2006) and the southern counterpart by Testori et al. (2008). As a result, an all-sky map of polarisation could be made (see Figure 12). This data set also gives information about directions where foreground polarisation is nearly zero, which is relevant to the Cosmic Microwave Background studies.

New surveys of polarisation along the Galactic Plane were made with China's Urumqi Radio Telescope at 6cm wavelength (see Sun et al., 2011, and references therein). These surveys showed numerous Faraday screens as well as new sources (SNRs). These results, showing high values of *RM* (when compared with the Effelsberg 21cm data at the same angular resolution), support the recent observations that were made of compact sources in the Galactic Plane by Brown et al. (2007) and van Eck et al. (2011). The record of best angular resolution of diffuse polarisation (1 arc minute) is now held by Landecker et al. (2010), made with a combination of Dominion Radio Astrophysical Observatory and

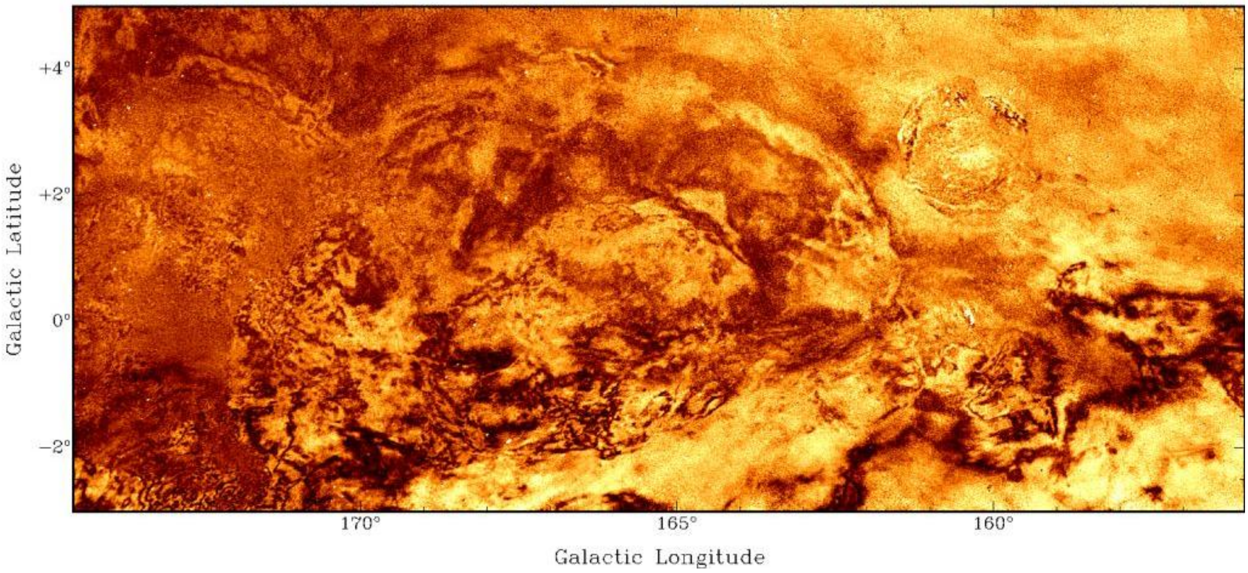

Figure 11: High angular resolution (1 arc minute) polarised intensity map of a section of our Galaxy (Landecker et al., 2010). This is a combination of Effelsberg and Canadian Galactic Plane Survey data. The display of polarisation is in colour, with high values bright, black being zero polarised intensity. The polarisation intensities were set to a correct zero level.

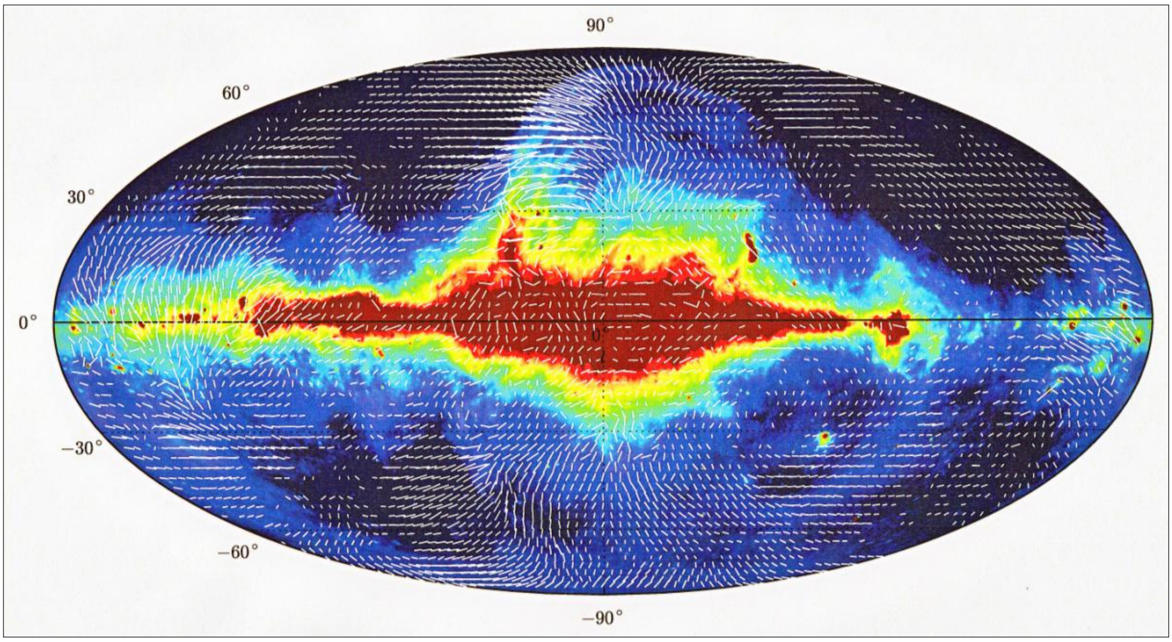

Figure 12: All sky polarisation (*E*-vectors) observed at 1400 MHz superposed on a total intensity colour map (courtesy: W. Reich). The plot was made by Maik Wolleben.

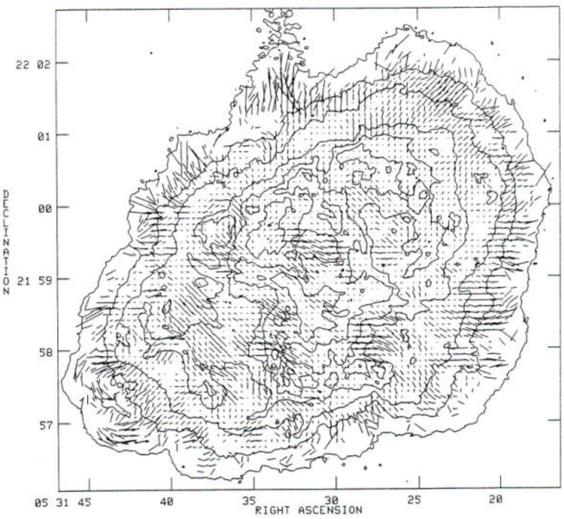

Figure 13 (left): The total intensity, percentage polarisation and projected magnetic field orientation in the Crab Nebula at 1410 MHz. Vector length of 30″ indicates 100% polarisation (after Bietenholz and Kronberg, 1990).

Effelsberg data at 21cm (see Figure 11). The *RM* synthesis (e.g. Brentjens and de Bruyn, 2005; Wolleben, Landeker et al., 2010) adds another new method in which polarisation is used to sample the ISM. Studies of the details of the *RM* in large galactic objects only became possible as a result of the application of *RM* synthesis (e.g. Wolleben, Fletcher et al., 2010).

Another interesting direction of study is that of the polarisation of the real background, the Cosmic Microwave Background (CMB). However the CMB is seen through the galactic foreground that must be carefully subtracted before any claim of cosmologi-

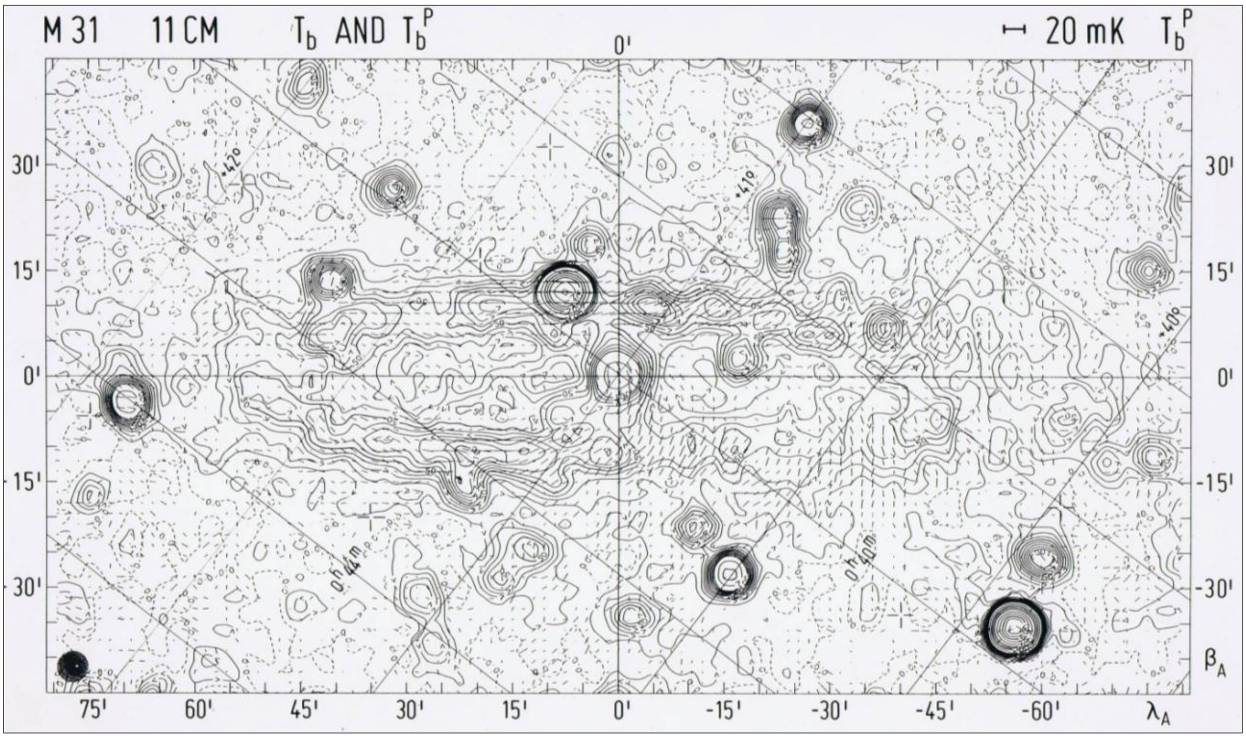

Figure 14: Polarisation of M31. *E*-vectors at 11cm wavelength are shown superposed on total intensity contours. In view of the low Faraday rotation a 90° vector rotation gives the 'B' field (after Beck, Berkhuijsen and Wielebinski, 1980).

cal polarisation can be made. Polarisation studies have been made with the WMAP satellite (Bennett et al., 2003; Kogut et al., 2007; Page et al., 2007; Hinshaw et al., 2009; Gold et al., 2009) and presented as all-sky maps. The observed data at 23, 33, 41, 61 and 94 GHz show the major polarisation features of the Galaxy at these high frequencies. There is good agreement with the 1.4 GHz maps of Wolleben et al. (2006) and Testori et al. (2008). The PLANCK satellite is also going to make an important contribution in this field of research at the highest radio frequencies. The gap in all-sky polarisation data between 1.4 GHz and 22 GHz is obvious and must be closed in the near future.

4.4 Supernova Remnants

The advent of new sensitive radio telescopes allowed the discovery of new SNRs as well as detailed studies of known objects. In the discovery process not only polarisation data were used; the IRAS surveys gave excellent information about thermal regions. Hence the separation of diffuse (unpolarised) HII emission from non-thermal (polarised) SNR became an easy exercise. Reviews of the progress in the discovery of new SNRs are found in Milne (1990) and Reich (2002). Discoveries of SNRs are still in progress: whenever a sensitive survey of a wider region of the Galactic Plane is completed new supernovae are found. While most of the more extended SNRs were found with large single dishes (e.g. Parkes or Effelsberg) the more compact objects were discovered by synthesis instruments (e.g. Green and Gull, 1984). In the very recent survey at 6cm by Gao et al. (2011) two new SNRs were detected. Important sources of information about galactic SNRs are the catalogues of Green (1984; 2009).

The other direction of research on SNRs was to make detailed maps of selected objects. The Effelsberg 100-m Radio Telescope allowed the mapping of SNRs to higher radio frequencies (e.g. Baker et al., 1973). Also, synthesis arrays became involved in polarisation studies of SNRs. For this purpose considerable computing power was needed. As an example I cite the work of Bietenholz and Kronberg (1990) on the Crab Nebula. Using the VLA and the Ontario Centre for Large Scale Computations, images of 1.8″ resolution were obtained for the whole 7′ × 7′ field (see Figure 13). These data match the best optical polarisation observations that were ever made. Several other SNRs have also been studied in such detail.

4.5 Nearby Galaxies

Originally optical polarisation observations indicated the presence of magnetic fields in nearby galaxies. There were optical observations of the polarisation of individual stars in the Magellanic Clouds as well as of diffuse polarisation in some nearby galaxies. The start of observations with the Westerbork Synthesis Radio Telescope in 1972 led to the first report by Mathewson et al. (1972) of the detection of radio linear polarisation in M51 at 21cm. These early results indicated the presence of magnetic fields along the spiral arms of the galaxy. Follow-up Westerbork observations of M51 were made by Segalovitz et al. (1976), and their 21cm and 6cm maps revealed polarisation in different areas: the 21cm map showed polarised vectors in the outer galaxy while the 6cm observations gave detections near the nucleus, a problem inherent in fixed interferometer arrays. M31 also was observed at Westerbork, but the limitations of aperture synthesis maps of extended diffuse objects were shown—most of the diffuse polarised emission was not detectable.

The opposite is the situation with observations of a large single dish like the 100-m Effelsberg Radio

Figure 15: High resolution map showing magnetic *B*-field in M51, derived from multi-frequency observations with both the VLA and the Effelsberg 100-m Radio Telescope (after Fletcher et al., 2011).

Telescope—the diffuse emission was detected and the angular resolution was just acceptable. This was demonstrated with the 11cm polarisation observations of M31 (Beck et al., 1978; 1980; see Figure 14). A very regular, ring-like magnetic field was detected in M31. To improve the angular resolution of a single dish higher frequencies were needed: in the case of the 100-m Radio Telescope the transfer to

6cm, 2.8cm, 2cm and 1.2cm observations (e.g. Klein et al., 1982; 1983; Krause et al., 1984; Beck et al., 1985; 1987) gave the much-needed improvement in angular resolution, while the Faraday effects became minimal. Also, the polarisation of edge-on galaxies was mapped (e.g. Dumke et al., 1995), allowing searches for halo magnetic fields. Polarised emission was detected in the halo of M82 by Reuter et al. (1994). The 100-m Radio Telescope in Effelsberg became the major source of information about the polarisation of nearby galaxies in those early days. A review on this subject at that time was published by Sofue et al. (1986).

There has been a revolution in the studies of magnetic fields in nearby galaxies in recent years. In this field of research the Effelsberg Radio Telescope has played a major role. With its great sensitivity to diffuse emission, maps of all large galaxies could be made. An atlas of the magnetic fields in galaxies can be seen on the home page of the Max-Planck-Institute für Radioastronomie (see http://www3.mpifr-bonn.mpg.de/div/konti/mag-fields.html).

Virtually every nearby galaxy has been studied by now. A big step in the studies of nearby galaxies was the combination of Effelsberg and VLA data on polarisation (Beck et al., 1998), a combination of good angular resolution and diffuse emission sensitivity. The Andromeda Nebula has been explored in detail (Beck et al., 2003; Fletcher et al., 2004). Also the galaxy M33 was examined by Tabatebaei et al. (2008). Edge-on galaxies received special attention as the question of halo fields was investigated (e.g. Reuter et al., 1994, for M82; Krause et al., 2006, for M104; Soida et al., 2011, for NGC 5775). Barred galaxies were investigated (e.g. Beck et al., 2005, for NGC1097 and NGC1365), showing that magnetic fields follow the gas motions. Also, irregular galaxies were investigated and showed surprisingly regular magnetic fields (e.g. Chyży et al., 2000). The influence of a cluster environment on the magnetic fields was investigated in NGC 4254 by Chyży (2008). Recently, the SINGS Survey from Westerbork (Heald et al., 2009) presented a large volume of consistent data on the polarisation of galaxies. The Effelsberg polarisation mapping system also was transferred to the Parkes Radio Telescope and used to study the Magellanic Clouds at various frequencies (Haynes et al., 1991). The combination of VLA and 100-m Radio Telescope data led to spectacular images, for example of M51 made at 3.6cm with an angular resolution of 15 arc seconds but with complete diffuse emission (Fletcher et al., 2011; see Figure 15).

There is considerable literature attempting to interpret the origin of magnetic fields in galaxies. The original interpretation of the presence of large-scale magnetic fields in addition to small-scale (local) structure still holds. In some galaxies 'magnetic arms' (e.g. Beck, 2007, for NGC6946; Han et al., 1999, for NGC2997) were detected, which seem to be mostly in the inter-arm (optical) regions. The dynamo theory offers the most plausible interpretation of the presence of magnetic fields in galaxies—a seed field is amplified by galactic rotation. A long list of reviews on this subject exists. I point out here only the reviews of Wielebinski and Krause (1993), Beck et al. (1996), Han and Wielebinski (2002), Wielebinski and Beck (2010), and Beck and Wielebinski (2012).

4.6 The Zeeman Effect

There has been considerable progress in Zeeman effect observations. For one, the controversies (see Verschuur, 1995) that built up about HI observations have been resolved. In addition, measurements using different molecular species (e.g. OH: Güsten et al., 1994; H_2O: Fiebig and Güsten, 1989; or SO: Ushida et al., 2001) have been made. Some of the recent Zeeman effect measurements have been made at mm wavelengths and will certainly be a driver for the future. An extended review about more recent Zeeman effect results is given by Heiles and Crutcher (2005). A recent claim for extragalactic Zeeman effect detection (Wolfe et al., 2008) cannot be substantiated. A discussion about the 'beam squint' problem can be found in Fiebig et al. (1991).

4.7 Clusters of Galaxies

The large surveys of *RM* of EGRS were used in attempts to detect intergalactic magnetic fields (e.g. Sofue et al., 1979). These early claims did not stand further scrutiny. On the other hand there was progress in the observation of individual clusters. Haloes were observed in numerous clusters (e.g. Willson, 1970; Wielebinski, 1978), proving the existence of non-thermal emission. Also, polarised sources in some clusters (e.g. A2256; Bridle et al., 1979) confirmed the existence of magnetic fields in the intergalactic space within clusters of galaxies. Observations of compact radio sources beyond the Coma Cluster by Kim et al. (1990) showed an increase in *RM* of sources in the centre of the cluster caused by Faraday rotation in the inter-galaxy magnetic fields. Thus far, various attempts to determine the polarisation structure (and hence magnetic fields) in the haloes in clusters of galaxies have failed.

5 CONCLUDING REMARKS

The data presented here take account of more than 50 years of radio polarisation studies. Starting from small beginnings, great progress was made. The next generation of radio telescopes should take the field much further.

Each new radio telescope project (ALMA, Lofar, Askap, Meerkat and the SKA) includes polarisation facilities. Also, multi-beam polarimeters for mm- and sub-mm wavelengths have been constructed. However, it will need great vigilance by the polarisation community. Often in large projects the polarisation capability is dropped due to technical difficulties. It certainly costs more to have a polarisation capability but this is compensated for by the new and unique data that can be obtained.

I will certainly watch the progress in the next years with great interest, and I wish all the 'magnetic people' good luck in their research.

6 ACKNOWLEDGEMENTS

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Richard Wielebinski was born in Pleszew, Poland, in 1936. His schooling was in Hobart, Australia. Studies at the University of Tasmania led to the degrees of B.E (Hons.) and M.Eng.Sc. At first he worked as an engineer for the Australian Post Office involved in the construction of TV stations. A scholarship took him to Cambridge where he was awarded the Ph.D. degree in 1963 for a thesis on 'Polarization of Galactic Radio Waves'. The next six years were spent at the University of Sydney, lecturing in engineering and doing research with the Parkes and Molonglo Radio Telescopes. Following an invitation from the Max-Planck-Gesellschaft he became a Director at the MPI für Radioastronomie in Bonn in 1969. His interests were instrumentation for radio astronomy, radio continuum observations, pulsar studies and investigations of cosmic magnetic fields. He was involved in the construction of the 100-m Effelsberg Radio Telescope and was in charge of the Electronics Division of the MPIfR for over thirty-five years. R. Wielebinski is an Honorary Professor in Bonn, Beijing and Townsville, a member of several academies and holds three honorary doctoral titles. He has published more than 500 papers and edited seven books. He retired in 2004 but is still active as an Emeritus Director at the MPIfR.

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THE PARKES 18-m ANTENNA: A BRIEF HISTORICAL EVALUATION

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Abstract: This short communication summarises the contribution to astronomy made by the 'Kennedy Dish', a stand-alone 18-m (60-ft) parabolic antenna that originally was located at the CSIRO's Fleurs Field Station near Sydney and subsequently was transferred to Parkes and used in conjunction with the 64-m Parkes Radio Telescope as the 'Parkes Interferometer'.

Keywords: 18-m Kennedy Dish, Fleurs Field Station, Parkes

1 INTRODUCTION

Australia has a long and proud history in radio astronomy that had its foundations in radar developments during WWII (see Sullivan, 2009). From the 1940s through to the 1960s much of Australia's radio astronomical research output derived from a network of field stations and remote sites maintained in and near Sydney by the CSIRO's Division of Radiophysics (e.g. see Orchiston and Slee, 2005; Stewart et al., 2010; Stewart, Orchiston and Slee, 2011; Wendt et al., 2011a, 2011b).

A feature of this period was the innovative range of new radio telescopes developed by the Radiophysics astronomers and engineers (Orchiston and Mathewson, 2009; Stewart, Wendt, Orchiston and Slee, 2011), but conventional antennas were also used, including Yagi arrays and single parabolic 'dishes' of various sizes. Initially the latter tended to be recycled WWII searchlight mirrors, but later purpose-built dishes were constructed and then in 1959 the Division purchased a prefabricated 18-m (60-ft) American antenna (Figure 1). This originally was sited at the Division's Fleurs Field Station, but in 1963 it was relocated to Parkes.

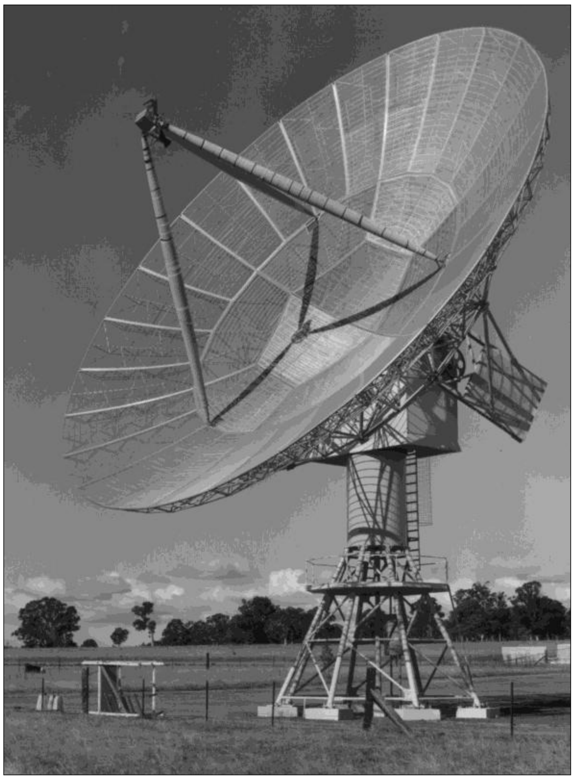

Figure 1: The prefabricated 18-m parabolic antenna (courtesy: ATNF Historic Photographic Archive).

After several decades of neglect the future of the '60-ft Parkes Dish' came under review in 2002, and I was asked to prepare a brief report on the historical significance of this radio telescope.[1] This short communication is based on that report, and its publication now—after a hiatus of ten years—was prompted by Don Mathewson's (2012) paper in this issue of the Journal, about his discovery of the Magellanic Stream.

2 THE FLEURS ERA

The Division of Radiophysics established a field station at Fleurs, near Sydney, in 1954 (Orchiston and Slee, 2002b), in order to provide a facility for the Mills Cross, Shain Cross and Chris Cross. These innovative radio telescopes were constructed between 1954 and 1957 (see Orchiston and Slee, 2005).

The Chris Cross was the world's first cross-grating interferometer, and was designed to generate daily 1423 MHz isophotes maps of the Sun (Orchiston and Mathewson, 2009). In order to use this instrument of an evening for non-solar astronomy the sensitivity had to be markedly improved, and the easiest way of achieving this was to install preamplifiers on the E-W arm antennas and to add a comparatively large parabolic antenna as a multiplying element at the eastern end of the E-W arm of the Cross. The antenna selected was the 18-m (60-ft) dish now at Parkes, and this prefabricated American antenna (known as the 'Kennedy Dish' after the manufacturer) was assembled at Fleurs in 1960 (Figure 2).[2] The resulting 'Fleurs Compound Interferometer' (Figure 3) had a 1.5 arc-minute fan beam (see Labrum et al., 1963), and was used by Labrum et al. (1964) to investigate the right ascensions and angular sizes of eight known discrete sources at 1423 MHz. Meanwhile, the 18-m Antenna could also operate independently of the Chris Cross, as a stand-alone radio telescope, and it was used in this mode by Mathewson et al. (1962a, 1962b) to survey the southern Milky Way at 1440 MHz.

3 THE PARKES ERA

In 1963 the 18-m Antenna was transferred to Parkes

Figure 2: An aerial view of the Chris Cross at Fleurs looking north-east, with the 18-m Antenna (far right) under construction at the eastern end of the E-W arm of the Cross (courtesy: ATNF Historic Photographic Archive).

to allow construction of the 'Parkes Variable-baseline Interferometer' (Figures 4 and 5). As Bachelor et al. (1969: 305) point out, this instrument employed a number of novel features, including

> … observation with one telescope in motion at up to 120 feet per minute on east-west or north-south tracks automatic path difference compensation and simultaneous operation at two different frequencies of 1402.8 and 467.6 MHz. The installation uses solid-state components throughout …

Unfortunately, phase instability associated with the exposed cable that linked the 18-m antenna to the 64-m Parkes Radio Telescope created problems (e.g. see Radhakrishnan, 1994) and so the Parkes Interferometer "… was never useful for position measurements, for which John [Bolton] had originally intended it." (Ekers, 1994: 574).

However, it did provide very useful data on source sizes (see Wall et al., 1968) and brightness distribution (Ekers, 1969a). It also showed that the lobes associated with double-lobed radio galaxies were not expanding with time and therefore could not have been formed from galactic explosions—as was the prevailing wisdom (Ekers, 1994). It was also used by Goss et al. (1970) for H-line work and by Radhakrishnan and Whiteoak (1967) for OH work.

As was the case at Fleurs, the 18-m Antenna also could function successfully as a stand-alone radiometer, and in this context Don Mathewson used it to map the Magellanic Stream (see Mathewson, 2012).

Finally, from an historical perspective, we should not forget that a youthful Ph.D. student named Ron Ekers cut his 'radio-astronomical teeth' on the Parkes Interferometer (see Ekers, 1969b).

4 CONCLUDING REMARKS

The Parkes 18-m Antenna (Figure 6) is an historically-significant radio telescope and deserves to be retain-

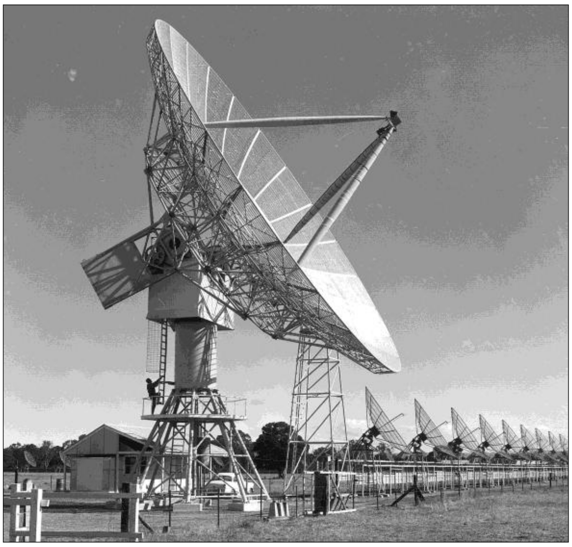

Figure 3: The completed 18-m Antenna at Fleurs, looking west along part of the E-W arm of the Chris Cross (courtesy: ATNF Historic Photographic Archive).

Figure 4: View showing the 64-m Parkes Radio Telescope and to the right of it the 18-m Antenna (courtesy: ATNF Historic Photographic Archive).

ed and preserved.[3] After the 64-m Parkes Radio Telescope, for a time the 18-m Antenna was the largest fully-steerable parabolic radio telescope owned and operated by the CSIRO's Division of Radiophysics.[4] It was part of the first high-resolution compound interferometer in the Southern Hemisphere, and was part of the first variable-baseline high-resolution interferometer in the Southern Hemisphere. While at Fleurs and at Parkes it contributed to international radio astronomy through published papers on H-line and OH work and on discrete sources, and was responsible for the identification and mapping of the Magellanic Stream. It also was associated with the Ph.D. of one of Australia's foremost astronomers, former ATNF Director and former IAU President, Professor Ron Ekers.

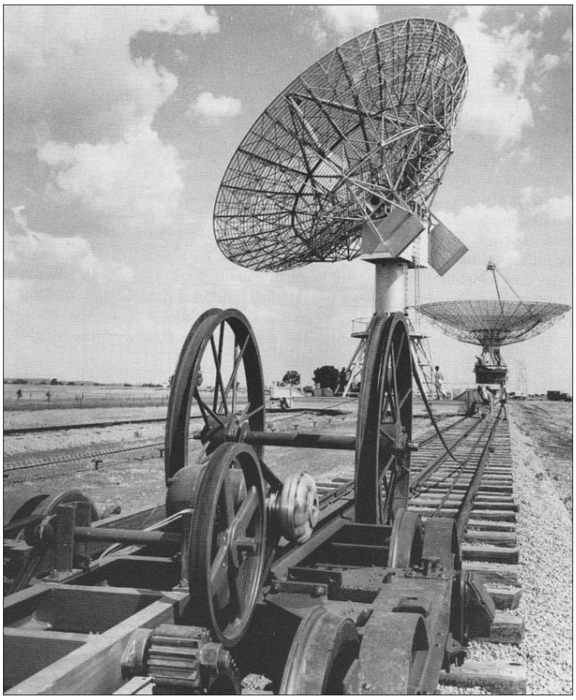

Figure 5: View of the Parkes Variable-baseline Interferometer, and the railway track used by the 18-m Antenna. The wheels in the foreground were part of the mechanism that drove the 18-m Antenna along the railway track (courtesy: ATNF Historic Photographic Archive).

5 NOTES

1. At the time Professor Ron Ekers was Director of the Australia Telescope National Facility (ATNF) and I was employed as the Facility's Archivist and Historian.

Figure 6: A picturesque view of the 18-m Antenna at sunset (courtesy: Roopesh Ojba).

2. Ekers (1994: 572) has erroneously stated that the 18-m radio telescope was located at the Murraybank Field Station, not Fleurs, before it was moved to Parkes. While it is true that Dick McGee lobbied for this radio telescope to be assigned to Murraybank, Joe Pawsey "… discounted this idea and a specification was drawn up for a new [much smaller] aerial … [to be sited there]." (see Wendt et al., 2011a: 437 for details).
3. But note that ATNF has since been superseded by CASS (CSIRO Astronomy and Space Sciences), which is now responsible for any decisions that might be made about the future of the 18-m Antenna.
4. Earlier, in 1951, a 21.9-m 'hole-in-the-ground' radio telescope was constructed at the Division's Dover Heights field station and in 1952 expanded to 24.4m diameter (see Orchiston and Slee, 2002a), but this antenna was not fully steerable and had ceased to exist by the time the 18-m Antenna was acquired.

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DISCOVERY OF THE MAGELLANIC STREAM

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Abstract: The story of the discovery of the Magellanic Stream is told and the initial endeavours to find its origin described. These centred about either a tidal or a ram pressure origin. The splitting of the Small Magellanic Cloud into two fragments and the ubiquitous double HI profiles of the SMC, parts of the Bridge and the beginning of the Stream are central in determining the age of the Stream as 0.3 Gyr. However a composite map from recent surveys by a large number of observatories has extended the length of the Stream by 40° making the previous theories untenable. A new tidal model based upon the increased length of the Stream has estimated its age to be about 1.5 Gyr, five times the earlier estimates which were made using sound independent observational evidence. We seem to be no closer to understanding the origin of the Stream than when it was discovered nearly forty years ago.

Keywords: Magellanic Stream, Large Magellanic Cloud, Small Magellanic Cloud, Magellanic Bridge, HI clouds, 210-ft Parkes Radio Telescope, Don Mathewson

1 INTRODUCTON

I became interested in high-velocity HI clouds at high galactic latitudes when discovering some of them using the standing paraboloid radio telescope of John Kraus when I was working at Ohio State University in 1966. So some years later, in late January 1973, whilst flicking through an *Astrophysical Journal* in the library at Mount Stromlo Observatory, an article by Wannier and Wrixon (1972) on high-velocity HI clouds caught my eye. They had extended an HI filament near the South Galactic Pole found by van Kuilenburg (1972) up to l = 90°, b = –30°, giving a total length of 60°. They suggested it was HI emission in our Local Spiral Arm. They found it had a sinusoidal variation of radial velocity along its length and thought it was due to rigid body rectilinear motion.

2 UNVEILING THE MAGELLANIC STEAM

A page of polar graph paper lay on the desk and I plotted their HI filament and extrapolated it past the South Galactic Pole and noted that it passed close to the Magellanic Clouds. I then extrapolated the sinusoidal velocity variation and found that the filament would have a velocity similar to the Clouds at their position. This really excited me, and though it was late on Sunday afternoon, I phoned Brian Robinson, who was Director of Research at Parkes, and told him that I had a really ‘hot’ one. I asked him if I could have the 210-ft Parkes Radio Telescope for a few hours. He laughed mirthlessly as I knew he would. It takes months—submissions, referee reports, committee meetings, selling your soul—to get even a few days on the heavily over-subscribed ‘Dish’; but then he threw me a life-line. He remembered that the engineers had the telescope for a few nights to install a new HI receiver and if they didn’t want it for a few hours I could have it, but no guarantees!

The next morning I was driving to Parkes from Canberra with a very attractive vacation student by my side. She was an Applied Maths student from Monash University. I don’t think she was very interested in HI filaments, but she certainly wanted to seize the opportunity to see the Dish.

When we arrived, the Dish was stowed and the engineers had their noses buried in the HI receiver in the Control Room. After dinner, the student and I walked down to the Dish and into the Control Room. The engineers’ eyes fixated on my rather beautiful companion. Engineers the world over are very weak in such matters, and their attention strayed from the HI receiver. When she announced a few hours later that she was bored and would like a game of table tennis, the engineers said almost in a single voice that they would give her a game. As I watched the taillights of their car receding down the road to the Observers’ Quarters, I pumped the air—I had the Dish.

There were uncertainties with the receiver. The engineers told me before they left that I had to hold my tongue in a certain way, twiddle this and that and “She’ll be right, mate”. The Duty Controller was snoring, spreadeagled in a big, leather armchair with a *Playboy* magazine on his chest. I let him sleep as I knew how to drive the Dish. Before I moved to Mt. Stromlo Observatory, I had worked for eleven years at the CSIRO’s Division of Radiophysics, and had participated in the commissioning of the Dish with Harry Minnett, John Shimmins, John Bolton, Jim Roberts and others.

It seemed to take ages to come out of ‘stow’ but finally I was starting the observations, the sheet of polar graph paper in my hands. The next few hours were highly charged emotionally. I expected nature to be capriciously teasing and lead me up the garden path—but not tonight. At every point along the extrapolated line of the HI filament, there was HI at the expected velocity. The connection with the Magellanic Clouds of the Wannier Wrixon/van Kuilenburg filament had been made. The Magellanic Stream was unveiled!

I went out the door of the Control Room and up the stairs to the Poop-Deck—the floor of the tower above the Control Room that contained the circular track upon which the Dish rotated in azimuth on its huge wheels. I gazed up in awe at the beautiful sculpture of the Dish—the precise geometric pattern of its orthogonally-intersecting ribs with the dainty mesh laid on top. The wind sighed through

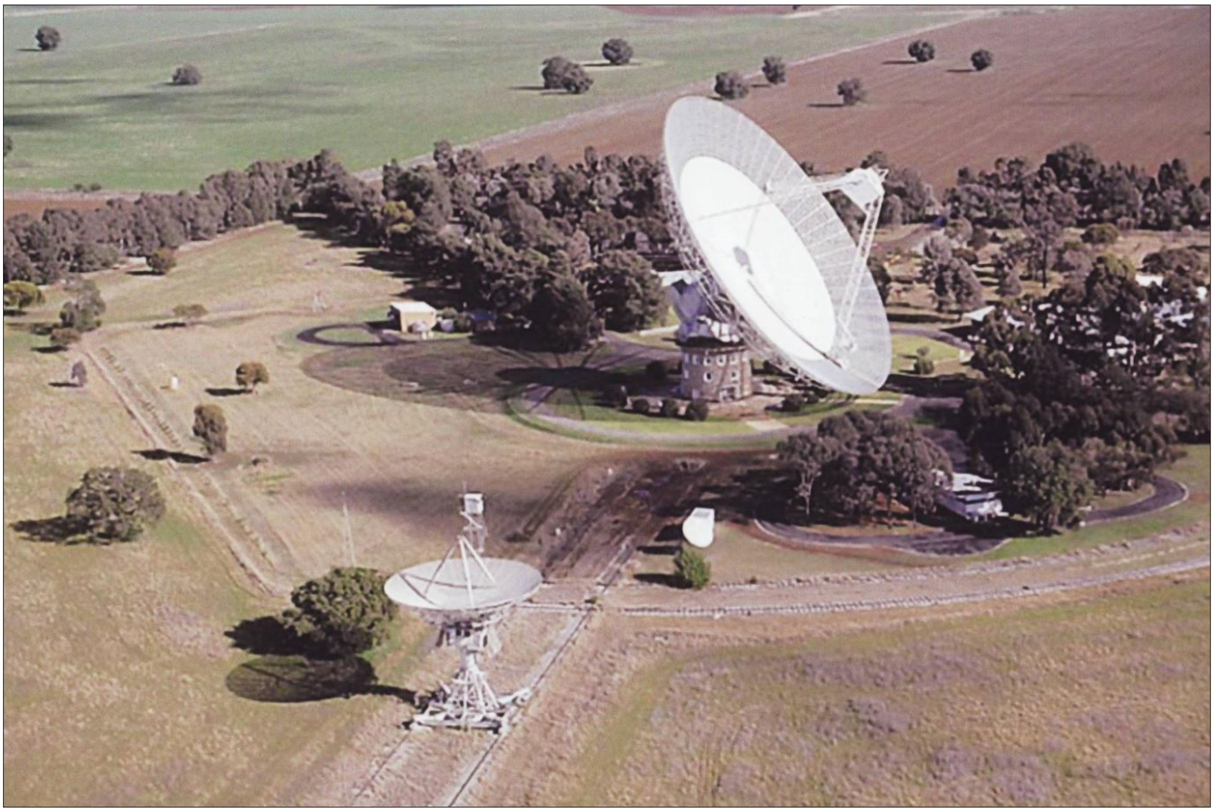

Figure 1: The 210-ft (64-m) Parkes Radio Telescope and 60-ft (18-m) 'Kennedy Dish' at the CSIRO's Parkes Observatory (courtesy: John Sarkissian, Parkes Observatory).

the structure as I traced an arc from the horizon to past the zenith. "That's the size of the Stream," I thought. "If only we had radio-eyes, what a wonderful sight it would make."

3 DELINEATING THE MAGELLANIC STREAM

But what now? What does the Stream really look like? I had observed only 20 points. We needed a large-scale survey of the southern sky to find out. My eye fell on the 60-ft dish looking lonely in a distant paddock silhouetted against the pre-dawn light (Figure 1). I had observed with it at the CSIRO's Fleurs Field Station near Sydney (see Orchiston and Slee, 2005) before it was taken to Parkes to be used with the 210-ft Dish as an interferometer (Ekers, 1994; Orchiston, 2012; Radhakrishnan, 1994). That work was finished and now nobody wanted to use it. It would be ideal to map the Stream.

The next week was frantic. John Murray, a first-class engineer from Radiophysics and an old friend, agreed to install an HI receiver on the 60-ft dish. He took out of moth-balls the back-end, the Parkes 64-channel spectrometer (Batchelor, Brooks, and Sinclair 1969). I borrowed a 35-mm recording camera from the John Curtin Medical School at ANU, to photograph the HI profile which was displayed on the oscilloscope screen after each integration (there were no computers at Parkes at that time).

A stroke of good fortune came when a vivacious Ph.D. student, Martha Cleary, arrived from Ireland and was assigned to me for her first year project. She was a great asset and we shared the observing and data reduction (Figure 2).

In early February 1973 we set up shop at the head of the first flight of stairs in the tower of the 210-ft Radio Telescope. There we could look through the window at the 60-ft dish as we drove it to the place where we would start the drift scan for the day. We developed the 35-mm film in the little toilet on the ground floor, the only dark room on site! We hung up the long lengths of film from the ceiling on the ground floor to dry and were soundly cursed by the Parkes staff when they accidently walked into the clammy film. We made a make-shift overhead projector to project the HI profile on the film onto a sheet of graph paper for reduction. This was Martha's and my routine for the next four months and it was wonderful to watch the Stream grow before our eyes.

In July, Martha and I returned to Mt. Stromlo

Figure 2: Martha Cleary and Don Mathewson observing the Magellanic Stream using the 60-ft Dish. George Day (right), the Station Manager of Parkes, is watching the observations (courtesy: Jack Masterton, CSIRO).

Observatory to finalise the HI maps of the Magellanic Stream. Alar Toomre, the master of tidal tails and bridges on interacting galaxies, was visiting the Observatory from M.I.T., and our discussions centred on tidal forces between the Magellanic Clouds and the Milky Way causing the bridge of gas between the Clouds and producing the Stream. Agris Kalnajs, a specialist in galactic dynamics, was very helpful in these discussions. Geoff Bicknell was particularly interested in the effects of ram pressure on the Bridge speeding through the diffuse halo gas and sweeping out its gas.

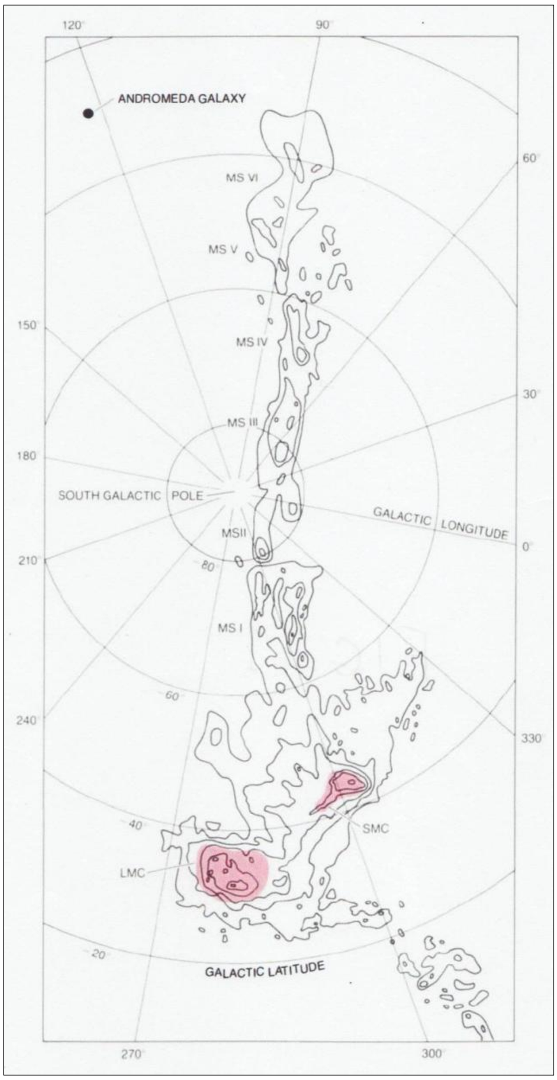

Figure 3: The distribution of HI in the Magellanic System in galactic coordinates. The outer contour is 10^{19} atoms cm^{-2}. The main features of the system are the HI in the LMC and SMC, the Bridge of gas between them, the Magellanic Stream and the Leading Arm feature. The Magellanic Stream is divided into six concentrations labelled MS I-VI. The optical extent of the LMC and SMC is shaded (after Mathewson, 1985b).

In August, IAU Symposium No. 58, 'The Formation and Dynamics of Galaxies', was held in the Academy of Science Dome in Canberra. Although not scheduled, Margaret Burbidge, the organiser, allowed me a ten-minute slot in the programme to introduce the concept of the 'Magellanic Steam'. There was strong international participation and the talk created a lot of discussion.

I was invited to present the same talk a few weeks later at IAU Symposium No. 60, 'Galactic Radio Astronomy' at Maroochydore on the Sunshine Coast in Queensland. I remember vividly Jan Oort, surrounded by astronomers, drawing in the sand his idea of the origin of the Stream. I'm sure the onlooking beach crowd thought we were some strange religious sect!

This early work was published by Mathewson, Cleary and Murray (1974). Figure 3 shows the HI from the Large and Small Magellanic Clouds, the Leading Arm, the Bridge of gas between the two galaxies and the 100°-long Magellanic Stream (Mathewson, 1985b). Later Putman et al. (2003) surveyed the Leading Arm Feature in much more detail.

4 THE ORIGIN AND EVOLUTION OF THE MAGELLANIC STREAM

The purpose of this paper is mainly to tell the story of the discovery of the Stream and not to review the hundreds of papers written about the Stream. However, I would like to pick out some pivotal points which have shaped our thinking about the origin of the Stream. I would like to show that after 40 years since its discovery, complete confusion reigns as to how this large-scale feature was formed.

Like any good detective story, the Stream has given us an abundance of clues. These include:

a) The Stream forms part of a great circle over its 100° length at right angles to the disk of our Galaxy.
b) It has a sinusoidal velocity variation along its length.
c) It is composed of a string of clouds.
d) The large velocity differences of 40-60 km/s between different parts of individual clouds, the mean velocity difference of 43 km/s across the Stream and the large velocity half-widths of the HI profiles of 20-50 km/s put severe restrictions on the age and permanence of the Stream. It is unlikely that the age of the Stream is much more than a few times 10^8 years.
e) No stars have been found in the Stream.
f) The HI profiles for at least 10° at the start of the Stream (around l = 293°, b = –57°) are double peaked and separated by 40 km/s, similar to the HI in the SMC and in the Bridge near the SMC.
g) If the mid-line of the Stream is extrapolated, it passes through the Inter-Cloud Region near the SMC and through the L1 Lagrangian Point where the gas is not bound to either the LMC or SMC.

The most attractive response to clues (a) and (b) is that the Stream is in a Keplerian orbit about our Galaxy and so forms a great circle on the sky as seen from the Sun which, comparatively speaking, is close to the focus, the centre of the Milky Way. The radial velocities will be proportional to the sine of the angular distance along the great circle (Mathewson et al., 1974). This is evidence that the Stream follows the orbit of the Magellanic Clouds. I have shown that the Stream lies close to the plane

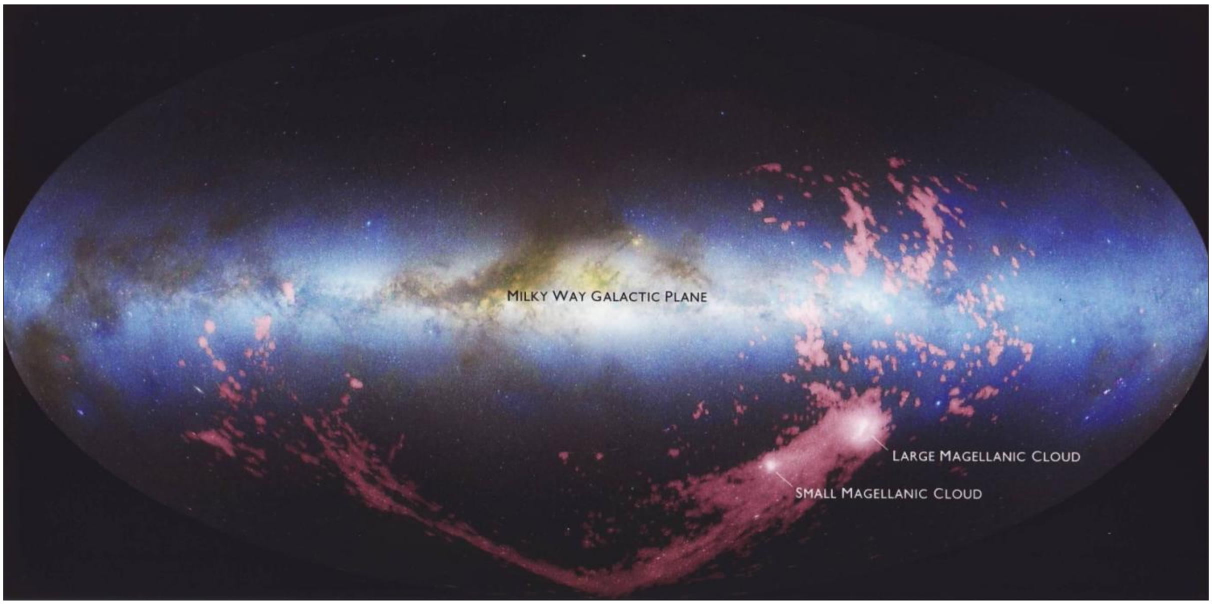

Figure 4: The Magellanic Stream and the Milky Way. Digitally superposed on an image of the Milky Way in visible light, the HI emission of the Magellanic Stream is shown in false colour pink extending across the sky and ending at the LMC and SMC on the lower right (courtesy: David Nidever et al., NRAO/AUI/NSF and A. Mellinger, LAB Survey, Parkes Observatory, Westerbork Observatory, Arecibo Observatory).

of the Local Group of galaxies (see Mathewson, 1985a: Figure 4) which would be expected if it follows the orbit of the Magellanic Clouds which also lie in that plane. This infers that the Magellanic Clouds are not satellites of our Galaxy but are now making their first passage to our Galaxy. This is reinforced by calculations using the distance and position of the Magellanic Clouds and the sinusoidal run of velocities along the Stream which show that the orbit is hyperbolic, the Clouds are near perigalacticon and their velocity is 300 km/s (Mathewson, 1985b). This is in good agreement with the velocity of the LMC of 378 km/s measured by Kallivayalil et al. (2006) from their proper motion measurements using the Hubble Space Telescope.

The sophisticated tidal modelling of Murai and Fujimoto (1980) showed that a close passage of the SMC to the LMC 2×10^8 years ago split the SMC in half and produced the Bridge. So Vince Ford, Vis Visvanathan and I observed 161 Cepheids which showed that the SMC had been split into two fragments 12 kpc apart. We called these the SMC Remnant and the Mini-Magellanic Cloud (Mathewson et al., 1986). This explained the double HI profiles seen in the SMC. They showed that the two fragments were separating at 40 km/s which gives the age of the splitting as 3×10^8 years, in good agreement with Murai and Fujimoto. Ca II absorption line measurements of stars in the SMC showed that the SMC Remnant, the lower velocity fragment, was closer to us than the Mini-Magellanic Cloud (Mathewson and Ford, 1984; Mathewson, 1985a).

As the HI in a large portion of the Bridge shows the same double profiles as the SMC, it is clear evidence that the tidal forces produced the Bridge at the same time as the splitting of the SMC. The double HI profiles are seen extending out to l = 294°, b = –60° in the Stream (Mathewson et al., 1974: Figures 1(a) and 1(b)). So the Stream must be about the same age as the Bridge, i.e. 3×10^8 years.

Figure 3 shows spurs in the Bridge pointing towards the Stream at the L1 Lagrangian Point where the gas is weakly bound. Meurer et al. (1985) believe that ram pressure from gas in the halo of our Galaxy swept the weakly-bound Bridge gas out to form the Stream. This explains why there are no stars in the Stream. If it had a tidal origin, stars would accompany the gas. Weiner and Williams (1996) found Hα emission at the leading edge of some of the clouds in the Stream, and they concluded that this strongly supported the ram pressure origin of the Stream.

At this point all of the clues had been satisfied. Then came the bombshell which turned all of the conclusions upside down. Figure 4 shows a composite map produced by Nidever et al. (2010a) of observations of the Stream from the Byrd Greenbank Telescope Survey, Leiden/Argentine/Bonn Survey, Parkes, Westerbork and Arecibo Observatories Surveys. Nidever et al. (2010b) claim that the Stream is now 140° long and if the HI clouds leading the Magellanic Clouds are included, the length of the Magellanic System is 200°. On both sides of the Magellanic Clouds the HI in the System reaches the disk plane of our Galaxy and beyond to northern latitudes.

The problem is that the hyperbolic orbit of the Magellanic Clouds is so eccentric that time scales in excess of 2 Gyr are needed to make their past orbit approach the disk plane of our Galaxy. Ram pressure and tidal models which took into account the much younger age of 0.3 Gyr for the Stream were no longer tenable.

Besla et al. (2010) produced a new tidal model based upon a LMC/SMC interaction some 2 Gyr ago which produced the Stream and reached the disk plane of our Galaxy. In their model the age of the Stream is about 1.5 Gyr, which is much older than the 0.3 Gyr estimated from very good observational evidence described earlier in this paper.

5 CONCLUDING REMARKS

An impasse has been reached after 37 years of hard work by many astronomers, and we are now no closer to reaching an understanding of the origin of the Magellanic Stream than when I was in the Control Room of the 210-ft Parkes Radio Telescope pumping air some 40 years ago! Perhaps there is something very fundamental about our Galaxy that we don't know?

If I could end on a word of caution from 'an old Streamer'. The Magellanic Clouds and Magellanic Stream lie in the Supergalactic Plane. This is a well-populated plane with Local Group galaxies, globular clusters and high-velocity HI clouds e.g., the HI clouds belonging to Sculptor, a galaxy in the Local Group (Mathewson et al., 1975). Be sure of the association of HI clouds with the Magellanic Stream or it could end up being 360° long!

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Don Mathewson joined Chris Christiansen at Fleurs in 1955, and helped him build the Chris Cross. Don lived at Fleurs with the Division of Radiophysics construction team, comprising Charlie Chenhall, Sid Hucker, Bill and George Coulter and Charlie Turrell. One of the proudest moments in Don's life was when he was invited into St. Marys to join them for their after-work beers and later to share their evening meals in a gypsy-style caravan parked on site at Fleurs. Life was not exactly 'a bed of roses': ten-hour days were the norm; the tents were draughty; there was only rainwater on site; an overhead bucket with a tap served as a shower, although everybody mostly used a large wash basin on the tank stand; a chocolate wheel was our toilet; all meals were cooked on 'Elsie' an old woodstove sheltered from the elements by corrugated iron; and any differences were settled by fisticuffs, generally after dinner —all very gentlemanly (and all very Australian)!

Don left Fleurs in August 1958 and presented some of the Chris Cross results at the Paris Symposium on Radio Astronomy. Then he spent several years at Jodrell Bank using the newly-commissioned 250-ft Dish. During this time he visited Bologna University three times as a consultant for the Italian Northern Cross antenna which was inspired by the Chris Cross. Returning to Australia, Don went back to Fleurs with two physics students, John Healey and John Rome, and used the 60-ft (Kennedy) Dish at the eastern end of the Chris Cross to survey the Milky Way at 20cm. Later this map was regularly used as a finding chart for the 210-ft Parkes Radio Telescope.

After three years at Parkes, Don worked in the US and Holland and then joined Mount Stromlo and Siding Spring Observatories, which he directed from 1977 to 1986. In 1995 he was farewelled at the Heron Island Workshop on Large Scale Motions in the Local Universe, although he remained active in astronomy as a Vice President of the IAU.

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IN MEMORY OF EUGENE (JENŐ) VON GOTHARD: A PIONEERING NINETEENTH CENTURY HUNGARIAN ASTROPHYSICIST

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Abstract: Eugene von Gothard was a Hungarian engineer/scientist, instrument-maker and astrophysicist who founded the Herény Astrophysical Observatory in 1881 and carried out pioneering work in astronomical photography and spectroscopy. In this paper we provide biographical material about von Gothard and describe his observatory, before discussing his astronomical observations and the contribution that he made to the early development of astrophysics.

Keywords: Eugene von Gothard, Herény Astrophysical Observatory, astrophysics, astronomical photography, spectroscopy.

1 INTRODUCTION

Eugene von Gothard (Figures 1 and 2) was born on 31 May 1857 in Herény, Hungary, the eldest son of a land-owning family (Harkányi, 1910). He received a degree in mechanical engineering from the Technical University in Vienna in 1879, and just two years later—at the age of 24—founded the Herény Astrophysical Observatory (Figure 3), which was acknowledged in the international scientific literature by the end of the nineteenth century. Von Gothard studied astrophysics, the 'New Astronomy', and he designed and produced instruments that were indispensable for his work.

Von Gothard expressed his philosophy rather beautifully at a party hosted by the Hungarian Scientific Association in 1886:

> … how versatile and mysterious the challenges are, which are still unsolved and the solutions of which are within an inch! And so are the utensils with which the adherents of Urania, sparing no time, no expense, no pains, expecting no appreciation, looking for no sensation, slowly but surely delve deeper and deeper into the sanctuary of nature pursuing the highest goal: the search for the truth. (von Gothard, 1886a: 23; our translation).

Between 1881 and 1895 he made important contributions to astronomical spectroscopy and astronomical photography before being appointed technical manager of the Vas Comitat Electric Works Inc., which was being built on the River Rába, and abandoning his astrophysical studies. In 1899 the first signs of serious heart disease were diagnosed, and von Gothard was forced to retire, but this did allow him to return briefly to his astrophysical studies in 1901. Eugene von Gothard died unexpectedly on 29 May 1909, just two days shy of his 52nd birthday. He was described by Harkányi (1910: 7) as

> … a very kind, reserved man, with great energy, and helpful to everybody who asked aid or advice. He was the recipient of many honors: in 1886 the Voigtländer silver medal from the Vienna photographic society; in 1887 the gold medal of the Vienna photographic exhibition; the highest distinctions of the photographic exhibition of 1889 in Berlin and of 1889 in Moscow. In 1890 he was elected corresponding member of the Hungarian Academy of Sciences in Budapest. He was also a member of the Royal Astronomical Society, of the Astronomische Gesellschaft, and of several other learned societies.

Apart from his valuable contribution to astronomy, Eugene von Gothard also conducting pioneering X-ray experiments (see Vincze and Jankovics, 2010).

Figure 1: Eugene von Gothard, 1857–1909 (courtesy: Gothard Astrophysical Observatory Archives).

Figure 2: The medal struck in 2009 to commemorate von Gothard's contribution to Hungarian astronomy.

2 EDUCATION AND THE FOUNDATION OF VON GOTHARD'S SCIENTIFIC WORK

Eugene von Gothard attended the Premonstratensian Secondary Grammar-School, and the love of nature that he brought from home achieved perfection under the influence of Adolf Kunc, who was his teacher.

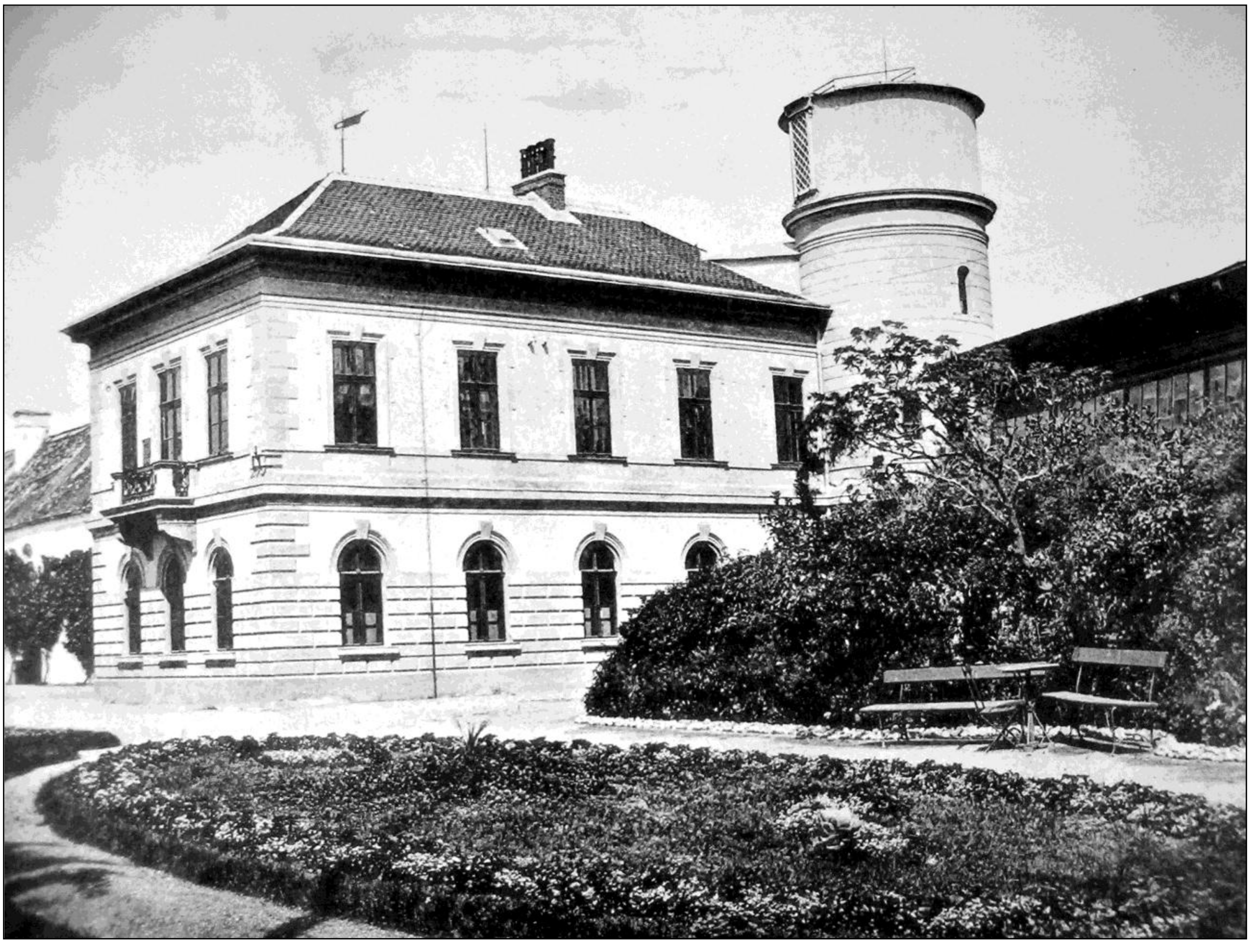


Figure 3: The von Gothard mansion and the Henéry Astrophysical Observatory (courtesy: Gothard Astrophysical Observatory Archives).

When he was still at secondary school von Gothard established physics and chemistry laboratories plus a workshop in a wing of the von Gothard mansion, where he carried out experiments and constructed scientific instruments.

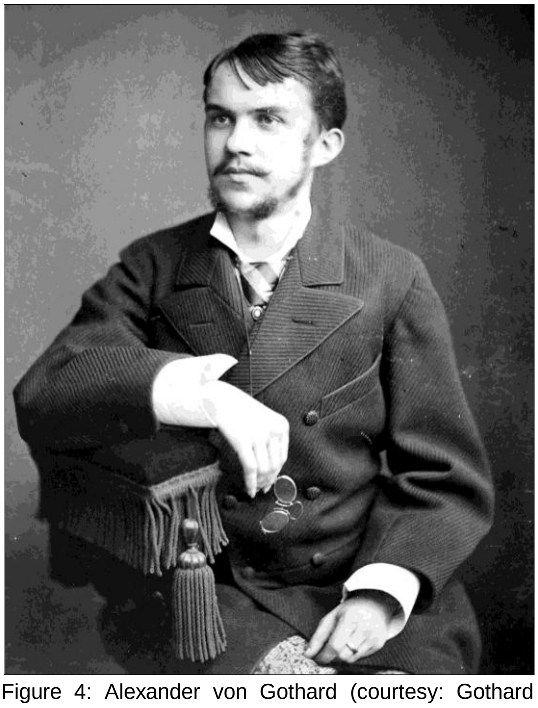


Figure 4: Alexander von Gothard (courtesy: Gothard Astrophysical Observatory Archives).

Von Gothard then carried on with his studies in Vienna at the Technical University (Polytechnische Hochschule), and after completing them he returned home and ran a farm in Herény with his brother, Alexander. This, of course, did not mean that he neglected his laboratory, for he spent his spare time experimenting and studying.

In 1880 von Gothard accepted an invitation from Nicolaus von Konkoly Thege (1842–1916) and visited the Konkoly Observatory at Ógyalla,[1] where his insatiable desire for science flared during his observations of the night sky and long conversations with Konkoly. This visit to Ógyalla not only gave von Gothard direction but it also led to a long and deep friendship.

3 THE FOUNDING OF THE HERÉNY OBSERVATORY

Inspired by Konkoly Thege, Eugene von Gothard and his brother Alexander (1859–1939; see Figure 4) founded the Herény Astrophysical Observatory in 1881 by reconstructing the eastern part of the mansion and at the same time extending the physics laboratory (Figure 5). The 11.22-m high observatory was designed by Professor Alajos Hauszmann from the Technical Universiy in Budapest. It was circular in cross-section, and 4.42 metres in diameter, and was made of stone. However, Eugene von Gothard designed the drum-shaped dome himself (Vincze and Jankovics, 2010), which featured twin shutters. These were each 1 metre wide, and could be moved to the side to ex-

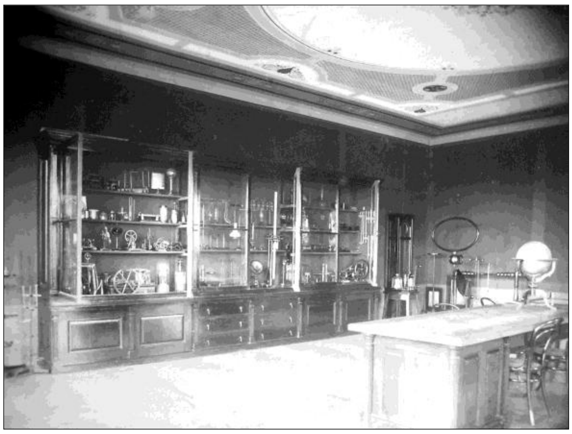



Figure 5: Two views of the refurbished physics laboratory in 1882 (courtesy: Gothard Astrophysical Observatory Archives).

pose a strip of sky. The dome was mounted on wheels and was rotated manually (von Gothard, 1882). Figure 3 shows the von Gothard mansion, and the Observatory after it was completed.

The main instrument in the observatory was an f/7 10.25-in (26-cm) silver-on-glass Newtonian reflector which was made by the British telescope-makers Browning-With[2] in 1874. This was on a solid equatorial mounting with a mechanical drive. There was a 2.25-in Steinheil guide scope and a 2-in Browning finder. Nine eyepieces (see Figure 6) came with the telescope (three Kelners giving 77×, 80× and 140×; three Huygenses giving 240×, 436×, 580×; and three Ramsdens giving 208×, 590×, 840×), along with various filters. When he purchased the telescope from his friend Konkoly Thege in 1881 there was also a Herschel wedge for solar observing, a calcite prism ocular spectroscope and square bar and ring micrometers (von Gothard, 1882). Figure 7 shows the telescope some time after von Gothard acquired it. With the passage of time, von Gothard manufactured various new instruments (e.g. spectroscopes, spectrographs, a spectrocolorimeter, a photometer and astrocameras) which he used with the telescope, and these are discussed below in Section 4.

In order to maintain a local time service the Herény Astrophysical Observatory included a transit annex, which housed a 27-mm Fraunhofer transit telescope that was made in 1879 (Figure 8), and two identical astronomical clocks (see Figure 9) that von Gothard made in 1881.

The Observatory was completed in October 1881, and the first observations, colloquially known as 'first light', were made on the 20th of that month (Vincze, et al., 2003).

3.1 Infrastructure at the Observatory

From the start, Eugene von Gothard set up a modern infrastructure at the Observatory so that whatever was necessary for his work could be found in every room there: gas, water, a telephone and electric power. Even before the Observatory was finished the mansion had lighting with the help of a Siemens dynamo (von Gothard, 1885a). The telephone and Morse code station were connected to the physics laboratory at the Premonstratensian grammar-school and to Adolf Kunc's private flat by permission of the State Telegraph Office Minister, so that the telephone and the telegraph could be used for scientific and experiment-

Figure 6: Some of the eyepieces that came with the telescope (courtesy: Gothard Astrophysical Observatory Archives).

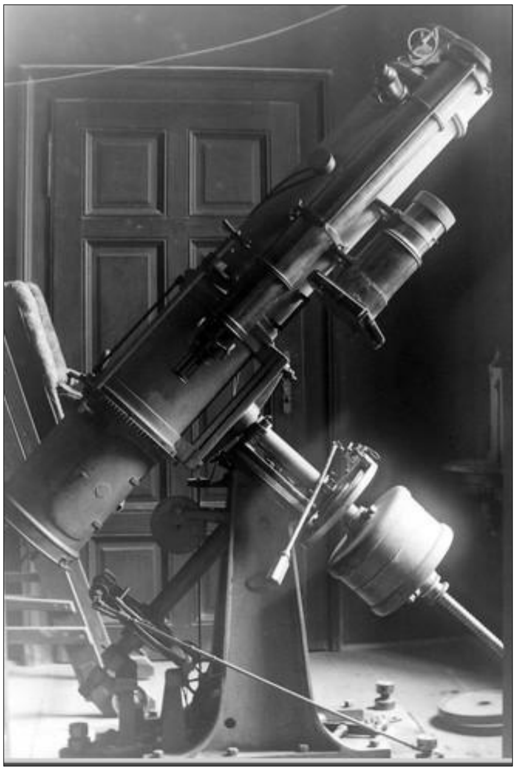


Figure 7: The 10.25-in Browning-With reflecting telescope at the Henéry Observatory (courtesy: Gothard Astrophysical Observatory Archives).

Figure 8: The 27-mm Fraunhofer transit telescope (courtesy: Gothard Astrophysical Observatory Archives).

al purposes (von Gothard, 1882). Meanwhile, von Gothard's well-equipped physics and chemistry laboratories and workshop housed all the latest equipment required for an observatory that was about to embark on a journey of discovery in astrophysics.

At the time he founded the Observatory von Gothard admitted that his library was quite small, but after 1884 he put considerable effort into extending the collection. In order to fill some of the gaps he established close relations with several foreign booksellers. His bills for books and journals reveal a broad-minded European scientist who added contemporary technical literature necessary for his research.

Figure 9: One of the 1881 astronomical clocks (courtesy: Gothard Astrophysical Observatory Archives).

He also acquired several second-hand rarities, including Kepler's *De Stella Nova in Pede Serpentarii* (1606), Scheiner's *Rosa Ursina, sive Sol* (1630), Bayer's *Uranometria* (1661), Ricciolo's *Almagestum Novum* (1651) and his *Astronomia Reformata* (1665), Hevelius' *Selenographia* (1647) and his *Machinae Coelestis* (1673), Brahe's *Historia Coelestis* (1666), and Marinonio's *De Astronomica Specula Domestica* (1745). Most of these can still be found in the von Gothard Collection (see Jankovics, at al., 1995).

4 CONSTRUCTION OF ASTRONOMICAL INSTRUMENTS AT HERÉNY

4.1 Introduction

Initially von Gothard used devices that he obtained, borrowed, exchanged, or purchased from Konkoly Thege, and adapted them for his astronomical observations. Soon, however, he decided to

> ... manufacture his own astrocameras and spectroscopic measuring instruments. He also reconstructed other types of instruments and developed them according to his own research objectives, in the process making them more convenient, more modern and more accurate. In these endeavours von Gothard was assisted by Jozsef Molnar, a technician who worked in the Observatory's workshop. (Vincze and Jankovics, 2010).

In the Herény workshop, von Gothard generally made two or three copies of each new instrument. He retained one copy for his own observatory, generally sent a second copy to Konkoly at Ógyalla, and sometimes supplied yet a third copy to any other observatory that had previously placed an order (Vincze, et al., 2003). In this way, he succeeded in strengthening the specialist astronomical instrumentation at not only his own observatory but at other European observatories and furthering the cause of international astrophysics.

During the manufacturing process, von Gothhard made all of the precision mechanical parts, mounting bases and supporting elements himself, whereas the specialized elements such as the optics were bought from the most famous producers in Europe. It is obvious from von Gothard's publications, and proved by the business letters and bills stored in the archives of the Gothard Astrophysical Observatory, that among the suppliers of the Herény Astrophysical Observatory were companies like Voigtländer & Sohn (Braunschweig), C.A. Steinheil & Söhne (München) and J.H. Dallmeyer (London). It is also notable that from 1881 all of the instruments produced in the Herény workshop were modified by von Gothard on the basis of experience he had gained during earlier observing programs. In this way he was able to improve their accuracy and/or their use.

4.2 Instruments for Spectroscopy

To increase dispersion and to observe the spectra of dimmer objects, von Gothard constructed a spectroscope of his own design, drawing on the advantages and disadvantages of spectroscopes that he had used previously. The Great Comet of September 1882 proved to be the primary incentive for completing this new spectroscope as von Gothard (1883b) wanted to observe its weaker spectral lines. The next astronomer to use the new spectroscope was C.N. Adalbert Krüger (1832–1896), the Director of the Kiel Observatory, who published favourable comments about it (see Krüger, 1884).

Von Gothard's quest for technical perfection is obvious from the fact that while using his new spectroscope he was already busy designing an improved version. For example, lighting of the 1884 'clarinet spectroscope' was solved not by using an oil lamp but instead a small Edison 4V filament lamp. Von Gothard used his own ideas to design and produce the new instrument, and as an expert in precision mechanics he built the optical parts with practical casings. He also redesigned the electrical components. When observations were to be carried out, the instrument could be inserted in place of the eyepiece of the telescope, whereas in the laboratory it was placed on a laboratory stand. This new spectroscope was made up of five rows of prisms in order to ensure high dispersion, and there was an adjustable reading-telescope at the end, the movement of which could be measured with an extra-fine measuring screw in order to accurately determine the positions of the spectral lines. The lighting of this scale was extremely convenient, lasting only during setting up and when readings were being taken, otherwise the observations were carried out in complete darkness. For comparison spectra, von Gothard transferred light from the Geissler tubes to the slit of the spectroscope, or when comets were observed a gaslight was used to identify the hydro-carbon lines (see von Gothard, 1884b).

In 1882 von Gothard made three identical spectro-colorimeters in the Herény workshop, for Jean-Charles Houzeau (1820–1888) in Brussels, for Konkoly in Ógyalla and for his own observatory The spectro-colorimeter was attached with a bolted joint to the Browning telescope, in place of the eyepiece. Using this innovative instrument the colours of stars could be observed visually using the colorimeter, or the spectral lines could be measured with the spectroscope. Having simultaneous access to these two different functions resulted in a more detailed classification of stars (see Konkoly, 1882).

In order to refine his measurements of stellar spectra von Gothard then began constructing spectrographs, and these supplemented the spectroscopes that he had previously used for visual observations. The challenge was to develop new refracting media, to refine the spectral characteristics of light-resolving devices, to get to know the resolving conditions and to achieve the precision mechanical development necessary for the solution of astrophysical tasks. In the development of von Gothard's spectrographs we can follow the early improvements in astrospectroscopy, from the direct low-resolution prism solutions applied in ocular spectroscopes, through prisms imaging larger ranges of the spectrum. These were developed intensively from the mid-1880s, and used new optical glass or modern gratings. The most important parameters of these devices were: dispersion, spectral purity, resolving power, free spectral range and light intensity. In von Gothard's instruments, these parameters were developing gradually.

In 1886, von Gothard published the technical description of the calcite prism spectrograph that he built which is shown in Figure 10.

Later in 1886 he constructed a Wernicke-prism spectrograph, which was born out of the need to achieve greater dispersion and to extend the ultraviolet range of the spectrum (see Konkoly, 1887).

Figure 10: The calcite prism spectrograph (Gothard No 9) made in 1886 (after von Gothard, 1886b).

Von Gothard also produced two spectrographs equipped with Rowland gratings, one for Josef Maria von Eder (1855–1944), who was a Professor at the Technische Hochschule in Vienna and Director of K.K. Lehr- und Versuchtanstalt für Photographie und Reproductionsverfahren, and another for his own observatory (Eder, 1896).

4.2 An Instrument for Visual Photometry

Besides investigating the spectra of stars von Gothard also was interested in measuring temporal changes in their brightness, and another innovative instrument he developed in the Herény workshop in order to achieve this was a wedge-photometer. This was constructed in 1885 (see Figure 11), and its main part was the gray wedge that could be placed in front of the eye or the eyepiece. It was very important that no extraneous light was cast on it between the two necessary adjustments, so it was not practical to read off the scale using a lamp. Instead, a self-recording machine was

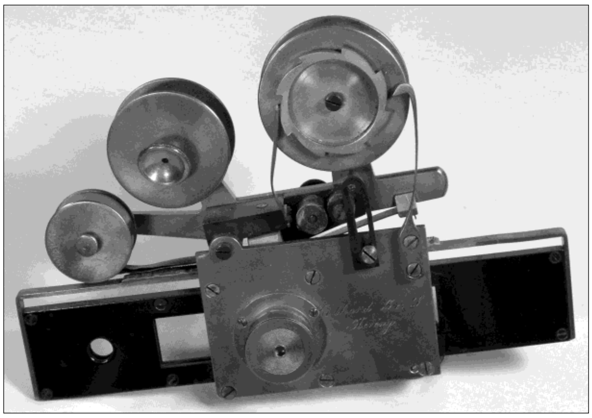
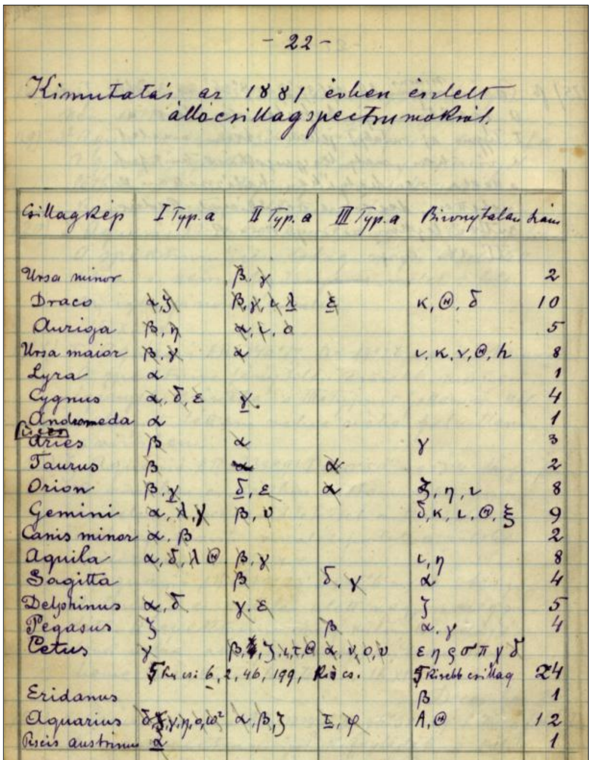


Figure 11: The wedge-photometer constructed at Herény in 1885 (courtesy: Gothard Astrophysical Observatory Archives).

Figure 12: The 10-cm aperture astrograph constructed by von Gothard in 1893 (courtesy: Gothard Astrophysical Observatory Archives).



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Kimutatás az 1881 évben észlelt állócsillagspectrumokról.

Csillagkép	I Typ. a	II Typ. a	III Typ. a	Bizonytalan	szám
Ursa minor		β, γ			2
Draco	α, ζ	β, γ, ι, λ	ξ	κ, θ, δ	10
Auriga	β, η	α, ι, a			5
Ursa maior	β, γ	α		υ, κ, ν, θ, h	8
Lyra	α				1
Cygnus	α, δ, ε	γ.			4
Andromeda	α				1
Aries	β	α		γ	3
Taurus	β	α	α		2
Orion	β, γ	δ, ε	α	ζ, η, ι	8
Gemini	α, λ, γ	β, υ		δ, κ, ι, θ, ξ	9
Canis minor	α, β				2
Aquila	α, δ, λ θ	β, γ		ι, η	8
Sagitta		β	δ, γ	α	4
Delphinus	α, δ	γ, ε		ζ	5
Pegasus	ζ		β	α, γ	4
Cetus	γ	β, ξ, ζ, ι, τ, θ	α, ν, ο, υ	ε η ς σ π γ δ	
	5 kis cs: 6, 2, 46, 199,	kis cs.		5 kisebb csillag	24
Eridanus				β	1
Aquarius	δ, ξ, γ, η, ο, ω²	α, β, ζ	ξ, φ	A, θ	12
Piscis austrinus	α				1
	20	34	29	12	39	114

Észlelések száma = 125

Észlelési napok száma = 10 nov. 9 10 12 15 16 18 19 20 21 dec. 25

Pisces 27, 29 XI. 2

Figure 13: An example of a page from von Gothard's observing notebook (courtesy: Gothard Astrophysical Observatory Archives).

applied. Also, the eye had to adapt to complete darkness at the beginning of the observations, and after half an hour of observing the astronomers had to change over due to the tiredness of their eyes. However, after long practice, measurements using this visual technique become more and more accurate. Choosing the appropriate natural wedge was very important so that the absorption of the wedge did not depend on wavelength. Knowing all this, von Gothard (1887b) created a perfect instrument for his time.

4.3 Instruments for Astronomical Photography

In order to photograph comets, diffuse nebulae and other objects Eugene von Gothard constructed a wide-angle astrograph which he mounted parallel to the optical axis of his Browning telescope at the Herény Astrophysical Observatory.

In handbooks that he published in 1887 and 1890 Nicolaus von Konkoly Thege described this astrograph and other photographic equipment designed, constructed or modified by von Gothard, and he included more than two dozen relevant figures. He emphasized the applicability, practicality, convenience and accuracy of von Gothard's instruments, and noted that:

> ... [he] is not only an extremely proficient and tireless photographer of the sky, but also a true artist in precision mechanics. (Konkoly, 1890: 163; our English translation).

A 10-cm aperture astrograph manufacted by von Gothard in 1893 is shown in Figure 12.

Eugene von Gothard's activity in developing technical instruments for his astrophyical research is extremely well documented in monographs and papers that he published (e.g. see von Gothard, 1883b; 1886b; 1887b).

5 VON GOTHARD'S ASTROPHYSICAL RESEARCH

5.1 The Early Visual Spectroscopic Observations

When the Herény Astrophysical Observatory was founded, Eugene von Gothard's aim was to carry out spectroscopic observations of stars and comets while his brother, Alexander, focussed on Mars, Jupiter and the Sun (Vincze, et al., 2003). From the beginning they kept a record of the observed phenomena, describing and drawing what they saw (e.g., see Figure 13).

In September 1882, von Gothard observed the spectrum of the Great Comet of 1882 (C/1882R1) and published this observations in the *Astronomische Nachrichten* (von Gothard, 1883a) where he called attention to the strong hydrocarbon lines in the spectra of comets. Later, during its perihelion passage, the nucleus of this comet split into eight discrete fragments (see Sekanina, 1997), but all of von Gothard's observations preceded this spectacular event.

Von Gothard then began observing stars, but only those whose spectra were especially interesting and possibly variable. By 1883 he had observed the spectra of 86 stars, and his examination of the hydrogen emission lines of the variable stars β Lyrae and γ Cassiopeiae was especially revealing:

> It is extremely important to study the spectra of these two stars thoroughly. This is because it points to the significance and precision of spectral analysis, which

will enable us to examine intensively stars that are billions and billions of miles away. We can not only see their chemical characteristics, but we can also follow their physical changes and their movements. First of all, this reveals the greatness of the human mind in its complexity, for which there is no distance, or magnitude it cannot comprehend and examine ... and secondly, it convinces us that even in the farthest depths of the Universe there is life, movement, change, development and decline, and it gives us a key to the mysteries of variable stars, although it does not reveal all of the answers. (von Gothard, 1884a: 2; our translation).

Then in 1885 he reported on the periodic appearance and disappearance of the hydrogen and helium lines in the spectrum of β Lyrae (von Gothard, 1885a). However, Vincze et al. (2003: 396-397) point out that this discovery "... did not get any attention, as there was insufficient astrophysical background [at that time] for the interpretation of the phenomenon."

In a publication titled *Publikationen des Astropysikalischen Observatoriums zu Herény Eugene von Gothard*, Eugene von Gothard (1885b) summarised the activities of the new Herény Observatory in 1884, and he sent copies to the most renowned astronomical institutes in the world and began to exchange publications with many of them. This scheme brought his work to the attention of the international astronomical community. Meanwhile, in 1881 and 1883 he joined the Astronomische Gesellschaft and the Royal Astronomical Society, respectively, but it was only in 1890 that he was elected a Corresponding Member of the Hungarian Academy of Sciences (Vincze and Jankovics, 2010).

5.2 Pioneering Astronomical Photography and Spectral Photometry

On 16 May 1882 Eugene and Alexander von Gothard launched their 'careers' as pioneering Hungarian astrophotographers by taking a series of photographs of a partial solar eclipse (see Figure 14), and by 1885—after carefully experimentation—they had almost completely abandoned visual observations. They then directed the focus of the Herény Observatory towards the new technologies of spectrography and astrophotography. In that year they photographed a supernova in the Andromeda Galaxy and carried out spectroscopic observations (von Gothard et al., 1885), and on 20 April 1885 Eugene submitted a work titled "Studies in photographing celestial bodies" (our English translation) to the Hungarian Academy of Sciences (von Gothard, 1885c). Then from 1886 Eugene von Gothard was completely engaged in the spectral examination of clusters, comets (e.g. see Figure 15) and gaseous nebulae. He was also the first to record an image of a faint previously undetected comet on photographic emulsion (von Gothard, 1887a), and in 1886 he was the first to photograph the central star of the Ring Nebula in Lyra (M57):

In the autumn of 1886 I photographed the Ring Nebula in Lyra. In the middle of this ring there is an extremely sharp, intensive star on the picture; after repeating the exposure with the same result, I asked some observatories with large instruments to observe this interesting star. The star could not be seen, so my credibility was already at risk when at last, a year later, with the huge, 27 inch refractor at the Vienna Observatory the small star was sighted, which, with my small 10-inch reflector

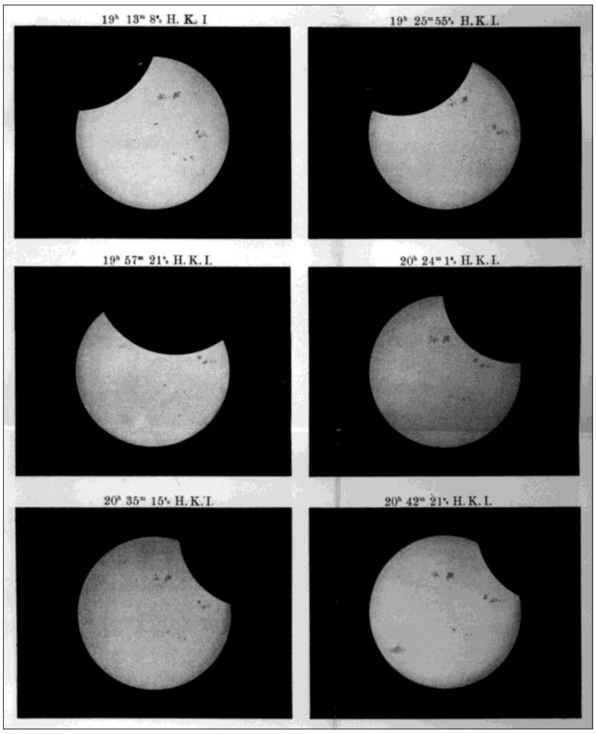


Figure 14: Von Gothard's photographs of the 16 May 1882 partial solar eclipse (after von Gothard, 1890).

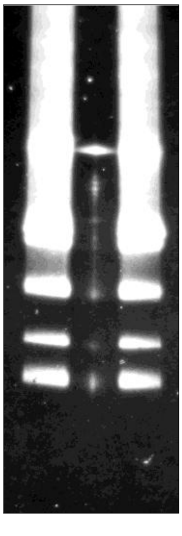
I can photograph easily any time ... [This] example palpably proves the practicability of photography. (von Gothard, 1890: 19; our English translation).

Hermann Carl Vogel (1841–1907), Director of the Potsdam Astrophysical Observatory, wrote about photographs of gaseous nebulae taken with the instruments at Herény:

Von Gothard's photographs prove that even with a modest instrument photography enables us to achieve scientific results that exceed by far what was attainable using visual observations and the largest instruments. (Vogel, 1888: 338; our English translation).

In 1890, as an experienced researcher in the field of astrophotography, Eugene von Gothard wrote a book on the applications of photography for scientific purposes. Its title, translated into English, was: *Photography. Practice and Applications for Scientific Purposes.*

Figure 15 (right): Spectrogram of Comet C/1892 E1 Swift (after von Gothard, 1892c).



In the ten years following the foundation of his Observatory, von Gothard had worked with energy and success in the fields of spectroscopy and astrophotography, and as an acknowledgement of his theoretical, practical and instrumental work he was accepted as a Corresponding Member of the Hungarian Academy of Sciences in 1890. On 20 April 1891 he presented his inaugural address titled "Studies in spectral photography" in which he summarised the results of his activities over the past six

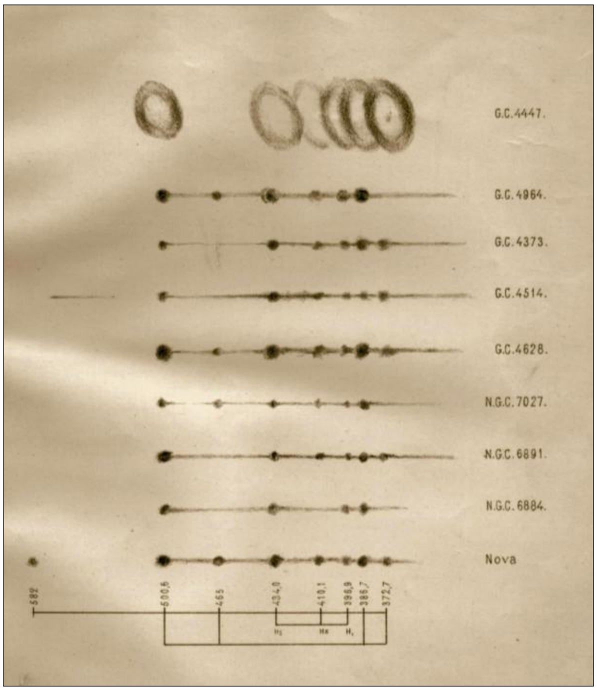


Figure 16: The spectra of Nova Aurigae and a few planetary nebulae (after von Gothard, 1892a).

years (see von Gothard, 1891). This study focussed on the identification of spectrum lines and the accurate determination of their wavelengths.

In 1892 von Gothard carried out a photographic examination of the spectra of planetary nebulae using a 250-mm objective-prism with the Browning-With reflector (von Gothard, 1892a). Then, while studying the spectrum of Nova Aurigae, he proposed a connection between novae and planetary nebulae:

> … the spectrum of the nova is identical to the spectrum of planetary nebulae [see Figure 16]. By working hard with photographic plates I succeeded in determining the wavelengths of the lines we had detected. I managed to identify several of them with terrestrial materials, and in this way extend our knowledge about these extremely dim celestial bodies, which has been fairly inaccurate thus far. I regard it as very important that I was able to find a closer relationship between nebulae, the new star and some other interesting stars and though I find it too early to draw conclusions, I can point to the direction which may lead to understanding the nature of nebulae and new stars. (von Gothard, 1892b; our English translation).

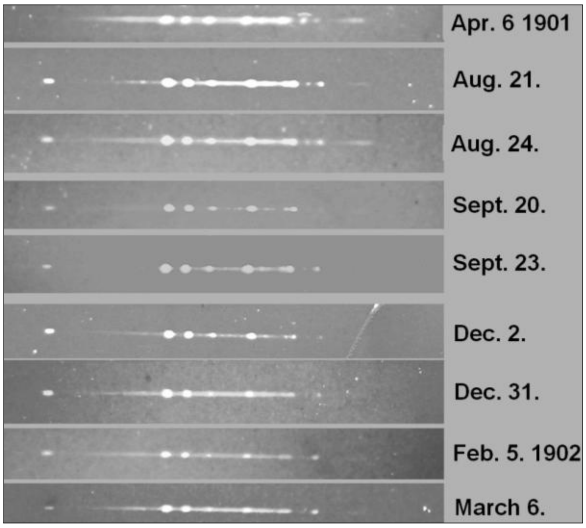


Figure 17: Spectroscopic observations of Nova Persei made in 1901 and 1902 (courtesy: Gothard Astrophysical Observatory Archives).

In our opinion, this discovery was the most outstanding achievement of von Gothard's work. His result is regarded by experts worldwide as one of the predecessors of theories of the later stages of stellar evolution (e.g. see Hearnshaw, 1986).

On 9 April 1892, von Gothard took a four-hour exposure photograph of the spectrum of Comet Swift in the spectral range between 3873 and 5673 Å (see Figure 15), and identified a number of hydrocarbon bands (von Gothard, 1892c).

Eugene von Gothard's astronomical activities were aborted in 1895 when he took on responsibilities at the Vas Comitat Electric Works Inc. which was being built on the River Rába, and it was only many years later, in 1901, that he was able to return briefly to astronomy. In this year he took a high quality and high resolution spectrogram of Nova Persei (von Gothard, 1901), and he then followed up by analysing the changes in the spectrum of this nova as it dimmed over the course of the following year (see Figure 17).

7 CONCLUDING REMARKS

Eugene von Gothard was a pioneering nineteenth century Hungarian astrophysicist who over a fifteen-year period built his own instruments and conducted astronomical research with them. He published his results in *Astronomische Nachrichten* and *Zeitschrift für Instrumentenkunde*, which brought him to the attention of the international professional astronomical community. Some of his papers on the spectra of comets, planetary nebulae and novae made useful contributions to astrophysics, and his successful application of photography and spectroscopy to astronomy brought him renown throughout Hungary.

Many of the scientific instruments constructed and used by von Gothard and astronomical records that he kept have been preserved by the Gothard Astrophysical Observatory at the Loránd Eötvös University in Hungary, and

> … a valuable part of this material is the astronomical plate collection of 455 pieces taken between 1882 and 1900, containing unique images of comets, star clusters, nebulae, galaxies and stellar spectra … (Vincze, et al., 2003: 394).

These same authors (2003: 397-398) stress that it is

> ... very important to preserve and to publish this unique and early collection in digital format and, in so doing, turn the attention of the astronomical community once again toward the scientific achievements of Gothard. Gothard Observatory.

Some of von Gothard's astronomical instruments mentioned in this paper are currrently on display at the Gothard Astrophysical Observatory of Eötvös University in Herény, Hungary (see Figure 18).

8 NOTES

1. At the time Konkoly was Hungary's foremost astronomer (see Sterken and Hearnshaw, 2001).
2. During the second half of the nineteenth century George With (1827–1904) of Hereford (England)

Figure 18: Von Gothard instruments and records on display at the Gothard Astrophysical Observatory.

and John Browning (1835–1925) of London combined their respective talents to make reflecting telescopes that were popular with amateur astronomers and professional observatories. With produced the optics, with primary mirrors up to 18 inches (45.7-cm) in aperture (King, 1979), while Browning manufactured the telescopes and mountings that accommodated these optics (ibid.).

3. In the literature, Eugene von Gothard's published papers written in German are listed under 'E. Von Gothard', while in the case of those written in Hungarian his name is given as 'J. Von Gothard' (with the J standing for Jenő).

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ADVANCING ASTRONOMY ON THE AMERICAN FRONTIER: THE CAREER OF FRANK HERBERT LOUD

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Abstract: Frank Herbert Loud came to Colorado Springs in 1877 to teach mathematics and became interested in astronomy after witnessing the solar eclipse of 1878. His nearly 50-year astronomical career included overseeing the building of two observatories, founding the Western Association for Stellar Photography, supporting expeditions for two solar eclipses, supplying astronomers with meteorological data for the Rocky Mountains, educating students, publishing astronomical articles and giving public lectures, and aiding and influencing two Directors of Harvard College Observatory. Despite this, Loud and the two observatories he directed have been mostly forgotten, although they were well known by contemporary astronomers. Loud and his work deserve to be remembered given the relative scarcity of astronomers and observatories in the American West (i.e. west of the Mississippi River) in the late nineteenth and early twentieth centuries.

Key words: Frank Loud, Edward Pickering, Donald Menzel, Western Association for Stellar Photography, Colorado College, Wolcott Observatory, Nob Hill Observatory, 1878 Eclipse, 1918 Eclipse

1 INTRODUCTION: FROM BOSTON TO COLORADO SPRINGS

Frank Herbert Loud (Figure 1) was born 26 January 1852 in Weymouth, Massachusetts. He graduated from Amherst College in 1873 and received an MA degree from Amherst in 1878. He later received another MA from Harvard (1899), and a PhD from Haverford College (1900).[1] Although his career was spent in Colorado (from 1877 until just before his death in 1927), Loud made frequent visits to Boston and other eastern cities. Keeping close ties to the east coast was perhaps the only way to undertake a program of sophisticated astronomical observation and instruction in the American west.

Loud taught mathematics at Amherst from 1873 to 1876 before accepting a position at Colorado College. Arriving in 1877 in Colorado Springs, Colorado, Loud was the first Head of the College's Mathematics Department. From its inception Colorado College (founded 1874) was envisioned almost as an outpost of Boston and its colleges, and soon provided western students to eastern schools. Although the founder of Colorado Springs, General William Jackson Palmer (from Pennsylvania), donated the land for the College, the rest of the early development of the school was guided by New Englanders. Colorado College was non-denominational (though 'under Christian auspices' per its charter); it was also coeducational. One of its very first Presidents was a New Hampshire Congregationalist, Edward P. Tenney, who revered Harvard and was friends with the wealthy Bostonian Henry Cutler; Cutler provided the funding for Colorado College's first building, Cutler Hall. Tenney and Cutler then borrowed $100,000 to purchase land for the school, which property they called 'New Massachusetts'. In 1888 William F. Slocum, a Congregational minister from Massachusetts, succeeded Tenney as President and brought further financial and educational support from Boston. Even the school's buildings were designed by Boston architects (Sprague, 1987: 260–63). The connection to Boston helps explain how a young Frank Loud was lured from established Amherst to fledgling Colorado College. It further explains the connections between Loud and astronomers like Edward C. Pickering of Harvard College Observatory and David Peck Todd (an Amherst graduate) of the United States Naval Observatory.

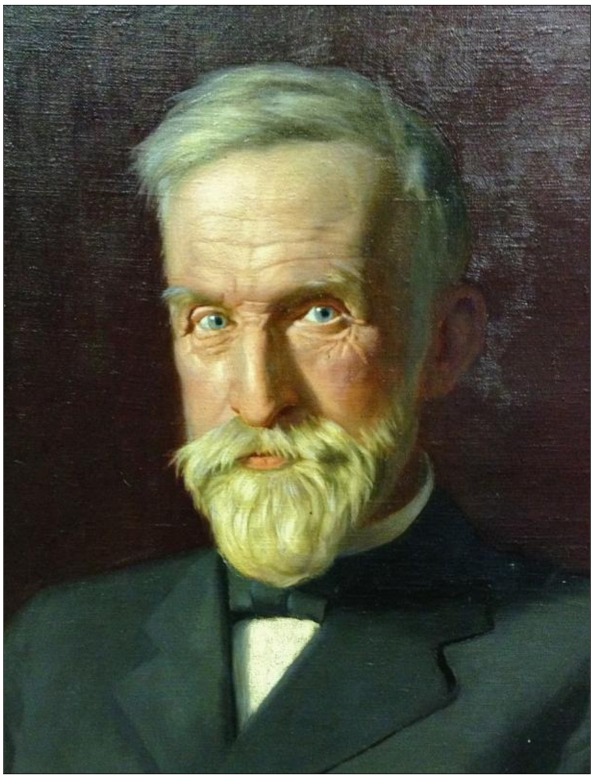

Figure 1: Frank Loud ca. 1923, oil painting by J.I. McClymont (courtesy: Colorado Springs Pioneers Museum, Starsmore Center for Local History).

Loud founded Colorado College's meteorology program. At the time the 14,115-foot (4302-m) summit of nearby Pikes Peak had the world's highest meteorological station. This resource, combined with his own daily readings, enabled him to provide meteorological data to astronomers interested in Rocky Mountain observing conditions. Loud published annual meteorological data and was on one occasion employed by the U.S. Weather Bureau. Loud's meteorology course ('Astronomy D') at Colorado College eventually attracted from 15 to 25 students and was known for its "… value for training in habits of observation." (*Proceedings of the Third Convention of Weather Bureau Officials*, 1904: 177). In addition to teaching mathematics and meteorology Loud was Colorado College's first Librarian from 1878 to 1886; Melvil Dewey, creator of the Dewey decimal classification system, was Loud's Amherst classmate.

Loud also started the Colorado College Scientific Society in 1890 with his better-known Mathematics Department colleague, Florian Cajori. The Society published its own journal, *Colorado College Studies*, which conveyed Loud's astronomical observations and annual meteorological data for Colorado Springs. He aggressively promoted this journal by sending subscriptions to observatories as far afield as Mexico City, Havana, Toulouse, Karlsruhe, Milan, and Melbourne —helping ensure that Colorado College received reciprocal exchanges.

Thus Loud's astronomical work was enhanced by his expertise in mathematics and meteorology, and these pursuits were themselves done to advance Colorado College's instruction in the sciences. Hence Loud's various titles over the course of his tenure ranging from Professor of 'Mathematics and Metaphysics' to 'Mental Philosophy; Mathematics; and Meteorology'. By 1889 he was 'Professor of Mathematics, Astronomy and Meteorology'. Let us start at the beginning, however, with the event that sparked Loud's interest in astronomy: the total solar eclipse that passed over the Rocky Mountains on 29 July 1878, the year after Loud came to Colorado.

2 THE ECLIPSE OF 1878

The total solar eclipse of 1878, which was viewed from Wyoming through Colorado and down into Texas, was perhaps the most impressive scientific event the western states and territories had yet experienced. Renowned astronomers like Norman Lockyer, Henry Draper, Charles Young, and Samuel Langley (to name just a few) spread out along the front range of the Rocky Mountains, from Wyoming down through Colorado (including Colorado Springs). David Peck Todd observed from Texas. The arrival of Langley's party and their equipment in Colorado Springs impressed Loud; all the activity and preparation was tremendously exciting—astronomers arriving with crates full of instruments, daily time checks at the local signal office, and telegrams back and forth from eastern observatories to the top of Pikes Peak where Langley would observe the event.

To ensure his own participation Loud drew upon his Boston connections in advance. In February 1878 Loud wrote to Todd that he was now at Colorado College, "… an institution which while it has in reality an excellent prospect for the future is but just established and has no completed buildings no instruments and very little money." He emphasized, however, that the school was "… right in the track of the coming total eclipse of July 29th …" and, in short, could Todd please advise how "… in such paucity of resources …" he could use the eclipse "… to the very best advantage for the benefit of the college and everybody else concerned." He concluded by reminding Todd of their mutual connection to "… old Amherst ... I remember the direction of your tastes in science." (Loud, 1878a).

Todd was eager to help and provided a small loaner telescope with which Loud practiced for the eclipse by first observing a transit of Mercury on 5-6 May 1878. In return Loud supplied Todd with local meteorological data, and later his report on the transit—Loud's first official contribution to astronomical science. "But for your encouragement," he wrote Todd, "we should not have attempted the observation, which has certainly been excellent practice for us, whether useful in any other way or not." (Loud, 1878b).

As the eclipse of 29 July approached Loud endeavored to make himself a resource both for residents of Colorado Springs and visiting astronomers. Loud gave public lectures, wrote articles in the local newspaper (the Colorado Springs *Weekly Gazette*) and provided meteorological data to help predict the chances for favorable weather. He attended to the professional astronomers and their instruments as they arrived in the weeks prior to the event, and was made "… voluntary observer at Colorado Springs …" to the U.S. Signal Service (Abbe, 1881: 29). Loud admitted he was simply an amateur and that his organization of a 'corps' of eclipse observers from Colorado College provided but "… a specimen of the degree of success …" that was achieved by the "… grand results from the observations of actual astronomers." (Loud, 1878c). Despite his modesty his report on the eclipse was called the "… best and most complete report ... received in Washington." (Cottam, et al., 2011: 370).

As a cultural and scientific event the eclipse was a huge success (Ruskin, 2008). Loud became hooked on astronomy, and Colorado College even received its first permanent telescope, a four-foot focal length instrument. The telescope was given to the College after a group of local donors raised the funds to purchase it from the astronomers who had brought it to Colorado from Brooklyn (Ruskin, 2008: 33). Loud would later boast "I am the first to handle a telescope belonging to Colorado College …"; presumably it was this instrument (Loud, 1901).

Within a few years Loud was actively making astronomical observations and teaching Colorado College students to do the same. During the transit of Venus of 1882 he observed as much of the four contacts of the transit as the cloudy weather allowed and reported that his students, "… with the aid of a small telescope ... and with smoked glass …" made competent observations as well (Loud, 1882). In just a few years Loud had transformed himself into one of the most active astronomers in the Rocky Mountains region.

3 LOUD AND THE BOYDEN-FUND COLORADO EXPEDITION

In 1887 Harvard received a large bequest from the wealthy amateur astronomer Uriah Boyden, who instructed that some of the funds be used to conduct high-altitude astronomical research. The Boyden Fund gave Harvard College Observatory's Director, Edward C. Pickering, the necessary means to build a high-altitude observatory to support his photometric and other astronomical research programs. Colorado was one of the first places Pickering sent an expedition, in part because of the favorable results of the 1878 eclipse. According to Becker (2009: 490), Loud's meteorological expertise made him an ideal local resource for Pickering. *Scientific American* publicized the Boyden-Fund Colorado expedition and Loud's role in it:

> The headquarters of the expedition will be ... Colorado Springs, a town of importance ... a social center of considerable dignity. Among the institutions is the Colorado College. Professor Loud, whose department includes instruction in meteorology, has volunteered his assistance and advice in the pending enterprise, which will be of special value from his personal familiarity and exact knowledge of the region ... (Harvard's New Observatory, 1887: 9715).

Pickering and Loud shared an affinity for the mountains. Loud was an avid hiker and built cabins above Colorado Springs on the slopes of Pikes Peak (Brunk, 1989: 18), and Pickering was a founder of the Appalachian Mountain Club. In 1883 Pickering published his influential article "Mountain Observatories" in the Club's journal *Appalachia*, in which he noted:

> Much attention has recently been directed to the question whether the conditions are more favorable to astronomical observations on the summit of a lofty mountain than at the level of the sea ... The question should, however, be decided ... valuable results would be obtained, even if the observations in the observatories on the mountain summit were not much better than those at a less altitude. (Pickering, 1884: 99, 106).

Loud had lobbied for Colorado as a location for high-altitude astronomy since the 1878 eclipse and knew that Pickering was nothing if not an advocate for the advancement of astronomy (Plotkin, 1978). He hoped that Pickering would become involved in Colorado, which could lead to a possible role for himself and Colorado College in Harvard's astronomical research. But from Pickering's perspective Loud's meteorological expertise was his real contribution to the project.

Becker (2009) has described Loud's work for the Boyden Fund expedition during 1887–1888, and interested readers are well advised to review her fine article. In short, Pickering relied on Loud to organize a series of volunteer meteorological stations at different points around Colorado. Loud was also asked to coordinate with the U.S. Signal Service for meteorological readings from the Pikes Peak station, which at Pickering's request remained open a year longer than originally planned (the station was slated to close). Loud had been so eager to prove himself useful to the expedition that he spent much of his free time traveling to the various sites around Colorado, keen to keep Pickering supplied with data. These efforts clearly stressed Loud's regular duties as a Professor and he confessed to Pickering (who reimbursed Loud's monthly Boyden-Fund expenses), "I am so behind my ordinary work that I have left several duties unperformed among them my monthly statement of expense for two months …." (Loud, 1887). Pickering was appreciative of Loud's hard work and acknowledged him in the Annual Report of the Harvard College Observatory:

> Important aid was rendered in the study of the climate of Colorado by Professor F.H. Loud, who was enabled to aid officially in this work by the courtesy of the trustees of Colorado College. With his assistance stations have been established upon Mt. Lincoln [14,286ft / 4,354m], Mt. Bross [14,172ft / 4,319m], and at various lower points. (Pickering, 1887: 9).

After reviewing over a year's worth of meteorological data, however, Pickering decided that Colorado's climate was not suitable for the Boyden-Fund project and ended the expedition, to Loud's great disappointment. Becker describes how desperate Loud was to involve Harvard in a project that might benefit Colorado College, "… in that distant day when there can be a science-making astronomical department here." (Loud to Pickering, as quoted in Becker 2009: 491), and she also notes that when Pickering pulled out of Colorado he did so with little evident concern for Loud's own ambitions. Her conclusion ("Pickering removed funding and instruments from Colorado, closing the stations one by one") can, however, leave one with the impression that after 1888 Pickering and Loud had no further collaboration (Becker, 2009: 493). In fact, their collaboration would continue, as will be described in Section 6 below.

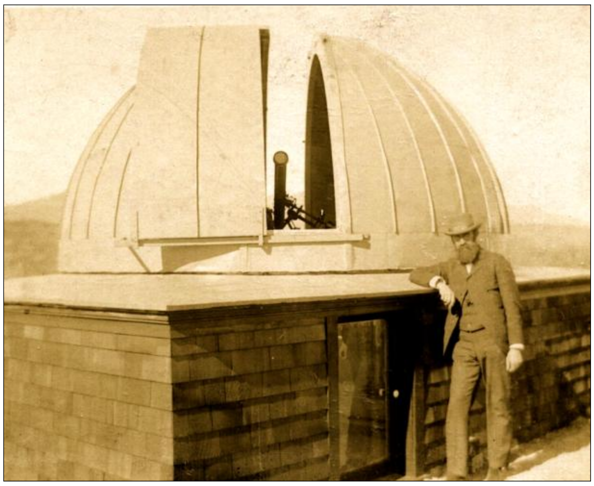

Figure 2: Frank Loud by the Wolcott Observatory dome (courtesy: Colorado College, Tutt Library, Special Collections).

4 THE WOLCOTT OBSERVATORY AND ASTRONOMY INSTRUCTION AT COLORADO COLLEGE

Since the 1880s Loud had desired a proper observatory building for Colorado College. In 1892 a four-inch equatorial telescope (by William Kahler of Washington D.C.) was donated to Colorado College by Henry R. Wolcott, a prominent Colorado citizen. Perhaps realizing that his legacy should be grander than just a telescope, in 1893 Wolcott donated $3,000 to build an observatory to house the instrument (Stone, 1918: 626). The Wolcott Observatory (Figures 2 and 3) was completed in June 1894, with a lecture room capable of seating 50 students and a large space on the roof for open-air lectures and observing events.

Coincidentally 1894 was an exciting year for astronomy in Colorado and the American west: Colorado College got its new observatory, and the University of Denver's massive Chamberlin Observatory, which housed a much larger 20-inch Clark-Saegmuller refractor, was also completed—at a cost of around $50,000 (Stencel, et al., 2006: 6). And that same year Percival Lowell (another astronomically-inclined Bostonian) established his observatory at Flagstaff, Arizona.

In 1901 Loud described the Colorado College Observatory and his students' coursework as follows:

> It contains, besides a lecture-room and a study, a dome-room in which a telescope of 4 inches aperture and

Figure 3: The Wolcott Observatory looking west with the front range of the Rocky Mountains behind (courtesy: Colorado College, Tutt Library, Special Collections).

> about 56 inches focal length is equatorially mounted, and a room on the lower floor in which are a sidereal clock and a transit instrument 21 inches long and of a little less than 2 inches aperture ... The work of the students in Astronomy is elective. Last year a class of 25 studied the descriptive branch for half a year supplementing a text book by essays written from study in the library. The next half-year, when instrumental work was the chief feature, the number was reduced to eight. Another class of one, Mr. L.R. Ingersoll,[2] has worked through the year on some problems of mathematical astronomy, succeeding a year's study of the calendars (Loud, 1901).

In 1906 the work of the Wolcott Observatory was further enhanced with a monetary gift from General Palmer, who had built the Denver and Rio Grande railroad and was a patron of local science. Palmer's gift enabled the purchase of a 'Palmer Library of Astronomy and Meteorology'. Books were purchased from "… the library of a European astronomer …" and included a 1607 edition of Oronce Fine's *La Theorique des Cieux et Sept Planetes*, Carl Friedrich Gauss' *Theoria Motus Corproum Coelestium*, and works by Christian Doppler, William Herschel, Percival Lowell, and Ernest Rutherford (Loud, 1907a: 382). At a larger institution such acquisitions might not have seemed so impressive but they were a real treasure for Colorado College. And Loud (1907a: 381) was thrilled to play librarian:

> The recent gift, enlarging the scope and utility of the collection previously at hand, has made apparent the necessity of a catalogue of the whole, which thus becomes the nucleus of an observatory library …

Figure 4: Frank Loud's house ca. 1901, complete with telescope and meteorological instruments (courtesy: Colorado College, Tutt Library, Special Collections).

5 SABBATICAL LEAVE AND RETIREMENT FROM COLORADO COLLEGE

Loud was absent from Colorado from 1899 to 1900 on sabbatical leave. During that time, as noted in Section 1, he completed an M.A. at Harvard (1899) and a Ph.D. at Haverford (1900). While at Haverford he traveled to Virginia to observe the total solar eclipse of 28 May 1900 (Loud, 1906). After this sabbatical he continued to teach at Colorado College until his official retirement in 1907, during which time he was "… classed among the best Meteorologists and Astronomers in the west." (Kerr, n.d.). In the decades after Loud's retirement from Colorado College the Wolcott Observatory languished, perhaps in part due to competition from the Chamberlin Observatory telescope a mere 70 miles away in Denver. Within a few decades the Wolcott Observatory was repurposed, indicating just how integral Loud had been for astronomy at Colorado College. By 1934 the observatory fell to a variety of non-astronomical uses until it was finally razed in 1969.

During Loud's tenure his astronomical publications, though not numerous, demonstrated his competence. Among his most significant published works were observations of the 1878 and 1900 solar eclipses, observations of the transits of Mercury in 1878 and 1881 and the transit of Venus in 1882. He also published an interesting article comparing the observations of the sunspot of 1905 made at Uccle in Belgium to those made at Colorado College (Loud, 1905a). Many of his academic papers were distributed via his semi-annual bulletin of the Wolcott Observatory in *Colorado College Studies*, and he also wrote a wide variety of astronomical articles for general readers. His last astronomical publication as a Colorado College professor was probably "A suggestion toward the explanation of short-period variability", which was published in the *Astrophysical Journal* (Loud, 1907b).

Upon retirement from Colorado College Loud received an annual allowance from the Carnegie Foundation for the Advancement of Teaching, the first for a Colorado College faculty member:

> [Loud] is well known throughout this country as one of its leading astronomers, and his many friends rejoice in this merited recognition of his untiring services to the cause of science. ("Among the Faculty", 1907: 75).

Loud was well-equipped to enter a productive retirement; his own house, built in 1878 just north of Colorado College, was itself a sort of private observatory, complete with a telescope and meteorological instruments (see Figure 4). Retirement also gave him more time for another project affiliated with Pickering and Harvard, the Western Association for Stellar Photography.

6 THE WESTERN ASSOCIATION FOR STELLAR PHOTOGRAPHY AND THE NOB HILL OBSERVATORY

6.1 Background

On 24 October 1904 Loud incorporated the Western Association for Stellar Photography. This Association was the administrative organization for a new observatory for stellar photography in Colorado Springs. This observatory had the support of Pickering but operated under Loud's local management. The officers elected at that first meeting were Pickering, Loud, Herbert Howe (Director of the Chamberlin Observatory in Denver), Otis Johnson (a Colorado Springs attorney), and Edward Giddings (another Colorado Springs resident, occupation unknown). Pickering's signature was the only one of the five not present on the meeting minutes, but this is not surprising as his role in the Association was primarily that of a figurehead. This probably suited Pickering just fine; at the time he was busy advancing astronomy across the country and around the world (Plotkin, 1978). Despite his absence Pickering was elected President by the other officers. Howe was elected Vice President and Loud was elected Secretary and Treasurer (Association Documents: 10).

The groundwork for the Association had been laid by Pickering and Loud a few years earlier, probably around 1899. The Boyden Fund project had not resulted in a joint Harvard-Colorado College partnership, but Loud still believed Colorado afforded important opportunities for high-altitude astronomy, including stellar photography. Pickering agreed, and it seems certain that he and Loud discussed this when Loud was at Harvard in 1899. Allowing Loud to run a small photographic observatory in Colorado was much less of a commitment than building and maintaining a Harvard-managed facility there. Pickering knew Loud was competent enough to manage such a project, and within a few years he sent Loud the requisite equipment. Colorado College relieved Loud from teaching duties for a year in 1904 so that he could "… be made the Director of the Astronomical and Meteorological Bureau in coöperation with Harvard University." (Hershey, 1952: 158).

In 1904 Pickering again mentioned Loud in his annual report, noting that as a result of his work with the Boyden Fund expedition Harvard was

> … still under great obligations to ... Loud of Colorado College for aid in many ways .... It has ever since seemed desirable that we might avail ourselves of his friendly aid in securing such observations as could be made to great advantage in the remarkably clear air of Colorado Springs. A plan is accordingly now being carried out which promises to give results of great value. By the aid of the Advancement of Astronomical Science Fund of 1902, a Cooke Anastigmat Lens has been sent to Professor Loud, and is now mounted and ready for work near Colorado Springs [see Figure 5]. It is expected that photographs showing the structure of the Milky Way, greatly superior to any that can be made here, will thus be obtained. (Pickering, 1904: 12).

Pickering further articulated this goal in a letter he wrote to Loud, which Loud then published as part of an article in the Colorado Springs *Gazette* entitled "Special Advantageous Conditions for Stellar Photography in Colorado". Loud wrote that:

> … the superiority of Colorado's qualifications ... can not be better summarized than in a letter written by Professor E. C. Pickering ... outlining his plan which has since been carried into effect in the work in stellar photography lately begun at Nob Hill, as follows .... (Loud, 1905b).

Loud then quoted Pickering at length:

> ... in Colorado ... it is believed that results could be obtained there, which would be wholly beyond the reach of ordinary astronomical observations. In planning astronomical work to be done in Colorado, it seems of especial importance to avail oneself of these advantages rather than to duplicate work already in progress at other observatories. A station possessing similar advantages has already been established by the Harvard college observatory at Arequipa, Peru. Much work has been done there on the southern stars, which, when extended to the northern stars at existing observatories, does not give results of equal value, on account of the haziness of the air ... It seems therefore desirable that the instrument in use at Arequipa, Peru, should be duplicated at Colorado Springs, and similar work undertaken with it, each instrument photographing a portion of the sky, which would be below the horizon of the other. (Pickering, as quoted in Loud, 1905b).

6.2 The Nob Hill Observatory

Pickering provided the Cooke lens, but Loud would have to provide the observatory. Initially the observatory was merely a 'station' but Loud had bigger plans. He had set up the camera as early as 1903 at which time it was reported he would "… spend his summer putting the new apparatus for astronomical photography into condition for the best possible service." (*Colorado School Journal*, 1903: 231). The location he chose was a rise east of Colorado Springs called Nob Hill.

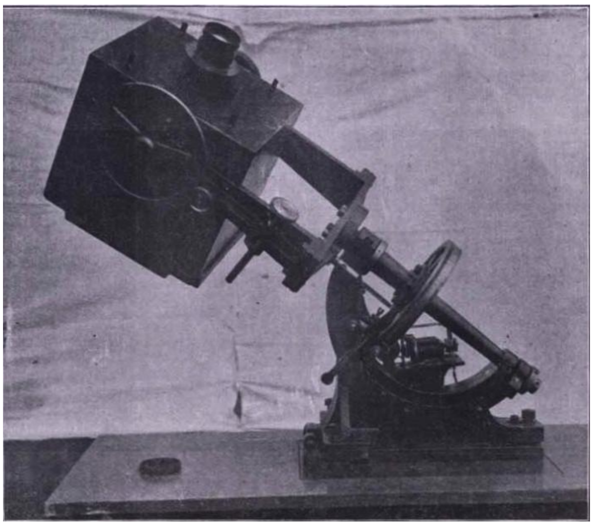

Figure 5: Nob Hill Observatory camera (courtesy: Colorado College, Tutt Library, Special Collections).

One of the purposes of the Western Association for Stellar Photography was to provide a proper observatory building for the Nob Hill camera. This required land and money and therefore a source of funding. Loud and the other local Association directors determined that soliciting public participation in the form of stock ownership might raise the funds they needed (note that Pickering was almost certainly not involved in this decision). The Association issued "… capital stock [to the] … amount of ten thousand ... dollars divided into one thousand shares …" worth ten dollars each (Association Documents: 7). Thus, any interested member of the public could participate by buying shares to help support the Association. A public announcement in the local paper summed this strategy up nicely: "Probing Secrets of the Heavens: Scientists and Capitalists Organize to Promote Investigations—Photographing the Stars" (Probing Secrets of the

Heavens, 1904).[3] On 27 July 1905 the *Gazette* announced that a site had been secured to build the observatory by aid of a generous donation of land from a Denver benefactor.

Loud's earlier success on Nob Hill with the Cooke lens and camera "… brought about the enlarging of the station and the work." (Observatory to be Built on Nob Hill, 1905). Although we know an observatory was in fact built, no photographs of it have been found. It was described as an observatory at least two stories high housing both the camera and meteorological instruments. It contained living quarters (including an exterior sleeping porch) and was likely used as a part-time residence by Loud and other observers. It even had a piano.

6.3 Ownership of the Photographic Plates

On 28 April 1905, the Association passed a resolution authorizing Loud to purchase "… the instruments now in use at the station on Nob Hill … [and] accessory apparatus [for] the preparation or utilization of the plates obtained from this instrument ..." (Association Documents: 13). Pickering appeared to be in agreement as the resolution cited a letter of approval from him. Yet there may have been a bit of a 'turf war' going on over the ownership of the plates taken by the Association's camera, as the officers then went on to pass a resolution ensuring that the photographic plates taken at Nob Hill remained the property of the Association. The secretary (in this case, Loud) was authorized

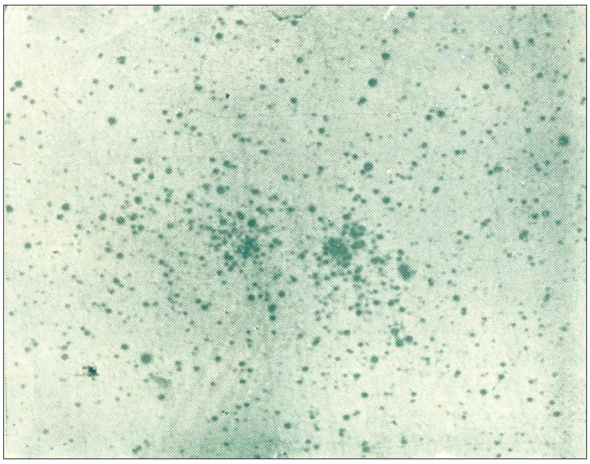

Figure 6: An image of double cluster in Perseus taken with the Nob Hill camera (courtesy of Colorado College, Tutt Library, Special Collections).

> … in regard to the ultimate disposition of the plates ... while conserving the highest scientific utility of the output of the station, to secure for the Association as large a permanent interest in the same as it may equitably claim. And no such arrangement, relating to the permanent disposition of the photographs taken at the station, shall be binding upon the Association until approved by a majority of the Board of Directors. (Association Documents: 13).

This last provision was key: a majority (of any three locals) could therefore override the President (Pickering) and one other member, thereby preventing the plates from going back to Harvard (or anywhere else for that matter) should such a request be made.

Whether or not there was an outright tug-of-war over the plates is unknown, but clearly Loud was keen to keep them in Colorado Springs, whereas Pickering might have preferred they go back to Cambridge. Perhaps as a result of the experience with the Association Pickering was more careful in the future. We have some hint of this from Pickering's visionary 1909 article "The Future of Astronomy" in which he outlines his ideal network of photographic observatories. This network would have a central

> … very large observatory employing one or two hundred assistants, and maintaining three stations ... one in the western part of the United States, not far from latitude +30º ... moderately high, from five to ten thousand feet. [In comparison, Colorado Springs is around latitude +38º and about 6000 feet high.] These stations … will not undertake much of the computation or reductions. This last work will be carried on at a third station, which will be near a large city where the cost of living and of intellectual labor is low. The photographs will be measured and stored at this station, and all the results will be prepared for publication, and printed there. The work of all three stations will be carefully organized so as to obtain the greatest result for a given expenditure. (Pickering, 1909: 115).

Pickering's vision of efficient calculation by distributing specific tasks among satellite observatories clearly differed from Loud's local, generalized ambitions to perform all work at one location. This does not prove the two were at odds with one another during Loud's management of the Nob Hill Observatory, but as Becker (2009) has demonstrated, Pickering and Loud had a history of not seeing eye-to-eye. Pickering desired control above all else as a precondition for effective astronomical progress and after his limited involvement with the Western Association for Stellar Photography he probably felt more convinced than ever of his vision for the future of astronomy.

6.4 Arson on Nob Hill and the Decline of the Association

It is not known how many photographic plates the Nob Hill Observatory produced (but see Figure 6), or to what degree the research ultimately proved useful to Loud or Pickering. Nob Hill certainly did not live up to Pickering's expectations as a North American Arequipa. We do know that the operations of the observatory were relatively short-lived. A tragedy befell the Nob Hill Observatory a few years after it was built and marked 'the beginning of the end' of the Western Association for Stellar Photography. On 5 July 1909 the observatory's caretaker, Lew Warriner, doused the floors with coal oil, set the Observatory on fire, and then shot himself. Loud was asleep elsewhere in the building when he was roused by the flames. According to the *New York Times*, Loud

> … was making a vain attempt to extinguish [the fire] when he heard the shot which ended the caretaker's life. Despondency [due to tuberculosis] is said to have caused Warriner's act … An examination of the burned structure shows that great damage was done to the scientific instruments, but the exact loss cannot be estimated. Special work for Harvard University was being conducted at the time of the fire. (Suicide in Observatory, 1909).

The extent of the damage is unknown but the camera and lens at least were spared.

Sparse record of the continued operation of the Observatory can be found after the fire. In 1910 the *Gazette* printed a photograph of Halley's Comet taken from Nob Hill. The article noted that the camera was still part of the Western Association of Stellar Photography and that "Professor F.H. Loud ... one of the officers, is in charge of the local observatory." (Much-Discussed Halley's Comet, 1910). At some point after 1910 the Association ceased regular operations. In 1922 Loud gave a brief history of the Cooke lens camera:

> Originally set up on Nob Hill, it was moved, first a few blocks, then across the city. The last transfer was interrupted by a trip of fifty miles to a point on the line of totality of the solar eclipse of June 8, 1918. (Loud, 1922).

It is not known what fate befell the Nob Hill Observatory itself, but two houses were built in 1958 where the Observatory once stood. We know that some (possibly all) of the photographic plates taken with the camera remained in Loud's possession because he occasionally published them in a magazine he edited from 1920 to 1924 called the *Colorado Sky*. Loud published this magazine under the auspices of the Association, although at that point its existence was merely nominal. The final issue of *Colorado Sky* (February 1924) effectively marked the end of the Western Association for Stellar Photography.

7 THE 1918 ECLIPSE

On 8 June 1918, forty years after the eclipse of 1878 that initiated Loud's astronomical career, another total solar eclipse was visible from Colorado. Loud was appointed to the American Astronomical Society's Committee to help "… facilitate the coöperation among the members of the Society …" in advance of the event ("Nineteenth Meeting of the American Astronomical Society," 1916: 582). He eagerly pitched in even though he was now in his late 60s. He and Florian Cajori from Colorado College played tour guide to Yerkes astronomer Edwin B. Frost, driving hundreds of miles northeast of Colorado Springs on dirt roads to scout out a suitable observing station (see Figure 7).

They located a small hill about two miles west of Matheson, Colorado, which they called the 'Colorado College Eclipse Station', and this is where Loud "… made preliminary arrangements for the observers." (Chant, 1918: 341). Contingents from four observatories would share the Matheson site: Washburn College (Kansas) which included a Yerkes party, Drake University (Iowa), the University of Toronto, and Colorado College. On 4 June Loud drove the 56 miles from Colorado Springs to Matheson by car, joined by his son, Francis, and his assistant, Kenneth Hartley.

As already noted Loud used the Nob Hill camera along with two others (another Cooke anastigmatic and a Goerz single anastigmatic) to photograph the eclipse. All three lenses were secured on a single mounting. To keep steady motion in right ascension Loud developed a clever device:

> Carefully sifted sand, placed in a sheet-metal tank, was allowed to run out through a small hole in the bottom; and as it ran out, a heavy weight placed on top of it descended slowly and uniformly. To this weight was attached a wire cable, which, after passing over several pulleys, was wound about the axis to be rotated. The apparatus worked admirably. (Chant, 1918: 342-343).

The photographs were a success, and the 1918 eclipse was Loud's final major astronomical event.

8 CONCLUDING REMARKS

8.1 Legacy and Influence

By the time of his death in 1927 Loud's astronomical career had spanned almost 50 years. He did not perform astronomical research that significantly advanced the field; yet he did do much to advance the science of astronomy in Colorado Springs, where astronomy went from non-existence to a cultivated science in just a few decades. By instructing students in astronomy, aiding fellow astronomers and helping to build two observatories, Loud laid the groundwork for further astronomical research in the area. Unfortunately when he was gone astronomy declined in Colorado Springs and astronomy's center of gravity in Colorado shifted firmly to Denver.

Figure 7: The scouting expedition for the 1918 eclipse, taken somewhere between Matheson and Simla, Colorado. From left to right: Guy Harry Albright (Colorado College), unidentified driver, Frank Loud (Colorado College), Edwin B. Frost (Yerkes Observatory), Roland R. Tileston (possibly Pomona College), and Florian Cajori (Colorado College) (courtesy: Special Collections Research Center, University of Chicago Library).

One interesting result of Loud's career, however, was the influence he had on Donald H. Menzel, the theoretical astrophysicist and an eventual Director of the Harvard College Observatory. Born in Colorado in 1901, Menzel studied chemistry at the University of Denver and in 1918 witnessed both the solar eclipse and Nova Aquilae from Colorado. Just as Loud had experienced forty years earlier, witnessing the 1918 eclipse heavily influenced Menzel toward a career in astronomy. Menzel left the University of Denver for Princeton in 1921 to work with Raymond S. Dugan and Henry Norris Russell. Although young Menzel did not yet have 'full credentials', Dugan pushed for his acceptance to Princeton because "… young astronomers are not appearing very fast at present and we would like to give this man any possible encouragement." (DeVorkin, 2002: 119). What early credentials Menzel did possess came to him in Colorado, in part via Loud. This we know from a footnote in *The Harvard College Observatory: The First Four Directorships, 1839–1919*, for which Menzel wrote the introduction. In an endnote from Chapter Six, on the Boyden Fund, the authors recall that Pickering played an important role in helping Loud establish astronomy at Colorado College. Then they note that Menzel, who would someday occupy the same position as Pickering, was himself nurtured by Loud:

> Nearly forty years later Professor Loud, in turn, gave encouragement to Donald H. Menzel in his study of astronomy. In 1952, Dr. Menzel became the sixth director of the Harvard College Observatory. (Jones and Boyd, 1971: 470).

After Menzel left Colorado for Princeton he kept in touch with Loud. As editor of *Colorado Sky* Loud was able to procure from Menzel an article entitled "Stars and the Atomic Theory" for the final issue of *Colorado Sky* in 1924. This may be one of Menzel's earliest and least-known published articles. In *Colorado Sky* Loud praised the then 23-year-old Menzel as

> … already well known to our readers, but perhaps not all of them know of the high quality of the work he has lately been doing, both at Princeton and at the Harvard College Observatory. Colorado has already reason, and will ere long have more, to take pride in the record of her new representative in the company of astronomers. (Loud, 1924: 2).

Loud was prophetic here and may have believed, via Menzel, that he was in some sense returning a favor to Pickering and Harvard. Of course Loud could not have known Menzel would someday occupy Pickering's former position as Harvard College Observatory's Director.

Like Loud, Menzel believed in the advantages of higher altitudes for astronomy. In his own career Menzel pushed for a high altitude observatory in Colorado. Having lived there he knew, as Loud did, what opportunities Colorado's mountains offered to astronomers. Although Loud did not live to see it, through Menzel Harvard finally established a high altitude observatory in Colorado. In 1940, just thirteen years after Loud's death, Menzel and one of his graduate students, Walter Orr Roberts, founded the High Altitude Observatory near Climax, Colorado.

8.2 Conclusion

While at Colorado College, Loud was one of the few active astronomers in the American west before 1900. Consider the list of participants at the Second Annual Conference of Astronomers and Astrophysicists, held in August 1898 at Harvard College Observatory. Of the 93 registered participants, 90 were from institutions on the east coast or no further west than Wisconsin. Two others were from foreign institutions (in Montreal and Leyden). Only one participant, Loud, was from an institution west of the Mississippi (Hale, 1898). Additionally, before 1900 the number of institutional and large private observatories established in the American west could likely be counted on two hands. There were a handful of institutional observatories: Colorado College's Wolcott (1894); Denver University's Chamberlin (1894); two in Nebraska, the Boswell Observatory at Doane College in Crete (1883) and the Creighton University Observatory (1886); and in Seattle, the Observatory at the University of Washington (1895). The school district of Oakland, California opened the Chabot Observatory for public viewing in 1883. Then of course there were the larger, private research institutions: the Lick Observatory at Mt. Hamilton, California (1888), Percival Lowell's observatory in Flagstaff, Arizona (1894), and the Mount Wilson Solar Observatory (1904). It seems clear that by his retirement in 1907 Loud's position as an active astronomer in the American west, though not unique, had placed him in limited company.

The career of Frank Loud represents not only that of a pioneer astronomer working on the American frontier, but also an important link between the astronomical research programs being developed in the eastern United States and the development of astronomy in the American west, in particular the push toward high-altitude astronomy. Loud was active in that cohort of American astronomers described by Lankford in the period from 1860 to 1899, which saw the rise of astrophysics and the application of photography to astronomy (Lankford, 1997: 10). Yet Lankford's thorough study, which included astronomers "… who stood far from the center …" (Lankford, 1997: 8), makes no mention of Loud despite Loud's close connections to Pickering, to Harvard College Observatory, and to the broader nineteenth-century astronomical community. This is not meant as a criticism of Lankford but rather underscores the paucity of historical coverage of western American astronomy during that period beyond the well-known observatories like Lick and Lowell.

Loud was a rare example of an astronomer who maintained a fairly-sophisticated program of astronomical research in a small frontier town far from the usual centers of astronomical work. Therefore, his career is significant in charting the history of nineteenth century American astronomy outside the better-known east- and west-coast astronomical institutions and observatories. Loud's efforts did not result in lasting astronomical fame, but his support of other astronomers as well as his instruction of Colorado students in the science of astronomy were themselves significant contributions, made all the more impressive by the limited resources available to him. Loud's expertise in mathematics, meteorology and astronomy demonstrates the many hats a frontier professor wore to be of service not only to science but to citizens of the American west. As a result of his expertise and passion, for a short time astronomy flourished in an unlikely location.

9 NOTES

1. Darin Hayton, Associate Professor of the History of Science at Haverford College, marshaled the resources of Haverford's library staff and Mathematics Department in an ultimately fruitless effort to determine which faculty granted Loud's Ph.D. in 1900; no thesis or dissertation (if there was one) could be located, but records do exist at Haverford

confirming that Loud was granted a Ph.D. For their efforts I am grateful.

2. The "Mr. L.R. Ingersoll" Loud mentions is Leonard Rose Ingersoll, the early twentieth-century University of Wisconsin Professor of Physics whose eponymous Physics Museum is well-known to many historians of science and technology (and their children) who have passed through Madison. Loud and Ingersoll presented a joint paper at the meeting of the American Association for the Advancement of Science in Denver in 1901, and Ingersoll's correspondence with Loud indicates he held his Professor in high regard.
3. The Association's account books indicate that only a minority of shares (315 total) were ever sold or otherwise distributed as gifts (Association Documents, Account Book: 3), which almost certainly means the Association did not raise enough money by selling stock to cover the cost of building the Nob Hill Observatory in 1905-1906. This leads to the conclusion that Loud paid for the construction of the Observatory, and purchased the camera and other equipment from Harvard himself. The fact that the Nob Hill Observatory was occasionally referred to as one of Loud's residences further supports this assumption. Loud came from an established Massachusetts family and may have had considerable personal wealth which he brought with him to Colorado, as he purchased land and built his own house just one year after arriving in 1878; yet given what we know about the College's initial lack of even its own buildings and limited funds Loud almost certainly could not afford to pay for a new house out of his teacher's salary. In the early years of Colorado College salaries were often 'overdue' and "… frequently little more than token payments." (Hershey, 1952: 132); concurrently residential land in Colorado Springs was selling for around $1000 per acre in 1878.

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PERFECTING 'A SHARPER IMAGE': TELESCOPE-MAKING AND THE DISSEMINATION OF TECHNICAL KNOWLEDGE, 1700-1820

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Abstract: Telescopes, reflecting telescopes in particular, underwent considerable development during the eighteenth century. Two classes of telescope maker, the for-profit artisan and the amateur 'gentleman-philosopher,' learned techniques of optical fabrication and testing and produced usable astronomical instruments. One means of disseminating technical knowledge was via the book. The year 1738 saw the publication of a highly-influential book, Robert Smith's *A Compleat System of Opticks*, a work that included detailed information on telescope-making. It was this book that helped spark the astronomical career of William Herschel, and with Smith's information Herschel produced large reflecting telescopes of exquisite quality. However, artisan-opticians, even the renowned James Short, appear to have cut corners on a portion of their production, thus permitting the sale of some instruments of inferior quality. The reasons for this were clearly economical in nature: artisans depending on telescope sales to earn a living simply could not afford the time required for perfection. The mere presence of written works disseminating technical knowledge did not ensure that such knowledge was universally adopted.

Keywords: telescope, telescope-making, economics, technology transfer

1 INTRODUCTION

The telescope was one of the most crucial developments in the history of scientific instruments. For the first time, one could see with one's own eye objects that would otherwise have been mere points of light in the sky, or misty specks on the sea's horizon. The telescope, along with the microscope, was one of the keys that propelled European civilization into the modern world. Science, navigation, exploration, war, and even recreation all benefited from the invention of the telescope. However, early telescopes were extremely crude devices and relatively little information regarding their manufacture was available at the time. Galileo Galilei, Johannes Kepler, René Descartes, Isaac Newton, and other mathematical-philosophers of the period wrote short treatises on telescopes, in addition to more extensive works on optics generally, but had relatively little to say concerning details of construction. There were several key steps involved in the perfection of the telescope and the transmission of knowledge concerning optical fabrication and testing that occurred between about 1700 and 1820. While the fundamental processes of making telescope lenses and mirrors changed little, drastic changes occurred in the materials used, and most especially, the methods of testing optics. Assorted experiments and experiences in telescope-making resulted in a considerable body of knowledge, but the successful transmission of such knowledge remained problematic. By the mid- to late-nineteenth century, the results of all these developments were commercially-made telescopes of great quality, but equally great expense.

The vast majority of telescope-owners were of the educated, genteel elite. The average cost of telescopes during this period was tremendous, far beyond the means of most. Until the mid-twentieth century much of the expense of telescopes derived from fabrication methods. Mass production was a thing of the distant future in eighteenth century Europe, and telescopes, like everything else, were individually hand-made. An option for those with some talent was to make their own telescope. However, construction of such a precise instrument required a high degree of technical knowledge and ability. Transmission of technical knowledge was central to the development of the reflecting telescope. A well-known text of the period, Robert Smith's *A Compleat System of Opticks* (1738), provided the first truly exhaustive description of the telescope-makers' art. How it influenced the work of two important and near-contemporary eighteenth-century telescope makers, James Short and William Herschel, illustrates the problems with the transmission of important technical knowledge concerning astronomical instruments. Smith's work was essentially a conduit of knowledge, rather than a seminal foundation of knowledge, and some telescope-makers, such as Short, appeared to dismiss some of the valuable information it provided for reasons beyond the purely technical.

2 TELESCOPE-MAKERS OF THE EIGHTEENTH CENTURY

Telescope making to about 1860 was dominated by two classes of telescope-maker: the professional artisan (e.g. see Figure 1) and the 'gentleman-scientist'.

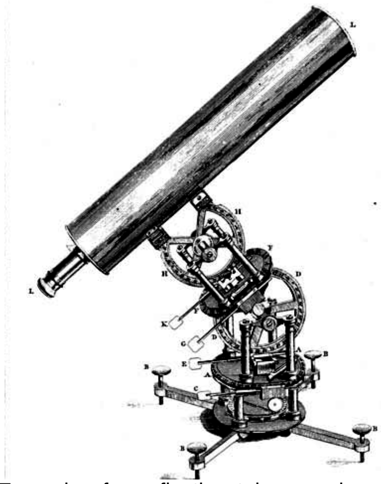

Figure 1: Example of a reflecting telescope by professional telescope-maker James Short (adapted from Wikimedia Commons).

Figure 2: Robert Smith, 1689–1768. Portrait by John Vanderbark, painted in 1730 (courtesy: Wikipedia).

The professional artisans—men such as James Short 1710–1768), John Dollond (1706–1761) and Peter Dollond (1731–1821)—were members of a larger class of scientific and mathematical instrument-makers who were in business to sell their wares. In a world where patent law was difficult to enforce, they tended to keep manufacturing methods a close secret, and relatively little can be learned from their surviving records (if any) concerning how they produced their instruments. European telescope-makers prior to 1900 were very much within the traditional European guild system, as were many other crafts, such as printing and dyeing. The influence of guild secrecy amongst professional European telescope and 'philosophical instrument' manufacturers was felt into the early twentieth century, even after the guilds had ceased to exist as such. The art and science of optical fabrication were passed down from master to apprentice, and there were neither formal training nor textbooks as such on the subject until the twentieth century. On the other hand, gentleman-scientists, or more correctly, 'gentleman-philosophers,' were not bound by secrecy as were the artisans; it was in fact their duty to expand the knowledge of all concerning science and scientific instruments. Some gentleman-philosophers were professionals (university and government employees) while others were amateurs (wealthy individuals with philosophical/scientific aspirations). It is from this latter group that most can be learned of optical production methods between 1700 and 1820. It was also the gentleman-philosopher who was the key in making these methods known to a wider audience in their own day.

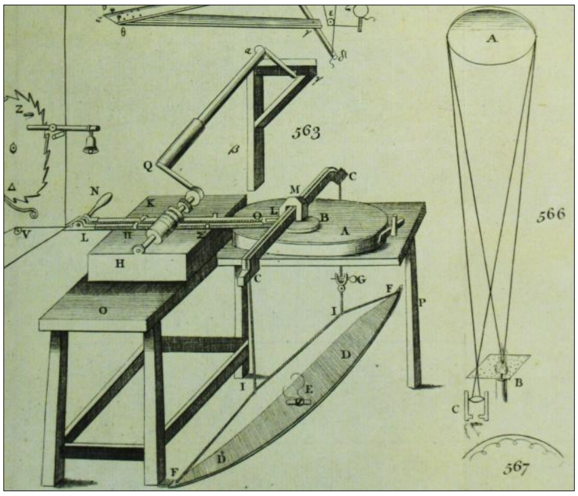

Figure 3: Illustration from Smith's *A Compleate System of Opticks* (1738). Figure 566 on the right is the original visual depiction of Hadley's mirror test. B, the perforated metal screen, and C, the observation lens, were both placed at the center of curvature of A, the mirror being tested. Figure 563 in the center is an example of a proposed treadle-operated lens grinding machine.

A complete, detailed history of the development of telescope technology is not the purpose here, nor is the uses to which telescopes were put. These subjects have already been covered elsewhere, particularly by Henry King in *The History of the Telescope* (1955). However, understanding the technical details of telescope-making between 1700 and 1820 and how information was communicated, altered, and re-transmitted, is of considerable importance in illustrating a particular facet of scientific-technical knowledge and communication within the broader context of eighteenth century European science and technology.

Scientific instrument-makers from the seventeenth to nineteenth centuries were a diverse group and produced diverse products, including telescopes. London was the center of both the scientific instrument and telescope-making world during much of the eighteenth and nineteenth centuries. British census records through 1851 do not indicate exactly how many 'opticians' and 'philosophical instrument makers' actually made telescopes, but surviving examples of telescopes and advertising suggest that at any one time there might have been several dozen instrument-makers who produced telescopes in England, Scotland and Ireland, most concentrated in London (see Burnett and Morrison-Low, 1989; Clarke, et al., 1989; and Clifton, 1995). The actual guilds to which telescope-makers and instrument-makers belonged were diverse, and sometimes unexpected. Robert Bancks (or Banks, who worked in London between 1796 and 1831), a known maker of both telescopes and microscopes, was a member of the Joiners Guild, and Francis Hauksbee (d. 1765) belonged to the Drapers Guild (Clifton, 1995: 16, 128). In truth, the whole subject of scientific instrument-makers, as opposed to the instruments they made, is a remarkably little-studied field in the history of science and technology, and is limited to a famous few, such as Jesse Ramsden. As a result, most of what is known of their work is limited to examination of extant instruments, and these have little to say about how they were made.

3 SMITH'S *A COMPLEAT SYSTEM OF OPTICKS*

Although some written accounts of the details of lens-making and mirror-making prior to the eighteenth century were made known publicly, these were very few and, in many cases, intentionally vague. In his *Opticks*, Isaac Newton (1642–1727) described some details of his own methods for fabricating his reflecting telescope; his techniques seem basically similar to those of other telescope-makers of his era, but even he gave few details (see Newton, 1721: 91-95). As stated previously, prior to effective enforcement of patent law, fabrication methods were a closely-guarded secret among members of the various craft guilds, a state of affairs that existed well into the nineteenth century. As a result, little is known, either then or now, of the details of the early lens- and mirror-making craft. Among the first widely-disseminated works on optical fabrication, as opposed to theory, was Robert Smith's *A Compleat System of Opticks* (1738). Smith (Figure 2) was a well-known natural philosopher at the time, serving as Plumian Professor of Astronomy and Experimental Philosophy at Cambridge from 1716 to 1760. Bsides contributing his own theoretical and mathematical knowledge, Smith compiled material on telescope-making from a number of well-known individuals, including the Dutch natural philosopher and astronomer Christian Huygens and the British astronomers Samuel Molyneux and John Hadley, among others, and it was Smith's book that later acted as a guide for the noted astronomer and telescope-maker William Herschel.

A Compleate System of Opticks was quite typical of any number of philosophical-technical works of the period, such as Diderot's *Encyclopédie* (1751-1772), or the earlier *Cyclopædia, or an Universal Dictionary of Arts and Sciences* (1728) of Ephraim Chambers. Books such as these provided a wealth of information to the educated layman on a host of technical subjects. Smith sought to put together a work that would expand on all previous ones, and would be useful to a wide range of readers. The 'popular' introductory section was non-mathematical and was "… for the use of those who would know something of Opticks, but want the preparatory learning that is necessary for a thorough acquaintance with that Science." (Smith, 1738: i). More importantly, Smith intended the introduction to be sound enough to permit readers to understand the later volumes in his work, "… especially if their heads be a little turned towards mechanical matters." (ibid.).

It is worth exploring the details of Smith's "Book III", as it describes the fundamental techniques involved in grinding and polishing lenses and mirrors (e.g. see Figure 3). Smith (1738: 281) acquired much of his knowledge of practical optics and lens production through his friend Samuel Molyneux (1689–1728). Molyneux served as Lord Commissioner of the British Admiralty and as such was no doubt interested, both personally and professionally, in passing on everything learned concerning astronomical and navigational instrumentation. Smith himself apparently knew little concerning the actual techniques of fabricating lenses and mirrors; what he presents in Book III is largely the work of others. As a result of Smith's unfamiliarity with fabricating technique, it is a somewhat confusing account at times, demonstrating some of the problems with communicating the technical details of scientific instruments and technology, even among 'experts'.

The section on lens production is based almost entirely on the work of Christiaan Huygens (Figure 4), which Smith (1738: 281) considered "… the best of any yet extant." Huygens produced a number of the largest and best refracting telescopes made in the late seventeenth century and used them to make various important discoveries (including the nature of Saturn's rings), and he worked out a number of fabrication techniques for lenses (King, 1955: 51). The objective lenses of all refracting telescopes up to about 1750 were made from a single piece of ordinary glass, referred to as 'crown-glass'. As a result, such simple lenses suffered from a number of problems, primarily spherical aberration and chromatic aberration, cured only by making lenses of relatively small diameter (a few inches) and of very long focal-length (over a hundred feet in some cases). Smith's description of Huygens' methods take the reader step-by-step through all aspects of lens production, including how to make the brass grinding tool, how to choose quality glass, the rough and fine grinding process, and polishing (Smith, 1738: 282-301). Although Huygens' methods would be familiar to telescope-makers today, there are some differences; for instance, the concave grinding and polishing tool (described by Smith as a 'plate' or 'dish') is made considerably larger in diameter than the finished lens, rather than the same size. Polishing appeared to be the problematic aspect of lens-making for Smith and Molyneux, as at least three different methods, or variations of methods, are described. An aspect of telescope-making that was, and continues to be, of crucial importance, is the quality of the glass required for lenses; this proved to be a major stumbling block to the improvement of refracting telescopes for many years (see Smith, 1738: 287-288). Grinding the curved surface of lenses then as now involved the use of an abrasive slurry, usually consisting of powdered emery (natural corundum, an aluminum oxide) and water. Once the curve had been generated by grinding with a coarse grit, finer and finer grades of emery were used to remove the large pits in the glass created by coarser stages of grinding.[1]

Figure 4: Christiaan Huygens, 1629–1695 (courtesy: Wikipedia).

Polishing the lens to remove all traces of grinding, thus making the lens completely transparent and free of pits and scratches, was generally done with an extremely fine abrasive such as jeweler's rouge (ferric oxide, Fe_2O_3), or 'tripoly' (decomposed silicaceous limestone), on a yielding surface. Huygens is quoted by Smith as using tripoly directly on a copper tool,

Figure 5: John Hadley, 1682–1744 (after Andrews, 1993: 28).

while others used linen, leather, paper, or other soft surfaces. Smith must have misinterpreted Huygens, since polishing directly on the metal tool would have left numerous fine scratches. Smith's narrative of the process admits some confusion, by use of the phrase "… if I understand Mr. Huygens right [the linen cloth is removed after using it to wipe the lens with tripoli]." (Smith, 1738: 293-294). Smith's confusion helps demonstrate how little was generally known about the craft of lens-making at the time. The majority of grinding work was done by hand, but polishing was considered by most workers to require considerable pressure, and so machines of one kind or another were used (Smith, 1738: 297-301). The last stage of lens production involved *centering* the lens; that is, making sure both faces of the lens had coinciding foci along the same optical axis. The centering process would often result in significant portions of the lens being cut away and discarded (Smith, 1738: 312-317). This last step seems to be the end of the process and nothing is really said about *testing* the final lens beyond the assessment involved in the centering process.

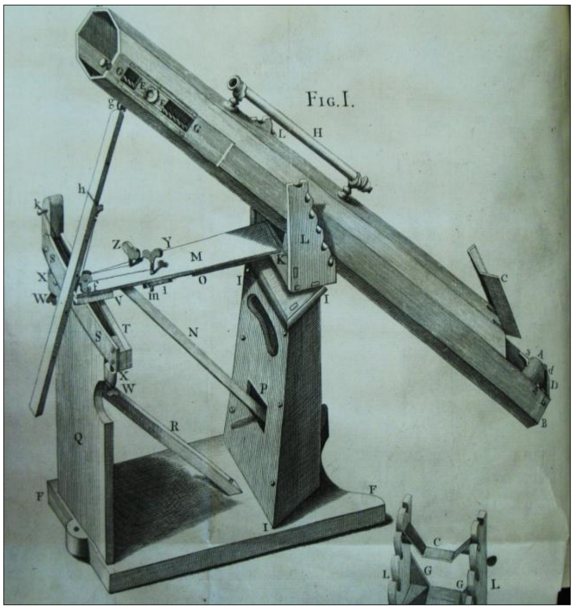

Figure 6: Hadley's 6.2-inch aperture Newtonian telescope. Though his was a highly efficient design for the dedicated astronomer, Hadley's arrangements lacked the fine materials and aesthetics of Gregorian telescopes (after Hadley, 1723: Plate 2).

Smith then goes on to describe the method for making 'specula', or telescope mirrors, as described by Samuel Molyneux and John Hadley. It is this section of Smith's book that gave William Herschel, and no doubt others, important clues to many details of telescope-making. Reflecting telescopes had been theorized about since the early seventeenth century, but it was Isaac Newton who produced the first working models of such telescopes in 1668-1670 using a mirror made of 'speculum metal', an alloy of copper and tin. After the experiments of Newton and a few others, little more was done concerning the fabrication of reflecting telescopes until John Hadley applied his knowledge and abilities to the problem.

Hadley (Figure 5), a mathematician and instrument-maker from Essex, was notable for producing the first 'large' Newtonian telescope, large being a comparative term as Newton's original had an aperture of less than two inches while Hadley's was a 6-inch. Hadley's reflecting telescope of 1719-1720 (see Figure 6) caused a sensation. The telescope worked well, as can be attested by the drawing of Saturn appearing with Hadley's description of his telescope in the *Philosophical Transactions* (Hadley, 1723: Plate 376; cf. Smith, 1738: 301-312).[2] Hadley's letter had little to say concerning how he made either the optics or mechanical parts of his telescope; fortunately, later correspondence with Smith provided many answers. *A Compleat System of Opticks* provides details of making the speculum metal disc from which the mirror was made, through rough grinding, fine grinding, and polishing (Smith, 1738: 304-305). The fabrication methods used were very similar to those for lenses at the time, aside from the different material used for the mirror itself (Smith, 1738: 306). The correct proportion of metals used was a matter of considerable argument and experimentation well into the nineteenth century. Hadley, with the assistance of Bradley, tried one hundred and fifty different formulae for speculum metal before they came across the one that worked best, a combination of two alloys, the first of three parts of copper and one part and a quarter of tin, the second of six parts of brass and one part of tin. Telescope-makers continued to fiddle with the details of these proportions, but speculum metal was essentially the same copper-tin/brass alloy.

Of particular note, however, is that Hadley not only described his method of *making* mirrors, but also of *testing* them. Optical theory, then as now, shows that in order to form a good image of an object at infinity the cross-section of the surface of a reflecting telescope's mirror must be a paraboloid. This is a very difficult surface to produce for a number of reasons. First, the method of making mirrors is like that of making lenses: two discs are ground against one another, one convex the other concave. The natural shape produced by the grinding process (and later, the polishing) is a sphere. It requires somewhat different motions to produce an aspherical surface on either a lens or mirror and the special techniques for this are quite demanding. A second reason for difficulty is that the difference between the required spherical and paraboloidal surfaces of a telescope's mirror is very tiny, of the order of a few hundred nanometers.[3] As a result, the difference between the two surfaces is impossible to detect by any normal means. Indeed, the testing of telescope optics was one of the major stumbling blocks to advances in telescope technology until the mid-nineteenth century. Hadley's method (see Figures 3 and 7), as described in *The Compleat System of Opticks*, continued to be used into the nineteenth century. Hadley understood well the basic geometry of optics and how light-rays behaved after being reflected from a concave mirror (Smith, 1738: 6-27; Willach, 2001: 3-18). The correct paraboloidal surface is slightly deeper in the middle than a spherical mirror of the same focal-length. Hadley's test took advantage of his theoretical knowledge and he developed a simple, graphical and qualitative test for different surfaces (Smith, 1738: 309-312).

Hadley's test was quite simple. Light from a candle was allowed to shine through a very small hole, commonly the size of a pin-point, in an opaque screen. The light would then reflect off the surface of the polished mirror, and the observer then examined the reflected image of the pin-hole by using a magnifying lens. Both the pinhole/light-source and the lens were located at the center of curvature of the mirror (twice the focal length), and the pin-hole served as an artificial star. Hadley clearly understood the test process in the same way as modern opticians: light-rays from the object reflect off the mirror's surface and are brought to a single focal point, or not, depending on any flaws (regions of the mirror that were either higher or lower than theoretically predicted) in the mirror's surface that might be present. The appearance of the artificial star's image at the focus as seen magnified by a lens could thus be used to interpret the mirror surface (see Figure 8):

> If the light, just before it comes to a point, have a brighter circle round the circumference [edge], and a greater darkness near the center, than after it has crossed and is parting again; the surface is more curve[d] towards the circumference and flatter about the center, like that of a prolate spheroid round the extremities of its axis; and the ill effects of this figure will be more sensible when it comes to be used in the telescope. But if the light appears more hazy and undefined near the edges, and brighter in the middle before its meeting than afterwards, the metal is then more curve[d] at its center and less towards the circumference; and if it be in a proper degree, may probably come near the true parabolick [sic] figure. *But the skill to judge well of this must be acquired by observation*. (Smith, 1738: 310; my italics).

Note that a spherical mirror tested at the center of curvature gives a perfectly sharp image at the focus and symmetrical intra- and extra-focal images. The importance of such a test as Hadley's cannot be over-emphasized; this is *the* most critical portion of the entire telescope-manufacturing process. Without it, fabrication of the telescope speculum was more guesswork than anything else, and resulting telescope

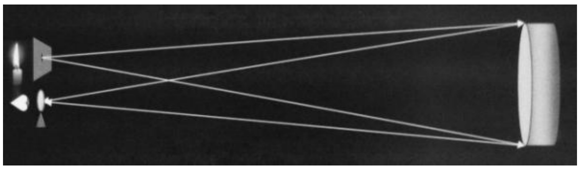

Figure 7: Hadley's arrangement for testing mirrors at the center of curvature (illustration by G. Cameron; cf. Figure 3).

performance could be mediocre at best. The problem with Hadley's test, as he clearly admitted, was that it is *qualitative*, rather than *quantitative*: the determination of whether the surface under examination was a *true* paraboloid or not was a matter of judgement requiring some considerable practice. As will be seen, modern tests of eighteenth century telescopes indicate that even some of the best opticians of the day produced mirrors of somewhat variable quality.

4 AN ARTISAN TELESCOPE-MAKER: JAMES SHORT

A few opticians in London made small reflecting telescopes after Hadley, but relatively little is known of these (see King, 1955: 84). It was James Short, a Scot who later moved to the center of the scientific instruments trade in London, who would dominate the manufacture of reflecting telescopes in Britain during much of the eighteenth century. Short was university educated and became interested in telescopes in the 1730s. He met mathematician Colin Maclaurin (1698–1746) at the University of Edinburgh during one of the latter's popular lectures on astronomy and the two worked together for a time, Short being allowed use of a room at the University for experiments in telescope-making (King, 1955: 84; Maclaurin, 2000). Short produced a few Newtonian telescopes, but the vast majority of instruments he made were Gregorian reflectors. Short had a long career as a telescope-maker, and a reputation as one of the best in his day (Willach, 2001: 16). Prices are known for his telescopes, and these ranged from 3 guineas for a diminutive "3-inch focus" telescope of 12-power magnification, to a "144-inch focus", of 24-inch aperture and 1200-power, for 800 guineas (see Table 1). The vast majority of telescopes produced by Short were in the smaller 7-inch to 18-inch focal length range (and just 2-inches to 3.5-inches in aperture). Most of Short's telescopes that were sold were quite small: of 1,342 made, only

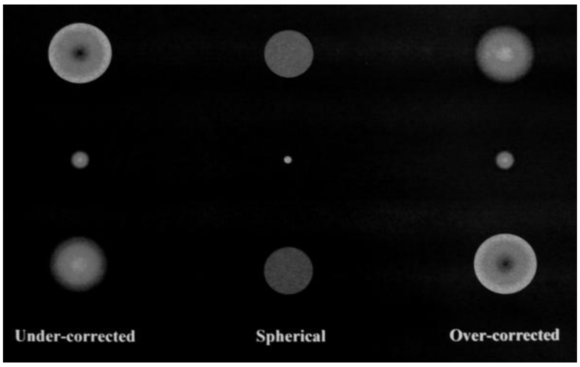

Figure 8: Hadley's testing method – images of artificial stars as seen with a magnifying lens at the center of curvature of a mirror. In each case, the upper image is what is observed just inside the focus, the middle image is at focus, and the lower is just outside the focus (illustration by G. Cameron).

Table 1: Catalogue prices for James Short telescopes ca.1760 (partially based on table reproduced in Clarke, Morrison-Low, and Simpson, 1989: 2).*

No.	Aperture (mm)	Focal Length of Primary (mm)	Overall FL (mm)	Magnifying Powers	Price (guineas)	Price (US$)
1	25	76	457	12 (terrestrial use only)	3	600
2	33	115	686	25 (")	4	800
3	48	177	1,067	40 (")	6	1,200
4	63	241	1,448	40 and 60	8	1,600
5	75	304	1,829	55 and 85	10	2,000
6	75	304	1,829	35. 55, 85, and 110	14	2,800
7	96	457	2,743	55, 95, 130, and 200	20	4,000
8	111	615	3,657	90, 150, 230, and 300	35	7,000
9	165	914	5,846	100, 200, 300, and 400	75	15,000
10	235	1,219	7,315	120, 260, 380, and 500	100	20,000
11	304	1,829	10,973	200, 400, 600, and 800	300	60,000
12	615	3,657	21,946	300, 600, 900, and 1200	800	160,000

* A full list of prices (date unknown, but likely c.1760) includes all known models of Short telescopes. Telescopes were listed by 'Number' and by the focal length, as was typical for all telescopes of the seventeenth and eighteenth centuries. Short and other makers of Gregorian telescopes gauged 'focal length' by that of the primary mirror rather than the overall focal length of the telescope. Secondary mirrors of Gregorian and Cassegrain telescopes magnify the image several times; thus the 'effective focal length' of the complete telescope would be much longer. My own analysis of data from some of Short's telescopes (described by Willach) gives a secondary mirror magnification of about 6× on average. Table 1 is a combination of data from Short's original price list cited above (columns 1, 3, 5, and 6), combined with the aperture, overall focal length, and approximate price in U. S. Dollars as of 2011 calculated by myself (columns 2, 4, & 7).

about 380 were of an aperture greater than 3 inches, the 2.5-inch size being most popular. Such small telescopes would have been of limited astronomical use and were equivalent in light-gathering power to refracting telescopes of half their aperture.[4] This, plus what little anecdotal information there is on Short's customers, would suggest that the vast majority of people buying these smaller telescopes were mostly interested in acquiring something they could use for casual viewing of terrestrial objects, and perhaps a glimpse of the Moon.

A modern analysis by Willach (2000: 8-14) of several James Short telescope mirrors shows that, while a few primary mirrors (about 20%) were considered good even by modern standards, the majority show considerable under-correction; many are in fact nearly spherical in cross-section. The small secondary mirrors of Short's telescopes are likewise far from the theoretical shape required. Views through the Short's under-corrected telescopes have a somewhat soft appearance as a result of spherical aberration when viewing various objects. Tests were performed on 16 different Short telescope mirrors ranging in size from 1.6 to 9.25 inches in aperture (40mm to 235mm). Though Willach considered Short's telescope mirrors to be fairly good, some of them would have suffered well over 1-wave of spherical aberration, which is about four times the amount that is generally found acceptable today.

An obvious problem in evaluating the optical quality of Short's telescopes, and indeed any speculum metal reflecting telescope, is the likelihood that the mirrors have been re-polished many times. As a result, knowing which optical surface was produced by a particular hand, Short's or someone else's, is problematic. Willach has argued that it is unlikely that the mirrors that he tested had been re-polished by their owners as the surfaces show a symmetrical figure without zonal errors or astigmatism that might result from buffing with a cloth (Willach, 2001: 16-18). This leaves the possibility that the Short mirrors were re-polished by a skilled optician, an idea that Willach also dismisses due to the nature of the various mirrors' optical figure.[5] This analysis, along with the fact that the speculum alloy used by Short appears fairly resistant to tarnish, strongly points to the sixteen telescopes tested having optics figured by Short, not by another optician or opticians.

While one can argue with Willach concerning whether the Short telescopes he has examined were not at some point repolished and refigured by another optician, *if* the mirror surfaces *were in fact* produced by Short, would not an optician of his skill have noticed the considerable differences in image quality between his best and worst instruments? Undoubtedly, he *would* have noticed and attempted to correct the defects. The difference in the appearance of objects as seen through a telescope with nearly perfect optics versus one with 1-wave of spherical aberration is readily apparent, even at low magnification. We are left with two possible conclusions. First, that the poorer-quality Short telescope mirrors were re-polished and refigured by someone else. Second, that Short left them as they were: in an imperfect state. There is thus an obvious problem here. The best telescope-maker of the mid-eighteenth century made and sold a fair number of inferior-quality telescopes.

Short was highly secretive about his manufacturing methods, so the tests he used remain a mystery. As Smith had related in *The Compleat System of Opticks*, the Hadley test depended greatly on the skill of the person doing the testing. It is likely that Short used Hadley's 'in-shop' method or some variation of it. Although Short was one of the most celebrated telescope-makers of the mid-eighteenth century, many of his instruments were far from perfect, even by his own standards (see Table 2). Therefore, the shock felt by those used to Short's telescopes when they observed with the vastly-superior telescopes made by William Herschel just a few years after Short's death can be understood.

Table 2: Evaluation of the optical quality of sixteen James Short telescopes based on data from R. Willach.*

Short Telescope Number	Aperture (mm)	Radius of curvature (mm)	Approximate surface error	Comments
1734 7.14	40	202	4.43λ	Basically a spherical mirror with slightly turned-down edges.
1735 10.45	47	282	1.73λ	Corrected to about 50% required of a parabola.
1740 29/269=7	47.7	346	0.76 λ	Smooth curve, good approximation of parabola.
1742 15/322=12	72	636	1.33 λ	Spherical with outer 30% over-corrected.
1741 4/297=24	120	1240	0.51λ	Approximately parabolic in outer 50%; spherical center.
1744 44/390=18	97	900	0.34λ	A good mirror.
73/556=18	97	883	0.46λ	A good mirror.
114/803=18	97	816	0.56λ	Approximately parabolic in outer 50%; outer zone over-corrected.
138/878=12	75	630	1.44λ	Spherical with outer 30% over-corrected.
244/1063=9.6	63	488	0.44λ	A good mirror.
189/1151=18	97	907	0.17λ	An excellent mirror.
42/1195=24	112	1228	0.97λ	Approximately parabolic in outer 50%; spherical center.
44/1198=24	111	1225	0.06λ	Superb—by far the best.
214/1235=18	96	895	1.35λ	Spherical with outer 30% over-corrected.
252/1313=18	97	881	1.65λ	Spherical with outer 30% over-corrected.
6/1364=49	235	2500	1.38λ	Spherical with outer 30% over-corrected.
Herschel's 7-foot telescope	170	4267	0.15λ	Would have been excellent even if left spherical.

* The table above is based on the data published by Rolf Willach (2001) along with my interpretation of Willach's test results. In calculating the approximate surface errors of the mirrors, the following equation was used:

$$\Delta z = [R - \sqrt{(R - h^2)}] - h^2/2R$$

An error of 0.25λ (Rayleigh's limit) has been utilized for many years as an indication of a reasonably good mirror, though more modern testing and fabrication methods have superseded it among professional opticians. Still, it gives a reasonable indication of overall optical quality. For comparison, results for a William Herschel 6.7-inch, 7-foot focus Newtonian were also calculated; note that, even if left spherical, the long-focus Newtonian is superior to all but one Short Gregorian telescope.

5 A 'GENTLEMAN-PHILOSOPHER' TELESCOPE-MAKER: WILLIAM HERSCHEL

In terms of both size and quality, reflecting telescopes of the late-eighteenth and early-nineteenth centuries reached their zenith with those of William Herschel (1738–1822). Herschel (Figure 9), originally a musician by profession, took up astronomy as a hobby after his move to England from Hanover, though he had been exposed to mathematics, astronomy and natural philosophy since boyhood (Hoskin, 2011: 11-30; Sidgwick, 1953: 17-20). Herschel had long maintained an interest in the sky, but this increased in the 1770s. His diary entries during 1773 repeatedly mention not only purchases of books on astronomy, but also the hiring of several small reflecting telescopes. Herschel also records the purchase of object glasses, tubes, and eyepieces for small refracting telescopes, and "… tools for making a reflector. Had a metal [mirror blank] cast." (Sidgwick, 1953: 47-55). Herschel bought several telescopes, the smallest being of 4-feet focus, magnifying 40-times, and longest of 30-foot focus, likely simple non-achromatic refractors. William's sister, Caroline (1750–1848), recalled that when they passed through London on one journey in 1773 virtually the only shops they stopped at were those of opticians. Among the books that William Herschel read was Smith's *Compleat System of Opticks* (Hoskin, 2011: 13, 28-30; Lubbock, 1933: 65-66; Sidgwick, 1953: 49).

Herschel became greatly interested in the relative compactness of the various types of reflecting telescopes, both Gregorians and Newtonians. But, as with many future amateur astronomers, he found the cost of commercially-available telescopes to be prohibitive, so he then decided to attempt making his own "… with the assistance of Dr. Smith's popular treatise on Optics." (Sidgwick, 1953: 55-56). One of Herschel's neighbors in Bath was an amateur telescope-maker who had given up the hobby, so William

Figure 9: Sir William Herschel, 1738–1822 (after Holden, 1881).

quickly purchased all of his tools and unfinished mirrors. The purchase of additional speculum metal discs for more telescopes soon followed, and Herschel became totally immersed in telescope-making in his spare time. Herschel quickly produced a Gregorian telescope by October, 1773 and a 4.5-inch Newtonian the next year (Gargano, 2012: 31; Hoskin, 2011: 30-32). By 1791, Herschel claimed to have produced 200 mirrors of 7-foot focus (6 to 6.7-inch aperture), 150 of 10-foot focus (8 to 10-inch aperture), and 80 of 20-foot focus (12 to 18-inch aperture).

Most of the telescopes Herschel made were of the Newtonian type, but, in an effort to reduce light-loss from multiple reflections, the larger sizes were of a single-mirror design now referred to as a 'Herschellian' (Sidgwick, 1953: 56-61). The large number of mirrors made for use by Herschel likely included numerous duplicates and failed experiments. Speculum metal is a difficult material to make and work with. There are many instances of speculum discs that shattered or became warped, possibly due to poor annealing. Besides this, makers of speculum-metal reflecting telescopes generally made at least a pair of mirrors for each telescope so that as a mirror became tarnished by exposure to the air, its 'twin' could be installed in the telescope while the original mirror was being repolished.

Herschel seems to have preferred testing his telescopes on the stars, rather than in the shop; however, the test he used was likely a variation of Hadley's method, substituting an actual star for the illuminated pin-hole. The crucial modification Herschel made to Hadley's test was that, when observing a star at infinity, the correct parabolic 'figure' of the mirror would produce the *same symmetrical series of intra- and extra-focal images* as produced by a spherical mirror tested at its center of curvature. Thus for Herschel, there would be no question of judgment as to whether the figure of the mirror was elliptical, parabolic, or some other figure as in Hadley's test; if one observed a good, symmetrical series of images, the mirror *had* to be perfectly parabolic (Sidgwick, 1953: 63-64). It is likely that other telescope-makers also did a final star-test of a telescope. The process of waiting for a clear night, mounting the mirror in a telescope tube, testing, then dismounting the mirror in order to polish it further would have been very time-consuming. While this would not have been much of an issue for an amateur telescope-maker like Herschel, it would have been a great annoyance for a professional optician struggling to meet orders.

Herschel's efforts at producing ever larger, ever improved telescopes, was driven by his observational interests. Unlike most observational astronomers of the eighteenth and early nineteenth century who were interested chiefly in the positions of stars and motions of the planets, Herschel wanted to know something of the nature of the stars and nebulae. This kind of study required a type of telescope that was quite different to those used for positional astronomy, as done at the Royal Greenwich Observatory in England, for example. Positional astronomy required very sturdy mountings, finely-graduated scales for measuring small angles, and the ability only to see relatively bright stars. For such a purpose, the then-standard, small aperture, long focal-length refractor was perfectly adequate. Herschel's work, on the other hand, required aperture and light-gathering power. In addition, his telescopes' relatively crude wooden mountings (e.g. see Figure 10) were perfectly adequate for his purposes (Lubbock, 1933: 64-65).

Besides producing telescopes for his own observational programs, Herschel also made telescopes for sale. Herschel was making the best large reflecting telescopes in the world around 1800, and the fame created by his discovery of the planet Uranus in 1781 without doubt encouraged many to purchase his instruments. Herschel could by no means be considered a mass-marketer of astronomical telescopes, even by the standards of his day, but he did offer more or less standard sizes at fixed prices. Records exist confirming the construction of at least 33 complete telescopes for sale, ranging in aperture from 5.5 inches to 24 inches. The most common size was the very convenient 7-foot focus telescope, which varied in aperture from 5.5 inches to 8.4 inches, though 6.7 inches was most typical; twenty-one 7-foot telescopes were made and sold between 1788 and 1812. The 10-foot focus telescopes were the next most popular (nine were produced), and were made with specula varying from 8.1 inches to 24 inches in diameter. The 14-foot, 20-foot, and 25-foot focus telescopes were each one-off items. Herschel stated in a letter dated 10 March 1794 that the prices of his complete telescopes—which appear not to have changed in over a decade—ranged from 100 guineas (£105 ca. 1800, which equates to about US$8,500 in 2012) for the small 7-foot (6.7-inch mirror) to 8,000 guineas (US$680,000) for a '40-foot' telescope with a 48-inch diameter mirror (Maurer, 1998: 15).

Purchasers of these telescopes were, to say the least, the elite of Europe. One of Herschel's best customers was none other than King George III, whose interest in astronomy led to Royal patronage of Herschel's research work; the King purchased several instruments as gifts for loyal subjects. Other buyers included King Carlos IV of Spain, Kaiser Franz I of Austria, Catherine the Great of Russia, Lucien Bonaparte, and the Grand Duke of Tuscany. How these telescopes were actually used is debatable, but they certainly served as "… showpieces." (Maurer, 1998: 4). Seven telescopes were purchased for use at various university and Government observatories around Britain and the rest of Europe. Individuals, such as the Italian astronomer Giuseppe Piazzi (1746–1826), purchased the balance (generally the smaller sizes), often for use in private observatories (see Gargano, 2012: 32).

While Herschel did in fact make telescopes for sale, the number sold was fairly small relative to the total number of mirrors made over his lifetime. Commercial telescope-making was clearly a sideline, something Herschel did to compensate himself for the time spent in producing telescopes for his own use. It was not a vocation, nor was it his means of livelihood. The fact that so many of Herschel's telescopes were made for prominent individuals might suggest that Herschel gained some status from his Royal patron. Compared to the commercial instrument-makers, Herschel could take his time and fabricate a series of superb instruments.

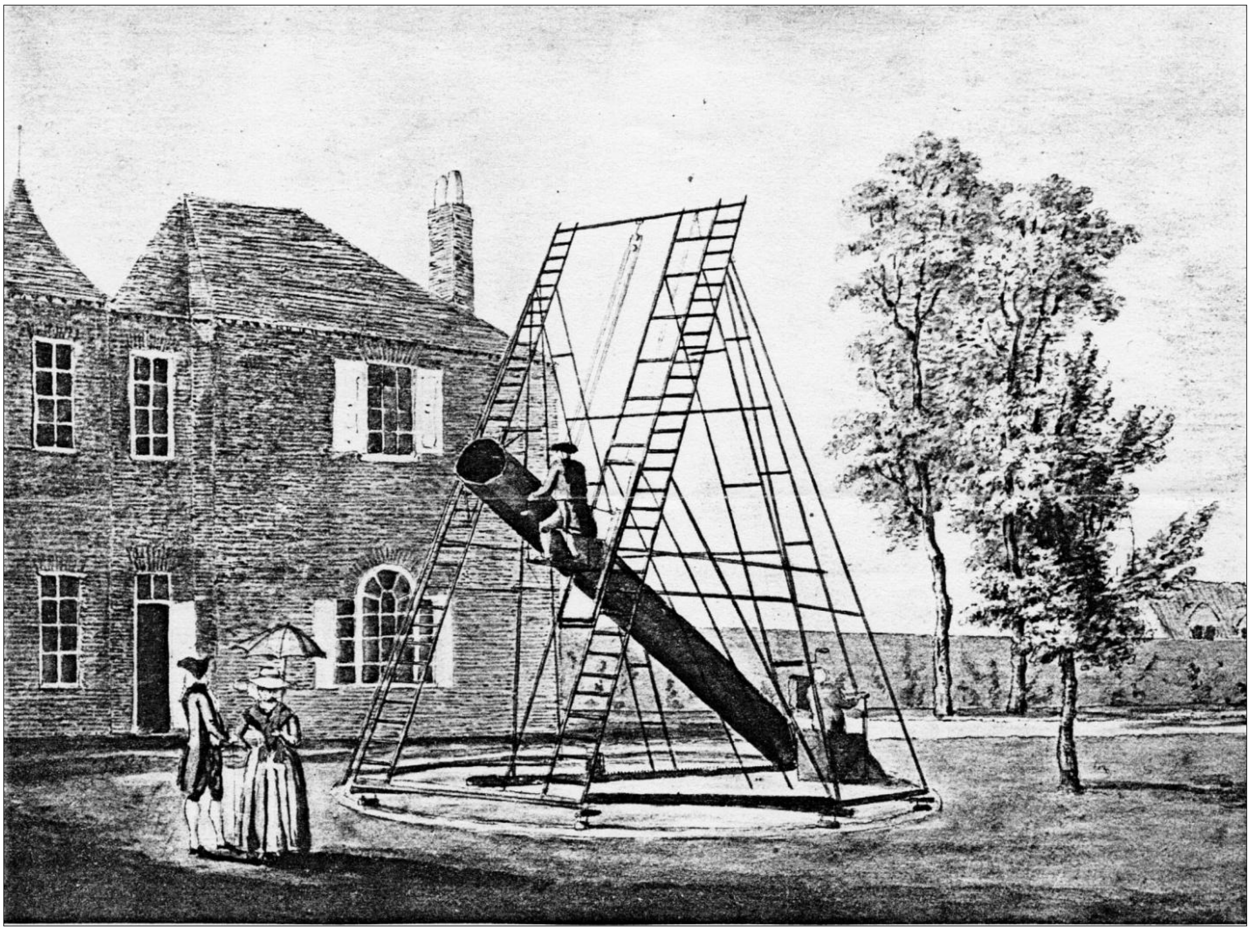

Figure 10: An example of one of Herschel's relatively crude wooden mountings (courtesy: Royal Astronomical Society).

6 CONCLUDING REMARKS

Although the reflecting telescopes of William Herschel represented a very high standard for such instruments, a level of both quality and size not surpassed until the 1840s, they were not entirely unique. Other astronomers were also involved in making reflecting telescopes for themselves in the early nineteenth century. One of them, the Reverend James Little, wrote a tract which was published in the *Journal of Natural Philosophy*, *Chemistry, and the Arts*, in 1807. Little's article provides considerable details of his own methods of casting specula, grinding, polishing and 'figuring' the mirror to the correct curve, as well as extremely detailed experimental analyses of problems of telescope design and fabrication (Little, 1807: 30-59, 84-100). Considering the seeming value of Little's treatise, it is remarkable that it fell into obscurity and later telescope-makers make no mention of it. Little's work is not mentioned in any later tracts on telescope-making, nor in King's *History of the Telescope*.

There were, in fact, a number of tracts available throughout the early nineteenth century for those interested in making reflecting telescopes. The mid-nineteenth century saw several large speculum-metal reflectors constructed by amateurs, primarily in Britain and Ireland. Some of these telescopes and their users made significant contributions to science, in particular the 6-foot diameter 'Leviathan of Parsonstown' (e.g. see Steinicke, 2012) which was constructed in 1845 by the wealthy William Parsons, 3rd Earl of Rosse (1800–1867). Parsons conducted many experiments on producing large telescopes, but his improvements were gradual. While his giant telescope was spectacular in appearance, its construction did not greatly advance reflecting telescope technology.

William Herschel was just one of a number of gentleman-philosophers who read Smith's, Little's and other similar tracts on telescope-making. The German lunar observer Johann Hieronymus Schröter (1745–1816), along with Johann Gottlieb Friedrich Schrader (1763–1833) and a gardener named Gefken collaborated to produce a number of fine-quality telescopes modeled on Herschel's pattern. The Italian astronomer Carlo Isimbardi was likewise experimenting with large reflecting telescopes in the 1790s and 1800s (Gargano, 2012: 32-33). None of these individuals was a professional optician, although Gefken apparently sold some of his mirrors as a sideline. The majority of individuals producing large, high-quality reflecting telescopes at the end of the eighteenth century were amateur astronomers who had enough time and resources to experiment and perfect their instruments.

What is to be made of the great differences in optical quality between the various James Short telescopes evaluated by Willach? As stated previously, it could simply be that a person or persons unknown repolished Short's speculae and destroyed an otherwise fine surface. Willach (2001) claims that this is unlikely. There is also the fundamental problem with

Hadley's test depending so heavily on the skill of the optician; however, James Short was an extremely experienced and skilled telescope-maker, as demonstrated by the considerable number of fair to excellent telescopes that he produced.

It seems most likely that the answer to this quandary is that Short produced excellent optics when he had the time, or when luck prevailed, but when time was limited and the purchaser might not recognize the difference between a good telescope and a poor one, Short and other opticians could produce and sell inferior-quality goods. In his *Opticks*, Newton noted possible problems with London opticians around 1700:

> Yet by this Experiment I satisfied my self that the Reflexion on the concave side of the Glass, which I feared would disturb the Vision, did no sensible prejudice to it, and by consequence that nothing is wanting to perfect these Telescopes, but good Workmen who can grind and polish Glasses truly spherical. An Objet glass of a fourteen Foot Telescope, made by an Artificer at *London* I once mended considerably, by grinding it on Pitch with Putty, and leaning very easily on it in the grinding, lest the Putty would scratch it. Whether this way may not do well enough for polishing these reflecting Glasses, I have not yet tried. But he that shall try either this or any other way of polishing which he may think better, may do well to make his Glasses ready for polishing by grinding them without that violence, wherewith our *London* Workmen press their Glasses in grinding. For by such violent pressure, Glasses are apt to bend a little in the grinding, and such bending will certainly spoil their Figure. To recommend therefore the consideration of these reflecting Glasses, to such Artists as are curious in figuring Glasses, I shall describe this optical Instrument in the following Proposition. (Newton, 1721: 94-95).

Considering how many telescope-makers, including William Herschel, mentioned Smith's *System of Opticks*, it seems highly unlikely that James Short and the better London instrument-makers would have been ignorant of this book. The test methods used by Hadley and Herschel were important in improving the reflecting telescope, but they were still clumsy and inexact. Texts on telescope-making by Smith, Little and others had been read by a number of telescope-makers, particularly gentlemen-philosophers and semi-professional opticians like Herschel.

The variable quality of James Short's telescopes, which ranged from poor to average to superb, can be understood without assuming the speculae had been re-polished by dilettante owners or incompetent opticians. The quality differences can be explained as simply having been due to production pressures. Although books such as Smith's *System of Opticks* were valuable conduits of knowledge, they had their limitations. Artisan telescope-makers such as Short appear to have known at least some of the techniques described by Smith, though they abandoned the time-consuming ones in favor of methods friendlier to the 'bottom-line'. On the other hand, gentlemen-philosophers like Hadley, Herschel, and Little fully embraced more sophisticated methods, particularly of testing, to produce qualitatively superior instruments. As a result, telescopes were either very expensive commercially-produced instruments of variable quality owned and used by wealthy individuals, or they were hand-crafted by a small number of skilled gentlemen-philosophers. Major improvements were made in the quality of speculum metal reflecting telescopes in the eighteenth century. However, the numbers of truly high-quality, large-aperture instruments remained very small.

The limits to advances in telescope fabrication did not depend on scientific or technological knowledge as much as on the dissemination and use of such knowledge for purely economic reasons. Small telescopes, such as the vast majority produced by Short, would probably have been purchased by individuals who were largely ignorant of their true optical quality. Despite the availability of Smith's book, artisan opticians could not afford the perfection achieved by their gentleman-philosopher cousins.

7 NOTES

1. "Large pits" is a relative term as those generated in coarse grinding are only about 1/100th of an inch across; these are quite noticeable and give the lens a frosted appearance. By the last stage of fine grinding the pits will have been reduced to less than 1/10,000th of an inch and the lens will be nearly transparent.
2. Hadley's description concentrates on the physical layout of the tube and mounting. His telescope was of about 6 inches in aperture and had a focal length of 62⅛ inches. In layout and accessories, Hadley's telescope is essentially the same as a modern Newtonian telescope. It had a 'slider' for adjusting the focus, a "… common Dioptrick [refracting] Telescope …" (Hadley, 1723: 306) with cross-hairs as a finder, and three eyepieces magnifying 188 or 190× (1/3-inch FL), 208× (3/10-inch FL), and 228-230× (12/40-inch FL). The eyepieces were of a single-lens convex type.
3. The generally-accepted maximum surface error for a telescope mirror is ¼ of a wavelength in green light, or about ±135 nanometers. The difference between a spherical surface and the correct parabolic one varies with both the diameter and the focal length of the mirror according to the formula $r^4/8R^3$, where r = the radius of the mirror (half of the diameter) and R = the radius of curvature (twice the focal length) of the mirror.
4. The lesser light-gathering power of early reflecting telescopes was due largely to the relatively low reflectivity of speculum metal. Even when freshly polished, a speculum metal mirror only reflected about 60% of the light falling on it. With two mirrors, as is the case with most reflecting telescopes, the total reflectivity would be 60% of 60% or only 36%. A reflecting telescope had only 25% of the light-gathering power compared to a refractor of equal size.
5. Although I think Willach's analysis of the Short telescope mirrors is largely correct, I strongly disagree with his statement "… that there are, in principle, only two methods of parabolizing mirrors in the sizes made by Short …": the use of either a star-shaped tool or a ring-shaped polisher (Willach, 2001: 14-15). I have made about 160 telescope mirrors for Newtonian, Cassegrain and several types of unobstructed reflectors. These mirrors range from 2.0 to 16.0 inches in aperture, with focal ratios from f/3.5 to f/30. I am familiar

with the use of sub-diameter tools and long-stroke overhang polishing, which is the most commonly-used technique among those telescope-makers I know.

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

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POSSIBLE ASTRONOMICAL MEANINGS OF SOME EL MOLLE RELICS NEAR THE ESO OBSERVATORY AT LA SILLA

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Abstact: This paper describes a peculiar, man-made circular stone structure, associated with the ancient rock engravings that are around the site of La Silla in Chile close to the European Southern Observatory, and are attributed to the El Molle Culture. Three stones of the circle, different from all the others, were likely to pinpoint the alignment of three bright stars close to the horizon, as seen from a specific vantage point inside the structure. The El Molle was the only period in which this alignment occurred significantly close to the horizon, moreover it was only in this epoch that it could also be associated with the transition from the warm to the cold season, a period of the year which was quite important for a society that supported itself by herding and farming.

Keywords: prehistoric stone circle, El Molle Culture, La Silla

1 INTRODUCTION

The slopes surrounding the buildings of the European Southern Observatory at La Silla are known to house several hundred rock engravings dating back to the pre-Columbian populations that once inhabited this region. Although precise archaeological studies are missing since none of these sites has been excavated, these petroglyphs are attributed to people of the El Molle Culture (Ballereau and Niemeyer, 1990), who around AD 300 had just abandoned their original lifestyle of hunting and gathering and developed more evolved settlements based on herding and farming. This Culture also produced the first ceramics made in the Norte Chico region. Between AD 700 and 800 the El Molle declined, giving way to a native cultural group called Animas, whose technical skills were presumably more advanced (see Castillo, 1989).

It is difficult to ascertain precisely the meaning of these rock engravings, but (at least) part of their content is clearly related to the daily life of herders. Among the many abstract and geometrical figures, there are several petroglyphs containing the simplified outlines of human figures and animals, the latter often gathered in large herds (e.g. see Figures 1 and 2).

One element of interest is the presence of various spirals scattered among the other figures, which are presumed to be schematic drawings of a snake—the most straightforward interpretation in some cases. Sometimes the spiral includes a straight line drawn outward starting from the centre, ending with a small bulge which could represent the head of the animal (see Figure 3). In other cases, however, where this feature does not clearly appear to be present (see Figure 4 and Niemeyer and Ballereau 1996), the spiral brings to mind the drawings of other ancient cultures widely scattered in space and time and commonly related to astronomical knowledge.[1] Though it was not our purpose to investigate this specific topic, such a characteristic feature made us wonder about possible, as yet undiscovered, astronomical aspects relating to the El Molle people. A circumstance of this kind would not be unusual for a community

Figure 1: Example of petroglyphs depicting stylized human and animal figures.

practising agriculture; nevertheless, we were not able to find any literary reference to this specific topic, even though

> These people had religious beliefs, and their lives were organized by means of ceremonies with the purpose of determining the seasons, or the beginning of the rainy and the dry seasons. (Ballereau and Niemeyer, 1996: 350; our English translation).

To our knowledge, the most recent and comprehensive publication about the El Molle engravings dates

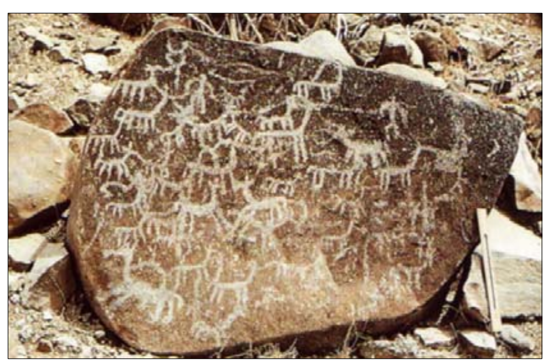


Figure 2: A large herd of animals (from http://www.eso.org/sci/facilities/lasilla/site/RockEngravings.html).

Figure 3: Example of spiral, probably representing a snake.

Figure 4: An example of spiral as an abstract shape (courtesy: Monica Rainer).

Figure 5a: The stone circle seen from Cerro las Vizcachas.

Figure 5b: A closer view of the stone circle. In the centre is the central stone, and to the right of it the two pillars.

to 1996 and is by the same authors of the above quotation, who also state that "Regarding the meaning of the … engravings, it escapes … a detailed study because of the lack of archaeological references." (Ballereau and Niemeyer, 1996: 350; our English translation).

2 THE STONE CIRCLE

One agglomeration of stone engravings is located in the region of Quebrada Los Tambos, a few hundred meters south-east of the dome of the 3.6-m Telescope (latitude –29.74°, longitude –70.67°, approximate elevation 2400m). These engravings can be reached quite easily in about half an hour, by walking along the pathway to Cerro Las Vizcachas. After about one kilometre the path turns right, and then left after another kilometre. After walking a further 200 meters along the pathway, you leave the beaten track and head down the gentle slope to the left, where there are two conspicuous upright stones that are taller than the average and are placed close to each other, like a couple of door jambs.

As you get closer to them, despite the great number of rocks scattered randomly all across the slope, it is easy to recognize the fact that these two stones are part of a larger structure forming a stone circle. This monument is made up of about ten flat stones composing a circle that is less than 20 metres in diameter, with another larger flat stone located in the centre (see Figures 5a, 5b). None of the stones forming the circle is engraved. It is also worth noting that all these stones are quite low, almost at ground level, except for the first two mentioned above, which are completely different in shape and are placed vertically. Finally, another stone is placed along the circumference more or less in the middle between the two 'jambs', but slightly closer to the left one, as seen from inside the circle (see Figure 6).

In the rest of this paper we will speculate on the significance of this distinctive structure and in particular on the interpretation of the three stones. We stress here, anyway, the artificial nature of the whole structure, which resembles a smaller-scale copy of other megalithic constructions found in several sites in Europe and around the world, and whose astronomical functions have been established beyond any doubt. Obviously no direct connection between this and the European structures is suggested; but we deem it interesting to note the alignments with the Sun of the Incan *huacas* discovered by Gullberg (2010) near Cuzco in Peru. It was the Incas who invaded the La Silla region about 400 years after the end of the El Molle Culture.[2]

3 ASTRONOMICAL ANALYSIS

Before giving a tentative astronomical explanation of the La Silla stone circle, we point out that our investigation was not the result of a planned expedition, but originated from a couple of excursions organized during an observing run at La Silla. Given the unexpected character of this discovery, it was not possible to conduct very accurate measurements because of the lack of time and suitable instrumentation. Nonetheless, it is our opinion that a possible astronomical interpretation of this structure can be suggested with a certain degree of accuracy.

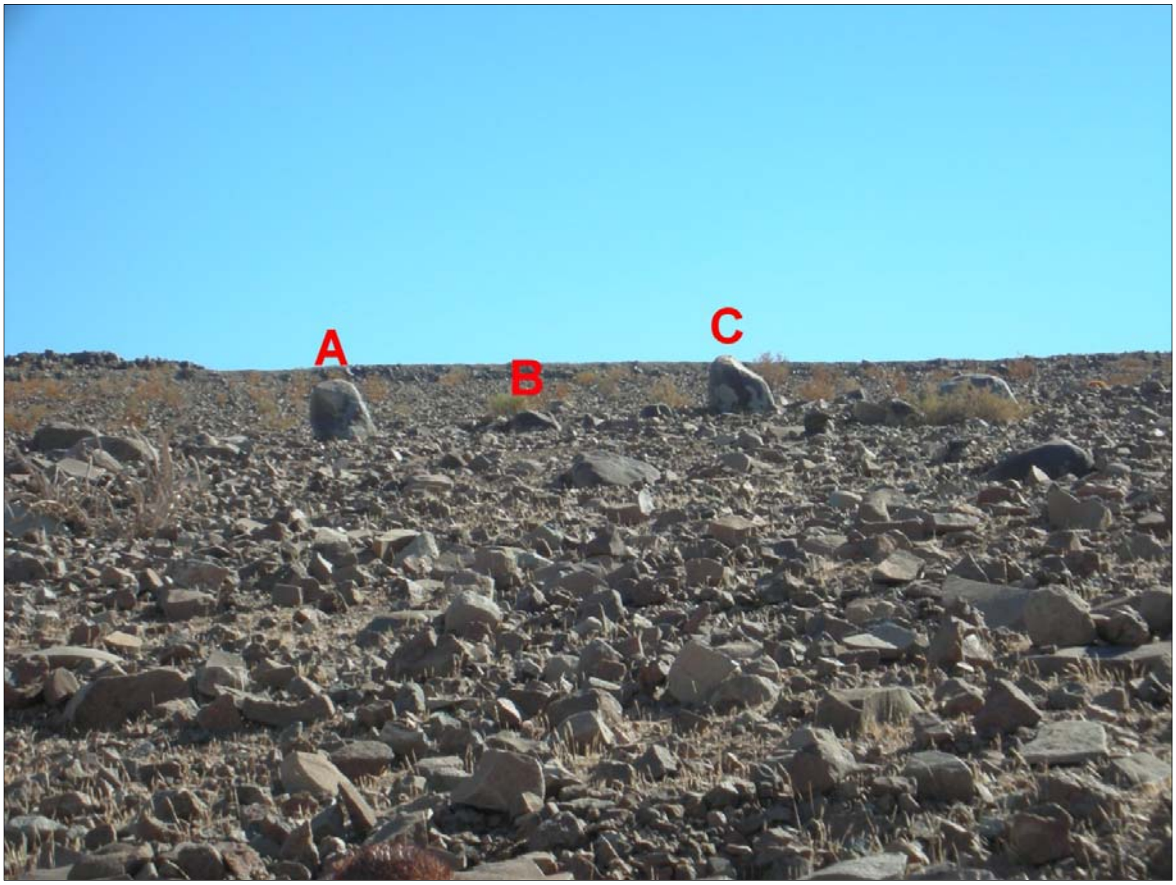


Figure 6: The two pillars (A and C) as seen from inside the circle, and the third lower stone in between (B).

To this aim, the first thing to do is to find the orientation of the circle, specifically of the 'entrance' formed by the two stones. Thanks to a simple magnetic compass, it could be established that the direction connecting the central stone with the middle of the entrance was South within ±10°.[3] Another noticeable thing is that the circle is placed in such a way that the entrance can look towards a direction where the slope is rising, but the horizon is relatively free from obstacles and quite horizontal. It seems plausible that such a position and orientation were chosen on purpose, since from here the profile rises both on the right and on the left.

Moreover, looking from the centre of the circle, the top of the two vertical pillars are quite accurately aligned with the horizon, as can be seen in Figure 6. This observing condition is obviously allowed because the structure is placed in such a way that the chosen direction is pointing toward the rising slope, and in our opinion it can hardly be considered accidental. At this point it is worth noting that it is plausible to assume that the horizon did not change very much because of human activities, since the pathway to Cerro Las Vizcachas follows the ridge line.

Given these premises, are there any possible astronomical interpretations of this configuration? First of all it should be noted that, though approximate, the estimated orientation is accurate enough to exclude any possible solar-related events, like sunrise during the solstices or at the equinoxes, simply because, in the Southern Hemisphere and at these latitudes, the Sun always crosses the horizon too far from these points. For similar reasons, one can very likely exclude any relation with the planets or the Moon, given the orientation of the Ecliptic. Therefore, it seems that the only plausible hypothesis could be the existence of a particular alignment of one or more stars with the stones of the circle, and most probably with the two vertical pillars. Moreover, if we accept that the stone circle relates to the El Molle Culture, then this hypothetical alignment would have occurred during the period spanning approximately from AD 100 to 800.

A couple of such alignments can be found for bright stars visible from the Southern Hemisphere: one is between α Carinae (visual magnitude −0.55, at present) and α Centauri (0.14), also known as Canopus and Rigil Kent, and the other one is between α Carinae and β Centauri (Hadar, magnitude 0.54). Before starting to explain the details of how we determined these alignments, it is worth noting that Antares, being a comparable bright star, could also be a good candidate, but it has to be excluded because of the configuration of the ridge. As indicated at the beginning of this Section, in fact the profile of the terrain rises on both sides of the pillars, so that Antares sets behind the mountain well before the dawn. In the following discussion we will get back to the importance of this particular point in the context of our interpretation.

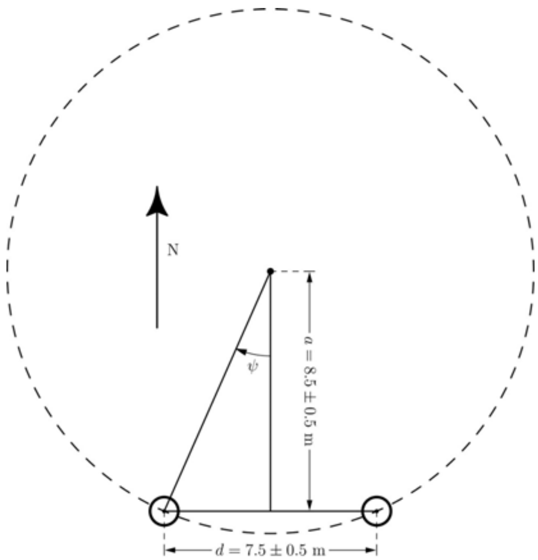


Figure 7: Schematic representation of the circle dimensions.

3.1 Tools Used in our Analysis

In order to predict the stellar positions in the past we implemented a FORTRAN code which invokes some routines of the SLALIB astronomical library (Wallace, 1994).[4] This provides an accuracy of better than 1 arcsecond for the calculation of precession throughout the time span of interest.[5]

For the computation of solar coordinates and the prediction of the sunrise time, we used the MDIC Solar Position Calculator.[6] The data resulting from these algorithms have been processed with Asymptote,[7] a powerful descriptive vector graphics language that provides a mathematical coordinate-based framework for technical drawings, which not only provided the tools for drawing the graphs, but also the algorithms to fit the ephemerides and find the data listed in the tables.

3.2 Orientation and Alignments

We measured the distance a from the centre of the circle (i.e. the central stone in Figure 7) to the midpoint between the two pillars, which we estimated to be 8.5 ± 0.5 meters, while the measured distance d between the two pillars was 7.5 ± 0.5 meters. For the geometry of Figure 7, this gives an angular distance, 2ψ, of 47.6° ± 5.3°, using the formula

$$\psi = \arctan(d/2a) \qquad (1)$$

The angular separations between the two pairs of stars during the historical period associated with the El Molle Culture was about 57.25° for Canopus and Rigil Kent and 55.5° for Canopus and Hadar (the precision is sufficient given the accuracy of our measurements). These two quantities are compatible with 2ψ at the 2σ level, but more stringent constraints can be fixed by other kinds of estimations, somewhat reducing the problems arising from the low precision of our measurements.

One is the determination of the alt-azimuthal coordinates of these stars when they become aligned with the horizon. Table 1 provides a list of these coordinates at the time of the alignment for the eight centuries between AD 100 and 800, where it can be seen that the alignment of Canopus with Rigil Kent finds Canopus 28-31° eastward from the south, and Rigil Kent 27-30° to the west, depending on the chosen year, while for the alignment with Hadar we have the former at 26-29° eastward from south and the latter at 27-30° westward.[8] Meanwhile, the orientations of the left (more eastward) and right pillars are +23.8°+/–10° ± 2.65° and –23.8°+/–10° ± 2.65° (to the west), respectively (+/–10° accounts for compass error). These constraints have more or less the same significance as the previous computations of the angular separations, with the additional information that the directions of the stars are approximately compatible with those of the stones; but a more interesting constraint comes from their altitude.

Table 1: Alignment data of the two pairs of stars.*

Year	Canopus		Hadar			Canopus		Rigil Kent		
AD	*A*	*h*	*A*	*h*	Δ	*A*	*h*	*A*	*h*	Δ
100	+153°56'	+3°12'	+209°33'	+3°12'	55°35'	+152° 51'	+4° 06'	+209°58'	+4° 06'	57°03'
200	+153°28'	+3°32'	+209°05'	+3°32'	55°35'	+152° 20'	+4° 30'	+209°31'	+4° 30'	57°06'
300	+153° 00'	+3°52'	+208°38'	+3°52'	55°35'	+151° 50'	+4° 54'	+209°05'	+4° 54'	57°09'
400	+152° 32'	+4°14'	+208°11'	+4°14'	55°35'	+151° 20'	+5° 19'	+208°41'	+5° 19'	57°12'
500	+152° 05'	+4°36'	+207°45'	+4°36'	55°35'	+150° 51'	+5° 44'	+208°17'	+5° 44'	57°15'
600	+151° 39'	+4°58'	+207°20'	+4°58'	55°35'	+150° 23'	+6° 10'	+207°54'	+6° 10'	57°18'
700	+151° 13'	+5°21'	+206°56'	+5°21'	55°35'	+149° 56'	+6° 36'	+207°32'	+6° 36'	57°21'
800	+150° 48'	+5°44'	+206°33'	+5°44'	55°35'	+149° 29'	+7° 03'	+207°10'	+7° 03'	57°24'

*Alt-azimuthal positions and angular separations (Δ) of the two couples of stars at the alignment at different years, from 100 to 800 AD. The left and right data refer to the alignment of Canopus with Hadar and with Rigil Kent, respectively. The altitude *h* is referred to the sensible horizon, which takes into account the elevation of the observing place (ca. 2400 m) and adds approximately 2° to the value of *h* referring to the geometrical horizon. This is done consistently with the sunrise data. However, the listed values do not consider the slope of the terrain, whose effect is to raise the horizon, and therefore to decrease the apparent altitude, as discussed in the article.

Table 2: Estimation of the distances between the three stones and their ratios based on pixel measurements of three different kinds of fiducial points: extremes at the base, extremes at the top and the single highest point of each stone. In the first two cases we have computed the distances (in pixels) using the average values $\langle x \rangle$ of the two extremes x_{left} and x_{right}. The δ_x columns are the estimated uncertainties, in pixels, of the measured pixel position of the left column. The σ_x columns are the estimated uncertainties on $\langle x \rangle$ obtained by standard error propagation. The ratio and its estimated error are shown in the last row.

	Base points						Top points						Highest point	
	x_{left}	δ_x	x_{right}	δ_x	$\langle x \rangle$	σ_x	x_{left}	δ_x	x_{right}	δ_x	$\langle x \rangle$	σ_x	x	δ_x
A	761	5	898	1	829.5	2.5	748	3	838	10	793.0	5.2	815	5
B	1224	2	1340	3	1282.0	1.8	1233	5	1278	30	1255.5	15.2	1255	5
C	1714	10	1860	3	1787.0	5.2	1708	5	1768	40	1738.0	20.2	1744	4
d_{AB}/d_{AC}	0.473 ± 0.003						0.489 ± 0.019						0.474 ± 0.006	
$\langle d_{AB}/d_{AC} \rangle$ (weighted)	0.473 ± 0.003													

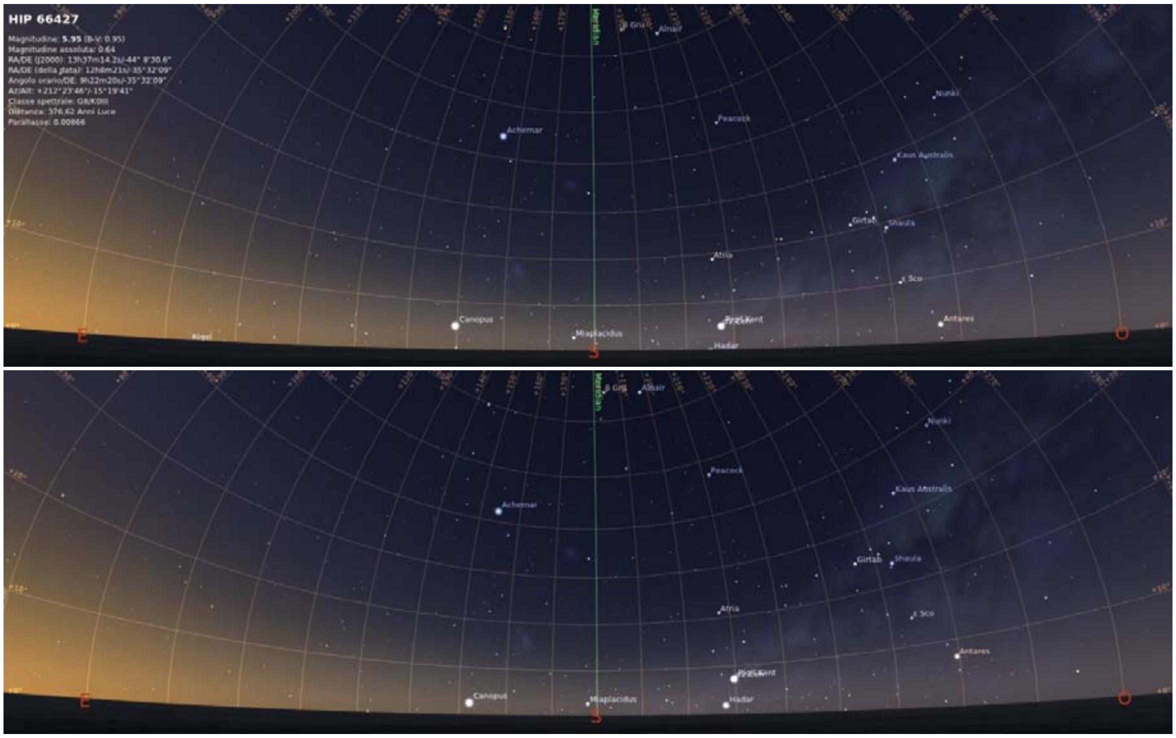
Table 3: Alt-azimuthal positions of Miaplacidus at the alignment with Hadar (left) and Rigil Kent (right) in different years from 100 to 800 AD. The last two columns give the angular separation between Canopus and Miaplacidus, and the ratio between this separation and that between Canopus and the farthest star. The same consideration of Table 1 about the altitude *h* applies here.

	Miaplacidus				*Miaplacidus*			
Year	*A*	*h*	Δ_{AB}	Δ_{AB}/Δ_{AX}	*A*	*h*	Δ_{AB}	Δ_{AB}/Δ_{AX}
100	+179°30'	+3°30'	25°33'	0.46	+178°25'	+3°33'	25°33'	0.45
200	+179°02'	+3°53'	25°33'	0.46	+177°55'	+3°57'	25°33'	0.45
300	+178°35'	+4°17'	25°33'	0.46	+177°26'	+4°21'	25°33'	0.45
400	+178°08'	+4°41'	25°34'	0.46	+176°57'	+4°47'	25°34'	0.45
500	+177°42'	+5°06'	25°34'	0.46	+176°29'	+5°13'	25°34'	0.45
600	+177°17'	+5°31'	25°34'	0.46	+176°02'	+5°39'	25°34'	0.45
700	+176°52'	+5°57'	25°35'	0.46	+175°36'	+6°07'	25°35'	0.45
800	+176°28'	+6°23'	25°35'	0.46	+175°10'	+6°35'	25°35'	0.45
	Alignment with Hadar				Alignment with Rigil Kent			

When referred to the alignment of Canopus and Rigil Kent, their altitude over the *sensible horizon*, which takes into account the elevation of the observing place, is about +4° 06′ to +7° 03′ (again depending on which year we are considering), while for the alignment between Canopus and Hadar they lie in the range 3° 12′ to 5° 44′. It is interesting to compare these altitudes with the actual altitude of the horizon, given by the mountain ridge, as seen from the stone circle. One can estimate that the distance of the structure from the ridge is between 100 and 200 meters, while the rise is around 10 meters, which implies an altitude of the horizon between 2.8° and 5.7°. In other words, the pairs of stars were close to the visible horizon at the time of their alignment. It should be noted that the precession makes these conditions disappear in years preceding the period examined (the stars were too low) and at the present day (the altitude is >10°).

Let us now consider a further element of interest concerning another stone positioned in a particular way, which we mentioned earlier. This is a stone that is higher than those forming the circle, but is lower than the two pillars, and is placed between them but a little closer to the left pillar (Figure 6). We tried to understand if this shift could be regarded as significant, so using our pictures we measured the distances (in pixels) between the three stones in three different ways: by considering the positions of their a) bases, b) tops, and c) highest points. The results of such estimations are reported in Table 2, and if we call the left and right pillars A and C respectively, and the middle stone B, the weighted mean of the three ratios d_{AB}/d_{AC} is 0.473 ± 0.003. It seems, therefore, that the third stone was placed on purpose a little to the left of centre. Quite surprisingly, it seems that the star Miaplacidus (β Carinae) can take the place in the sky that B has in the stone circle. It is still quite bright—at visual magnitude 1.67 it is the brightest star in between the two stars of the pair—but at the same time is significantly fainter than the other two, regardless of whether C is associated with Rigil Kent or Hadar, and the ratio between the corresponding angular distances in the sky is about 0.45 for the former and 0.46 for the latter (see Table 3).

We want to stress here the different nature of this kind of coincidence. This is, in fact, a relative measurement that holds irrespectively of the uncertainties of the previous estimations on the precise absolute orientation of the two pillars. Obviously this correspondence would be significant only if the middle star were conveniently aligned with the others. In fact, if we consider the time of alignment of the main pair with the horizon, we can see that the altitude of Miaplacidus is quite similar: it goes from 3° 30′ to 6° 23′ if we identify Hadar as the second star, and from 3° 33′ to 6° 35′ in the case of Rigil Kent. In the first case, Miaplacidus is a little lower than the two brighter stars, while in the latter case the three stars are almost perfectly aligned. In add-



Figures 8a and 8b: From Stellarium (http://www.stellarium.org) the alignments among the three stars in 400 AD in the case of Rigil Kent (a) and of Hadar (b). These renderings should only be viewed as graphical aids to aid the interpretation. Actual computations have been made with the software reported in Section 3.1, and these, and the plots given in Figures 9a and 9b, should be considered for a more precise evaluation.

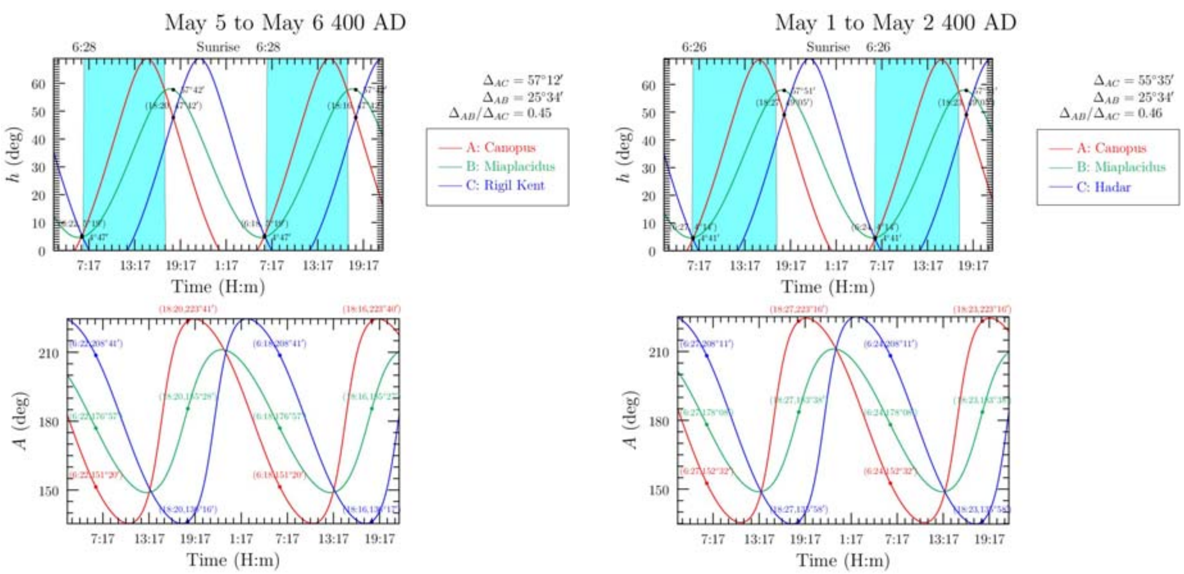


Figure 9a (left) and 9b (right): Two examples of how the graphical tools have been used to find the coordinates and time of the alignments in the case of Rigil Kent and of Hadar. In each figure, the top panel plots the altitude relative to the sensible horizon (see Table 1) of the three stars vs. time (approximately two days, negative altitudes are not shown). A fit of each curve provides the intersection points between stars A and C, which give the times and the altitude at the alignment for each day. A similar fit is used to find the altitude of B at the time of alignment. The filled areas represent the daylight. These data have been obtained by the MDIC Solar Position Calculator with the following input: starting date, March 01, end date August 01 (same year), time interval between two points, 10 minutes, site location: latitude –29.74°, longitude –70.67°, elevation 2400 m, time zone, –4.711333. The bottom panel, instead, shows the azimuths, and their values at the time of alignment are obtained with similar fits. At the top, to the right of each plot, the angular distances between A and B and A and C, and their ratios, are reported.

ition to this, it has to be noticed that Miaplacidus is a circumpolar star now and was in the past until the El Molle period, but this characteristic did not apply in earlier times: two thousand years ago its lowest altitude was <3° (i.e. still circumpolar, but it probably was below the horizon as seen from the stone circle), while some centuries before this it was no longer a circumpolar star.[9]

Table 4: Summary of the astrometric data for the four stars (J2000.0) from the Hipparcos catalogue (Perryman et al. 1997; van Leeuwen 2007) (New Reduction, Vizier code: I/311/hip2). Spectroscopic and photometric data (radial velocities and magnitudes) from Anderson and Francis (2012). Extended Hipparcos Compilation, Vizier code: V/137/XHIP.

Star	α	δ	μ_α (mas/yr)	μ_δ (mas/yr)	π (mas)	v_r (km/s)	V
Canopus (α Car) HIP 30438	6h 23m 57.1s	–52° 41' 44.4”	19.93 ± 0.52	23.24 ± 0.69	10.55 ± 0.56	20.3	–0.55
Rigil Kent (α Cen) HIP 71683 A	14h 39m 36.5s	–60° 50' 02.4”	–3679.3 ± 3.89	473.67 ± 3.24	754.8 ± 4.11	–21.4	0.14
Hadar (β Cen) HIP 68702 A	14h 03m 49.4s	–60° 22' 22.9”	–33.27 ± 0.50	–23.16 ± 0.41	8.32 ± 0.50	5.9	0.54
Miaplacidus (β Car) HIP 45238	9h 13m 12.0s	–69° 43' 01.9”	–156.47 ± 0.14	108.95 ± 0.11	28.82 ± 0.11	–5.1	1.66

In summary, it seems that during the El Molle period, a triple alignment existed of three bright stars, but with a possible uncertainty as to whether α or *β* Centauri should be considered part of the group. Whatever the choice, this group of stars was visible just above the horizon at the time of day when they were parallel to it, and Figures 8a and 8b give an artistic impression of this event. This triple alignment is reproduced and can be identified with significant accuracy for an observer standing at the centre of the stone structure, by using the three stones of the circle, whose dimensions, moreover, might be connected to the stars' relative magnitudes. This astronomical event was not visible before the period of interest, because it occurred below the observed horizon, and it is much less significant at the present day, because of the relative distances of the three stars and because of the increased altitude at which this event occurs. Table 4 summarizes the data for the four stars taken from the Hipparcos Catalogue, while Figures 9a and 9b give an example of how to interpret the plots used to exploit the data coming from the software listed in Section 3.1.

4 POSSIBLE FUNCTION OF THE STONE CIRCLE

Having found a noticeable connection of the stone circle with an astronomical event, though with a certain degree of approximation, it is logical to explore the existence of a practical function for such a structure and how it was used by the people who built it. Moreover, since the relatively low accuracy of the measurements makes our deductions less compelling, the discovery of a possible role for this structure could also provide further evidence supporting our astronomical interpretation.

It has to be stressed that the orientation of the line connecting the three stars is, in a certain sense, mainly ruled by the Earth's rotation around its axis, and therefore this particular alignment with the horizon does indeed occur every day. The two other motions of the Earth affecting this astronomical event are precession and the orbital motion of the Earth around the Sun. The former, as we pointed out in the previous Section, influences the altitude of the alignment with respect to the horizon, while the latter determines the time of day when this event is visible, so that in some parts of the year it may be impossible to see it because it happens during daylight, while on other dates it will happen during the night.

The case of the heliacal rise of Sirius can give us some useful hints for our investigation. It is well known in fact that for the Egyptians this event signalled the period of the year when flooding by the Nile River occurred, which was a fundamental date in their calendar because of several activities connected with the farming needs of their society. Following this suggestion, we searched for the periods of the year when the alignment occurred at dawn or at twilight.

It was easy to discover that over the period of interest during the El Molle Culture the alignment coincided with the dawn between the end of April and the first half of May (see Table 5 and Figure 9a and 9b for a more detailed explanation on how these data have been obtained), which is quite an interesting coincidence since during this period of the year the winter was approaching. According to Niemeyer and Ballereau (1996) in the past the climate was different to the present one: rain was more abundant, feeding non-permanent water courses, and this region was much less arid than it is today. The surviving traces of human occupation scattered all around Cerro La Silla support this hypothesis. It is therefore possible that the farmers of the El Molle Culture herded their livestock (whose existence is testified by the rock engravings, as shown in Figure 2) here and on other high ground pastures during the warm season, and only descended to the plains when the winter was approaching. In this scenario, the occurrence of the stellar alignment at dawn would have indicated the right moment for this annual migration. The stone circle therefore would have helped the farmers to pinpoint this event easily and without any doubt, and could well pertain to a culture which—as with many other prehistoric populations around the world—probably held ceremonies to acknowledge the changing of the seasons (Ballereau and Niemeyer 1996). If this interpretation is correct, then the time at which the alignment occurs at dusk is much less significant because it happens in the second half of October, when the cattle might have just started populating the pastures. In this case, an astronomical event heralding the right time for the migration to higher ground should have been determined beforehand from the plains.

5 CONCLUSIONS

In this paper we proposed that archaeological relics close to the La Silla Observatory can be interpreted in an astronomical sense. In particular, the most intriguing find was a circle of stones, three of which are clearly distinct from all the others. The site is

Table 5: Dates at which the triple alignment occurred at dawn, and the hour of the dawn for the corresponding year. The dates listed here are expressed in the Proleptic Gregorian calendar, which is closer to the actual season of the year. During the range of interest for this table, the differences with the (historical) Julian calendar went from –2 days to 4 days. In order to choose the day, we adopted the criterion that the alignment should occur at least 2 minutes before dawn. Different criteria, however, cannot change the date by more than one or two days.

	Alignment at dawn with					
	Hadar			*Rigil Kent*		
Year	Day	Hour	Dawn	Day	Hour	Dawn
100	29 Apr	06:19 AM	06:24 AM	01 May	06:20 AM	06:25 AM
200	30 Apr	06:22 AM	06:24 AM	03 May	06:20 AM	06:26 AM
300	02 May	06:21 AM	06:26 AM	04 May	06:23 AM	06:27 AM
400	02 May	06:23 AM	06:26 AM	05 May	06:28AM	06:28 AM
500	04 May	06:22 AM	06:27 AM	06 May	06:26 AM	06:29 AM
600	05 May	06:25 AM	06:28 AM	08 May	06:25 AM	06:30 AM
700	07 May	06:24 AM	06:29 AM	09 May	06:28 AM	06:30 AM
800	07 May	06:27 AM	06:30 AM	10 May	06:28 AM	06:32 AM

attributed to the El Molle Culture which dominated the region from the first centuries of our era to about AD 800, and we showed that during this period the three stones seem to reproduce, or indicate, the positions of three bright stars (Canopus, Miaplacidus, and Rigil Kent or Hadar) which from the centre of the circle could be observed almost perfectly aligned with the horizon. The accuracy of our measurements does not allow a confirmation of this interpretation beyond any doubt, but different independent coincidences seem to support it. For example, this alignment does not concern a single star, but three, and the alignment was visible only during the historical period of the El Molle Culture because in earlier epochs the stars in question were below the horizon whereas today they are in a much less significant position well above it. Moreover, during the El Molle epoch this region was less arid than now, and probably supported pasture that was grazed by livestock during the summer months. We discovered that during this prehistoric period this astronomical alignment happened at dawn when the warmer months were starting to give way to a colder period, signalling to the farmers that it was time to drive their livestock from the high grounds down to the plains. Future, more accurate, measurements at the stone circle site could provide further evidence for this interpretation.

6 ACKNOWLEDGEMENTS

We wish to thank the referees for their helpful comments.

7 NOTES

1. The astronomical interpretation of the spiral, and its presence in stone carvings attributed to many prehistoric cultures, is well known. For example, carved spirals with a well-established astronomical meaning are found in Malta and at Newgrange during the fourth millennium BC, but also in New Mexican sites almost five thousand years younger (see Sofaer et al., 1979 and the references in http://www.solsticeproject.org/research.html, for papers about the New Mexican sites).
2. *Huacas* were a kind of sacred shrine of the Incas, and were represented by a particular location or object, and regarded to "… manifest the superhuman." (Gullberg, 2010). Where *huacas* were represented by alignments of carved stones or pillars on a mountain ridge these were often associated with significant positions of the Sun, as during the solstices. But some stones were classified as "… non-astronomical rocks …" by Gulberg, because no alignment with the Sun could be found for them. It should be noted, however, that the title of Gullberg's paper clearly indicates that any kind of astronomical alignments differing from those with the Sun were considered beyond the scope of his research.
3. The measurement was made in 17 April 2011, when the magnetic declination at the place was approximately 38′ (NOAA: http://www.ngdc.noaa.gov/ geomagmodels /struts/calcDeclination), i.e. much less than the accuracy of the compass.
4. The SLALIB code can be found at the Starlink project URL http://starlink.jach.hawaii.edu/starlink.
5. Given the accuracy of the measurements, nutation effects have not been included.
6. Measurement and Instrumentation Data Center, of the National Renewable Energy Laboratory (NREL). See http://rredc.nrel.gov/solar/codes and algorithms/solpos/ for the C source and http://www.nrel.gov/midc/solpos/solpos.html for the web interface to the binaries.
7. http://asymptote.sourceforge.net/
8. About the possibility that Antares could also be considered by the ancients, one should notice from Figure 8a that this star is more or less aligned with Canopus and Rigil Kent, but its azimuth is >65°. Because of the profile of the ridge (which is not reproduced in our figure) this star would not have been visible during the alignment. This is further indirect evidence in support of our thesis.

9. Also the alignment condition has changed with time because of the different proper motions of these stars. While in the past Miaplacidus was aligned with Canopus and Hadar, at present the alignment with Rigil Kent is better.

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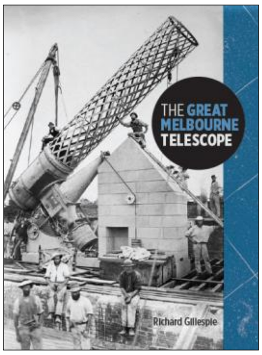
BOOK REVIEWS

***The Great Melbourne Telescope*, by Richard Gillespie (Melbourne, Museum Victoria, 2011), 188 pp., ISBN 978 1 921 83305 2, AU$29:95 (paperback), 200 × 250 mm.**



The Great Melbourne Telescope—or GMT as it is affectionately known in Australia—is an icon of Australian astronomical history. Once the largest equatorially-mounted reflecting telescope in the world, great things were expected of it when it saw first light in Melbourne in 1868. However, this did not happen, and it has been viewed internationally by many as a 'white elephant'.

Precisely how this categorization came about is examined in a fascinating new book penned by Dr Richard Gillespie, Head of the Science and Technology Department at Museum Victoria in Melbourne, Australia.

In England, the Great Southern Telescope Committee assembled a suite of research objectives for the GMT, involving an investigation of the southern nebulae. But the open lattice tube of the telescope which vibrated in even the gentlest of Melbourne's winds and forced the observers to make drawings of these tenuous objects rather than take photographs of them, partly militated against this, as did the use of speculum mirrors which rapidly tarnished in the salty Melbourne air, and required repolishing and figuring. Regular 'public nights' when visitors could queue and look through the telescope also ate into valuable observing time that otherwise would have been devoted to research. Eventually, staffing cuts during the economically-turbulent 1890s and the Observatory's new-found involvement in the demanding international Cart du Ciel Project effectively sounded the death knell of the great telescope as a Melbourne icon. Yet it would rise from the ashes, phoenix-like, to emerge in two totally different incarnations, first at Mount Stromlo Observatory in the years following WWII, and then towards the end of the twentieth century back at the Melbourne Observatory site itself—but more on this anon.

Richard Gillespie weaves all of these threads into his account of the GMT, but he also provides a socio-political dimension to the telescope by supplying biographical information about those who planned it and used it, and on the rapidly-changing city of Melbourne during the life of the telescope. For instance, I knew that William Parkinson Wilson, the young foundation Professor of Mathematics at the University of Melbourne, and George Verdon, the equally-youthful Treasurer of the colony of Victoria, played key roles in making the dream of a 'Great Southern Telescope' a reality, but Gillespie shows how they skillfully used their political acumen and contacts in both Australia and Britain to actually make this happen.

I also knew that Albert le Sueur—the first GMT 'Observer', who was trained in England for the role—prematurely returned home, but I was surprised to read that he was a mere 16 or 17 year old recent mathematics graduate from Cambridge, with no formal astronomical education or observing experience, when in 1866 he was appointed to conduct research with what was then the most advanced astronomical telescope in the world. I found it fascinating to read about the various problems—some genuine, others of his own making—that le Sueur encountered with the telescope, and the conflicts that arose through his dual commitments to the Royal Society in London (which appointed him) and the Government of Victoria (which formally employed him and paid his salary). Eventually it all became too much for the youthful, inexperienced and somewhat naïve le Sueur and he tendered his resignation and returned to England. Once there he lost his supporters, and he was soon abandoned by the astronomical fraternity.

Farie MacGeorge succeeded Le Sueur as the GMT Observer, but his stay at Melbourne Observatory was equally short-lived, and Gillespie explains why: Farie and his wife were heavily involved in spiritualism (which was very popular in Melbourne at the time), and observing sessions with the great telescope took him away from meetings that he wished to attend. Eventually he tendered his resignation, for, as Gillespie explains, "MacGeorge was seeking a greater understanding of the universe then he could find in the eyepiece of the telescope." (page 94).

Gillespie does an excellent job covering these topics, and others, in a mere 188-page book that is also liberally sprinkled with historical illustrations, some of which I had not seen previously. After discussing the concept of a 'Great Southern Telescope' in Chapter 1, he explains in the following three chapters how this became the 'Great Melbourne Telescope', then he summarises the observational efforts of le Sueur, MacGeorge and the third GMT 'observer', professsional photographer Joseph Turner. However, this book is designed for the interested public, for amateur astronomers and for professional astronomers who seek an overview on the telescope, so those expecting a detailed account of the telescope's research achievements must look elsewhere (to Andropoulos, 2012; and Orchiston et al., 2013).

Yet this very focus on the non-research aspects of the telescope's history is one of its strong points. For instance, I found Chapter 6 on "The Telescope in the City" compelling reading. After introducing us to Britain's popular young 'royals', Prince Albert and Prince George, who shared an evening with the GMT in July 1881, Gillespie shows how an evening visit to the GMT was mandatory for distinguished visitors to the city and members of Melbourne society, until this practice reached the point where it seriously interfered with the Observatory's research programs and Director, Robert Ellery, was forced to write the Government and request a reprieve. Thus, by 1881 the GMT

> … had become the city's scientific icon. As well as a key instrument in an international scientific research program to understand nebulae, the telescope had become woven into the life of the observatory and the city. The telescope took on a public life that was as

> much ceremonial as scientific, becoming a focal point for the public understanding of science. (pages 119 and 121).

The final chapter, titled simply "Rebirth", addresses the telescope's rebirth in the 1950s as the Stromlo 50-inch reflector (complete now with a silver-on-glass primary mirror), which for several decades serviced the ANU's astrophysical research programs, in league with the Grubb-Parsons 74-inch reflector. At the end of the 1980s the 50-inch was refurbished and then was used for the MACHO Project, the search for evidence of missing mass in our Galaxy and the Universe, until the disastrous Canberra bush fires of January 2003 abruptly aborted this project.

Fortunately, by this time the surviving elements of the original GMT had been transferred to Melbourne, thereby allowing the third reincarnation of this remarkable historical telescope. This ambitious project is currently underway as a joint venture between Museum Victoria and the Astronomical Society of Victoria, and when brought to fruition will see the reconstructed GMT back in its original roll-off roof building at Melbourne Observatory. Once more the GMT will be available to the people of Melbourne through educational programs and public viewing nights, but this time it will feature a modern glass mirror instead of a speculum metal mirror.

Completing the book is a 2-page "Chronology" which lists key dates between 1834 and 2008 associated with the history of the GMT; an "Acknowledgements"; a 7-page Bibliography; 9 pages of Notes; and a detailed "Index".

As we enter an era involving Australia's formal commitment to the Giant Magellan Telescope, the 'GMT' acronym is destined to acquire two distinctive Australian connotations, one that looks to the future and the other that reflects a time when Australia was home to the largest equatorially-mounted research telescope in the world. This is a sobering thought when contemplating Gillespie's excellent little book.

My final assessment? Well, I think that *The Great Melbourne Telescope* is an attractive, well-written, profusely-illustrated and very reasonably-priced book. It is compelling reading and deserves to grace the bookshelf of every astronomer interested in the history of Australian astronomy or the evolution of the telescope.

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