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COVER IMAGE

This shows Jusepe Ribiera’s oil-on-canvas painting, “Allegory of Sight”, which is in the Franz Meyer Museum in Mexico City. Painted in about 1615, this is thought to depict the Neapolitan astronomer Francesco Fontana, who claims to have invented the astronomical telescope (i.e. with two convex lenses) in 1608. For more on Fontana and the birth of the astronomical telescope see the paper by Paolo Molaro on pages 271–288 in this issue of *JAHH*.

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ANALYSIS OF FRENCH JESUIT OBSERVATIONS OF IO MADE IN CHINA IN AD 1689–1690

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Abstract: The methods and quality of seventeenth century timings of immersions and emersions of the Galilean satellite Io were studied. It was found that the quality of the observations was very good but that in the cases where these observations were used for longitude determinations, the results were impaired by the inaccuracy of Cassini's ephemerides that were used.

Keywords: geographical longitude, China, clock correction, Io immersion, Io emersion

1 INTRODUCTION

The rise of the colonial powers in Western Europe during the seventeenth century fuelled by travels to distant countries created a need for methods to determine geographical longitude. The methods available at the end of the seventeenth century involved timings of astronomical events that were simultaneous for all observers on the Earth, such as lunar eclipses or immersions and emersions of the satellites of Jupiter. Timing such an event at the local time in two different locations and calculating the time difference between the timings determined the longitude difference between the two locations. These timings required a precise knowledge, preferably accurate to one second, of the local times. In the seventeenth century, timings were in general made with pendulum clocks that, however, were not very reliable. During his voyage to Siam the French Jesuit missionary-astronomer Guy Tachard (1648–1712; Orchiston et al., 2016: 31–32) found that his master clock was slow by more than three minutes per day (Tachard, 1686: 332). Consequently, these clocks had to be rectified frequently by determining the apparent (true) local solar time from some external source. Also needed were accurate tables of times of lunar eclipses or tables for calculating immersions and emersions of the Galilean satellites, such as those issued by the Paris Observatory Director, Giovanni Domenico Cassini (1625–1712) in 1683. Immersions and emersions of the Galilean satellites were the preferred events to use for determining the longitude because these events occur frequently and could be used practically every day. Lunar eclipses are not very frequent and the shadow edge is not well defined, which makes accurate timings difficult. Cassini (Goüye, 1688: 232) wrote an extensive article on how to use observations of the Galilean satellites in order to determine the longitude.

Jean de Fontaney (1643–1710), a French Jesuit, was asked by King Louis XIV to set up a mission to China in order to spread French and Catholic influence at the Chinese court. Father Fontaney assembled a group of five other Jesuits to accompany him, all highly skilled in sciences: Joachim Bouvet (1656–1730), Jean-François Gerbillon (1654–1707), Louis Le Comte (1655–1728), Guy Tachard (1651–1712), and Claude de Visdelou (1656–1737). Before setting out for the Far East, they were admitted to the Royal French Academy of Sciences and were trained and commissioned to carry out astronomical observations in order to determine the geographical positions of the various places they would visit, and to collect various types of scientific data (see Udias, 1994; 2003).

After being provided with all the necessary scientific instruments, the Jesuit Fathers sailed from Brest on 3 March 1685 with Father Fontaney as leader. After spending some time in Siam,[1] where Tachard remained (see Orchiston et al., 2016), they finally arrived in Peking on 7 February 1688. The Jesuits were well received by the Kangxi Emperor (Figure 1). Father Bouvet and Father Gerbillon stayed in Peking, teaching the Emperor mathematics and astronomy.

Françoise Noël (1651–1729) was sent in 1684 as a missionary for Japan and arrived in Macao in August 1685. After trying in vain to reach Japan, he was sent to China where he besides making astronomical observations also translated the works of Confucius. He returned to Europe in 1709 and published his work *Sinensis imperii libri classici sex* in Prague in 1711. A detailed account of the mission can be found in the excellent paper by Landry-Derons (2001).

Jean de Fontaney returned to Europe in 1699 but went back to China in 1701, then returned to France in 1702 where he became Rector of the Collège Royal Henry-Le-Grand. Joachim Bouvet later served as the Chinese Emperor’s envoy to France and returned to his home country in 1697. In 1699 he arrived in China for the second time and from 1708 to 1715, he was engaged in a survey of the country and the preparation of maps of its various provinces. Jean-François Gerbillon remained in China working for the Chinese Emperor among other things as interpreter for a treaty with Russia regarding the boundaries of the two empires. Louis Le Comte returned to France in 1691 as Procurator of the Jesuits. In 1697 he published *Nouveaux Mémoires sur l'État Présent de la Chine*. Claude de Visdelou acquired a wide knowledge of the Chinese language and literature. In 1709 he moved to Pondicherry in India where he remained until his death.

2 ADJUSTING A CLOCK FOR TRUE LOCAL SOLAR TIME, THE 17TH CENTURY WAY

Two main methods were used to rectify the clocks: using the altitude of a reference star and using two identical altitudes of the Sun, before and after noon. These will be investigated below.

2.1 Using a Reference Star

This method had the advantage that it could be used almost at any time of the day or night and thus in rather close connection with the timing observation. In most cases a star was used as a reference; since stars are point-like objects, well-defined location and altitude measurements only had to be corrected for atmospheric refraction. If the Sun was used, one of the solar limbs had to be used to get a well-defined altitude and you then also had to correct for the semi-diameter of the Sun as well as for refraction.

Given quantities:

a = the known altitude of a reference star, measured and corrected for refraction.

δ = the known declination of the star from a star catalogue.

α = the known right ascension of the star from a star catalogue.

Both the declination and right ascension of stars are slowly varying quantities with time and a reasonably up-to-date star catalogue had to be used.

α_S = the known right ascension of the Sun, computed for the given date or taken from a precomputed table.

ϕ = the known geographical latitude of the location, measured earlier.

H_0 = the measured local clock time of the observation. Time is reckoned from noon and negative before noon.

We then have the following relation (after Meeus, 1998):

$$\sin a = \sin\phi \sin\delta + \cos\phi \cos\delta \cos H \qquad (1)$$

We use (1) to compute the hour angle H. We choose the positive value of H if the reference star is west of the meridian and otherwise the negative value. The sidereal time, θ, is then $\theta = \pm H + \alpha$. The hour angle of the true Sun is $H_S = \theta - \alpha_S = \pm H + \alpha - \alpha_S$. This is the apparent local solar time. Comparing this with the measured clock time will give the clock correction $\Delta = H_S - H_0$. In case the Sun itself was used as the reference star, $H_S = \pm H$.

As an example where the Sun's altitude was used, we can use one of the observations made by Father Noël to determine the longitude of Hoai-ngan (Huai'an) in China on 14 September 1689 (*Mémoires*, 1729: 779). The geographical latitude was 33° 34′ 40″. The clock time was 1 hour 50 minutes after noon and the corrected altitude of the Sun was then 52° 47′ 4″. The declination of the Sun was 3° 11′ north. Using the formula above we compute the true local solar time as 1 hour 31 minutes 58 seconds, thus the clock was 18 minutes 2 seconds fast.

Figure 1: The Kangxi Emperor (en.wikipedia.org).

The same observation also timed and measured the altitude of the stars α Lyrae (Vega) and α Aquilae (Altair) just before the emersion. The computation in this case gives a clock correction of 20 minutes and 19 minutes 45 seconds respectively. Unfortunately, Father Noël identified what was the satellite Ganymede wrongly as Io in this observation.

The right ascension of the Sun is a function of time, changing by about 1 degree per day. In order to determine the current value using tables of the solar right ascension set up for instance for Paris you needed to have some previous idea of what the longitude difference to Paris of your location was, or use successive approximations in order to find the current solar right ascension for your local time.

2.2 Using Two Altitudes of the Sun

The fundamental idea is to measure the clock times when the Sun has the same altitude before and after noon. The clock noon will be the average of these times. Often the upper limb of the Sun was used. However, the afternoon timing has to be corrected for the change of the Sun's declination between the measurements and the altitudes corrected for atmospheric refraction. Sometimes the upper limb was used before noon and the lower limb was used after noon. Then you will then also have to correct for the semi-diameter of the Sun. The drawback with this method was that the computations were quite involved and that the measurements had to be made during daytime while the lunar eclipse or immersion/emersion observations were normally made after sunset and thus there could be a rather long time interval between the determination of the clock correction and the application of it during which the clock correction could have changed.

2.2.1 Father Fontaney's Method

Jean de Fontaney has described this method in detail (*Mémoires*, 1729: 860) and applied it to several observations. Following is my English translation:

> Of all the methods that one uses to correct the clock by observations of the Sun, observed before and after noon, I have chosen the following as I am more used to it than to other methods.
>
> I take the difference between the times of observation in the morning and in the afternoon. I change the half of this difference to degrees of the parts of the great circle that gives me how much the Sun, at the morning observation, is distant from the meridian, more or less precisely. With this distance [H], the complement of the altitude of the pole [ϕ] and the corrected altitude [a] of the upper limb of the Sun, I find what is called the solar angle [ξ], by this analogy: *As the sine of the complement of the corrected altitude of the Sun is to the sine of the complement of the altitude of the pole; so is the sine of the distance of the Sun from the meridian (the hour angle) to the solar angle.*
>
> I then take the difference of the declination of the Sun in 24 hours on the day of observation of which I take the part of the difference in declination proportional to the interval of observation before and after noon, to which, as the Sun describes a parallel with the equator, I add (i.e. divide by cos δ) the proportion coming from the difference between the equator and the parallel of the day: and with this difference of declination increased in this way I have: *As the sine of the solar angle is to the part of the difference in declination, proportional to the interval between the observations, increased by the proportion of the equation to the parallel of the day: so is the sine of the complement of the solar angle to parts of 360° hour angle, which, reduced to time measure, gives the correction to the time of observation in the afternoon.*
>
> This correction, when the Sun is in the descendant signs, has to be added to the hours in the afternoon and to be subtracted when the Sun is in the ascendant signs.
>
> With the time in the afternoon, thus corrected, I take the difference between the times in the morning and the corrected afternoon time, I add half of this difference to the morning observed time; the sum gives the hour that the clock shows when the Sun at true noon, and the difference between the time that the clock shows and 12 hours, is how much it is slow or fast. The demonstration of this practice is very easy unless you think the movement of the Sun would be pointless to take into account.

This method was also used by Tachard (1686: 76, 78) when he determined the longitude of Cape Town in 1685, using the upper and lower limbs of the Sun.

2.2.2 Mathematical Formulation

Expressed in mathematical language the first statement is equivalent to

$$\sin \xi = \sin H \cos \phi / \cos a \qquad (2)$$

where ξ is the 'solar angle',[2] H the hour angle of the Sun, ϕ the geographical latitude, and a the altitude of the Sun, corrected for refraction.

The second statement can be written

$$\Delta H = -(\Delta\delta / \cos \delta) / \tan \xi \qquad (3)$$

where ΔH is the time correction due to the change in declination, δ is the solar declination, and $\Delta\delta$ the change in solar declination between the morning and afternoon measurement.

Both of these formulae can be verified using standard spherical trigonometry. If T_1 is the time of the altitude measurement before noon and T_2 the time of the corresponding measurement after noon, the formula for the clock correction in hours is $\Delta = T_1 + (T_2 + \Delta H - T_1) / 2$.

An example of this method is the determination of the longitude of Si-ngan-fu (Xi'an) on 12 July 1689 by Father Fontaney (*Mémoires*, 1729: 860). He used three pairs of observations of the solar upper limb in the morning and afternoon to set his clock. I have checked his calculations, and they are correct to the seconds within rounding errors.

3 THE OBSERVATIONS

In my analysis I have used observations of immersions and emersions of the Jupiter satellite

Table 1: Observations from Hoai-ngan.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1689-10-07	Emersion	23	13	58	15	16	03	119	29
1689-11-01	Emersion	18	01	20	10	03	07	119	33
1689-11-08	Emersion	19	56	14	11	58	11	119	31
1689-11-15	Emersion	21	50	30	13	52	34	119	29
1689-12-01	Emersion	20	05	00	12	07	33	119	22
1690-09-10	Immersion	22	12	20	14	18	29	118	28
1690-09-17	Immersion	24	12	23	16	15	28	119	14
1690-10-05	Emersion	19	16	08	11	16	43	119	51
1690-10-12	Emersion	21	13	00	13	13	19	119	55
1690-10-19	Emersion	23	08	50	15	10	02	119	42
1690-12-04	Emersion	23	30	40	15	31	48	119	43
						Average		119	29

Io in 1689 and 1690 in China taken from Pingré (1901), supplemented with information taken from *Mémoires* (1729) and Goüye (1692). I have deleted two observations that are certainly other Galilean satellites mistaken for Io.

It is impossible to determine which of the ephemeris tables issued by Cassini for the movements of the four Galilean satellites were used by the Jesuit observers in China. The tables that I have been able to consult (Cassini, 1668; 1693) do not by my computation render the precise time values cited in the observations.

Another problem is that Cassini's tables are not accurate, having time errors of some minutes: "It is true that often there are still a few minutes difference in time between the Ephemerides and the Observations." (*Mémoires*, 1730: 180; my English translation).

Also, the immersion and emersion times computed from the tables and cited by the Jesuits in the *Memoires* are only given to one minute precision (or in one case, to half a minute precision). As I have been mainly interested in the quality of the Jesuit observations, I decided to use as a benchmark a modern ephemeris program, available on the web at the Institute de Méchanique Celeste de Calcul des Éphémerides (IMCCE), in order to determine the immersion and emersion times.

An immersion or emersion of a satellite is not an instant in time; for Io, the event typically has a duration of a little more than four minutes. A time interval of four minutes corresponds to about 1° of longitude, thus it is important to define the precise moments that are chosen to represent the immersion or emersion respectively. For an immersion, the modern definition is the time when the satellite just disappears completely in the shadow of Jupiter, the 'last speck', and for an emersion, it is the first appearance, the 'first speck'. These are given in the IMCCE ephemeris in Universal Time (UT), with a precision of seconds. In practice, for an observer the precise timing would to some extent depend on the telescope's magnification. With a stronger magnification, one would expect to follow a diminishing satellite crescent a little longer and discover its appearance a little earlier. It is then to be expected that the observed timing of an immersion would be slightly too early and for an emersion slightly too late as compared with the ephemeris, resulting in a slightly-too-large longitude difference for emersions and slightly-too-small longitude difference for immersions. It could also be expected that such timings would be somewhat observer dependent, although the Jesuit missionary-astronomers were trained scientists.

There are six sets of observations for different Chinese locations, and these are discussed separately below. The modern Chinese names are given in brackets.

In the following tables, the times given by the observers are reckoned from noon and are shown in the first column. I have added 12 hours to these times in order to have the standard modern astronomical reckoning from midnight. The observers also use apparent local solar time as was standard during the seventeenth century and used the terminology 'true time' for this. The second column shows immersion/emersion times according to IMCCE where I have converted the UT ephemeris time into apparent solar time using the equation of time as computed from the algorithm in Meeus (1998). The last column shows the longitude computed using the difference in time between the observed immersion/emersion time and the IMCCE time and the relation that 15° in longitude difference corresponds to one hour in time.

3.1 Observation Set 1

These observations (see Table 1) were made by Father Noël from Hoai-ngan (Huai'an) in 1689 and 1690.

The official modern longitude of Huai'an is 119° 8′. As expected, the emersion longitudes are larger than the immersion ones. There are few immersion longitudes, a fact that will increase the average longitude as the emersion longitudes will dominate. Pingré notes that the

Table 2: Observations from Si-ngan-fu.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	′
1689-06-03	Immersion	28	18	00	21	04	16	108	26
1689-06-19	Immersion	26	31	22	19	18	18	108	16
1689-07-12	Immersion	26	36	56	19	23	06	108	28
1689-08-04	Immersion	26	46	56	19	33	24	108	23
1689-10-23	Emersion	20	55	05	13	38	22	109	11
1689-11-08	Emersion	19	15	20	11	58	11	109	17
1689-11-15	Emersion	21	09	07	13	52	34	109	08
						Average		108	44

Table 3: Observations from Canton.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	′
1690-09-10	Immersion	21	49	03	14	18	27	112	39
1690-09-17	Immersion	23	46	14	16	15	34	112	40
1690-10-12	Emersion	20	46	25	13	13	18	113	17
1690-10-19	Emersion	22	42	49	15	10	02	113	12
1690-10-28	Emersion	19	06	46	11	34	17	113	07
1690-11-04	Emersion	21	02	38	13	29	24	113	19
						Average		113	02

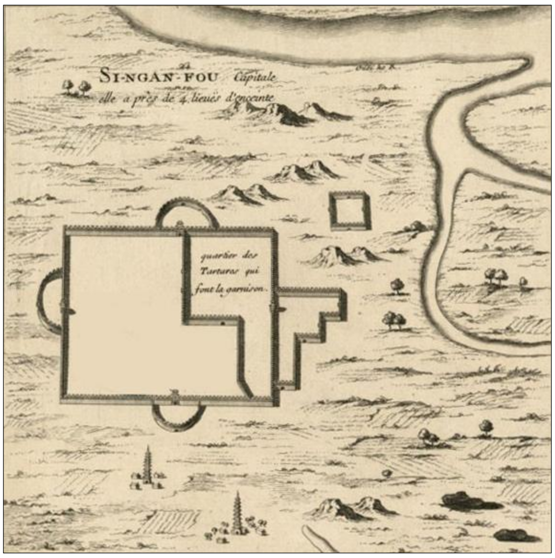

Figure 2: Si-ngan-fu (BnF).

location for the observations were a little to the east of Huai'an. The standard deviation of the emersion longitudes is 11′. Father Noël used the five first observations (*Mémoires*, 1729: 779) to determine the longitude from Paris as 116° 30′, i.e. 118° 50′ from London. The time errors (all positive) from the cited Cassini ephemerides have an average of 2.6 minutes.

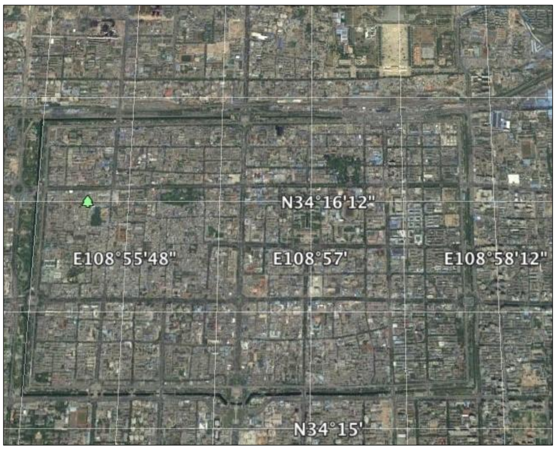

Figure 3: The old city in Xi'an (Google Map Pro).

3.2 Observation Set 2

These observations (Table 2) were made by Father Fontaney from Si-ngan-fu (Xi'an) in 1689. Figure 2 shows a contemporary map of Si-ngan-du, while Figure 3 shows the still existing old city layout in Xi'an.

The official modern longitude of Xi'an is 108° 54′. The standard deviations of the immersion and emersion groups are both 5′. Father Fontaney used observations number 3, 5, and 7 (*Mémoires*, 1729: 855) for his longitude determination and got an average of 108° 44′, identical to the average result in the table. This is a pure coincidence, as the cited Cassini ephemerides are in error by about –1.4, 1.8, and 2.1 minutes respectively.

3.3 Observation Set 3

These observations (Table 3) were made by Father Fontaney from Canton (Guangzhou) in 1690.

The official modern longitude of Guangzhou is 113° 16′. The spread is very small within the immersion and emersion groups separately, indicating that Fontanay was a very good observer. The emersion longitudes have a standard deviation of 5′. Father Fontaney used the first and third observations each with three clock corrections where he used his method with pairs of equal solar altitudes. He arrived at the same longitude value as the average in the table (*Mémoires*, 1729: 870). Again this is sheer luck although in this case the errors in Cassini's ephemerides are –0.8 and 0.35 minutes respectively.

Table 4: Observations from Shanghai.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1689-07-28	Immersion	25	42	49	17	38	48	121	00
1689-08-06	Immersion	22	06	24	14	02	11	121	03
1689-08-31	Emersion	19	07	12	11	01	05	121	32
1689-09-07	Emersion	21	04	07	12	57	51	121	34
						Average		121	17

Table 5: Observations from Nankin.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1689-10-16	Emersion	19	37	27	11	42	04	118	51
1689-10-23	Emersion	21	33	50	13	38	22	118	52
1689-11-01	Emersion	17	59	12	10	03	07	119	01
1689-11-08	Emersion	19	54	00	11	58	08	118	58
1689-11-15	Emersion	21	48	13	13	52	29	118	56
1689-12-01	Emersion	20	03	06	12	07	34	118	53
						Average		118	55

Table 6: Observations from Peking.

Date	Type	Observation Time			IMCCE Apparent Time (Greenwich)			Longitude	
		h	m	s	h	m	s	°	'
1690-09-10	Immersion	22	03	29	14	18	29	116	15
1690-10-12	Emersion	21	00	00	13	13	19	116	40
1690-10-19	Emersion	22	56	15	15	09	29	116	41
1690-10-26	Emersion	24	51	14	17	05	25	116	27
1690-11-04	Emersion	21	16	42	13	29	24	116	49
1690-12-13	Emersion	19	39	24	11	52	01	116	51
						Average		116	37

3.4 Observation Set 4

These observations (Table 4) were made by Father Fontaney from Chang-hai (Shanghai) in 1689.

The official modern longitude of Shanghai is 121° 30′. Again, Jean de Fontenay's emersion longitudes are larger than the immersion ones. The spread is extremely small for both the immersion and emersion longitudes: 2′–3′.

3.5 Observation Set 5

These observations (Table 5) were made by Father Fontaney from Nankin (Nanjing) in 1689.

The official modern longitude of Nanjing is 118° 46′. The longitudes are very consistent, with a small standard deviation of 4′. Also here Pingré notes that Fontaney was located to the east of Nanjing.

3.6 Observation Set 6

These observations (Table 6) were made by Fathers Bouvet and Gerbillon from Peking (Beijing) in 1690.

The official modern longitude of Beijing is 116° 23′. The standard deviation of the emersion longitudes is 9′.

4 CONCLUDING REMARKS

From the data we can conclude that the longitudes derived from the emersions are in general a little too large and that those derived from the immersions are a little too small. This is to be expected, as explained above. Father Fontaney's observations clearly show that he must have been a very skilled observer, given the very good internal consistency in his timings of the immersions and emersions.

In general, all the observations are quite consistent and of good quality, the standard deviations are with one exception very small and the computed average longitudes above agree quite well with the actual longitudes. Looking at the whole data set, the Jesuit fathers had a timing difference of about 20 seconds relative to the IMCCE first and last speck times. Due to the time errors in Cassini's ephemerides that were of the order of two minutes, the contemporary longitude determinations had an inherent error of at least half a degree. Actually, this is not bad, as the Longitude Act, issued on 8 July 1715 by Queen Anne of England, stipulated a prize of £20,000 for a method to determinate longitude to an accuracy of half a degree of a great circle. However, the Jesuit observations were made on firm ground with rather large instruments that had been extensively calibrated. On the heaving deck of a ship you could not expect very accurate results using their methods.

5 NOTES

1. While temporarily in Siam they observed a total lunar eclipse on 11 December 1685 (see Gislén, 2004; Orchiston et al., 2016).

2. When we consider a spherical triangle P is the North Pole, Z the zenith and S the Sun, the angle PSZ is the 'solar angle'.

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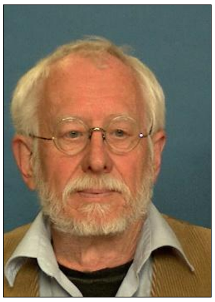

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FRANCESCO FONTANA AND THE BIRTH OF THE ASTRONOMICAL TELESCOPE

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Abstract: In the late 1620s the Neapolitan Francesco Fontana was the first to observe the sky using a telescope with two convex lenses, which he had manufactured himself. Fontana succeeded in drawing the most accurate maps of the Moon's surface of his time, which were to become popular through a number of publications that appeared throughout Europe but did not acknowledge the author. At the end of 1645, in a state of declining health and pressed by the need to defend his authorship, Fontana carried out an intense observing campaign, the results of which he hurriedly collected in his *Novae Coelestium Terrestriumque rerum Observationis* (1646), the only publication he left for posterity. Fontana observed the Moon's main craters, such as Tycho (which he referred to as 'Fons Major'), their radial debris patterns and changes in their appearance due to the Moon's motion. He observed the gibbosity of Mars at quadrature and, together with the Jesuit Giovanni Battista Zupus, he described the phases of Mercury. Fontana observed the two—and occasionally three—major bands of Jupiter, and inferred the rotation of the major planets Mars, Jupiter and Saturn, arguing that they could not be attached to an Aristotelian sky. He came close to revealing the ring structure of Saturn. He also suggested the presence of additional moons around Jupiter, Venus and Saturn, which prompted a debate that lasted more than a hundred years. In several places in his book Fontana claimed to have conceived the first positive eyepiece in 1608, and he provides a declaration by Zupus that his telescope was in use from 1614. Finally, we suggest that the telescopes depicted in the two paintings *Allegory of Sight* and *Allegory of Sight and Smell* by J. Brueghel the Elder might have been made by Fontana, and that he might by portrayed in the *Allegory of Sight* by Jusepe Ribera.

Keywords: Francesco Fontana; astronomical telescope; *Novae Coelestium Terrestriumque rerum Observationis*; observations of the Moon, Mercury, Venus, Mars, Jupiter and Saturn; positive eyepiece; paintings: *Allegory of Sight* and *Allegory of Sight and Smell*.

1 INTRODUCTION

The scarce information we have on Francesco Fontana is given by his contemporary Lorenzo Crasso (1623–1691), who in 1666 dedicated a book to the outstanding people of his time and counted Fontana among them. From Crasso's short biographical notes we learned that Fontana was born in Naples sometime between 1580 and 1590 and that at the age of twenty he graduated in Theology and Law, obtaining his Doctorate at the University of Naples Federico II. However, he never practiced in that profession and, following a vocation he had shown interest in ever since his childhood, he taught himself mathematics and devoted himself to grinding lenses. Crasso (1666) reported that Fontana used to say he preferred the truth of science to that of the Forum. Upon the death of Giovan Battista Della Porta (1535–1615), whom Fontana considered as the inventor of the telescope, Fontana made several unsuccessful attempts to obtain Della Porta's instruments.

In Naples Fontana was close to Camillo Gloriosi (1572–1643), who corresponded with Galileo Galilei (1564–1642) and in 1610 succeeded him at Padua University. Fontana also was close to the Lyncean Fabio Colonna (1567–1640), who commissioned him to make microscopic observations in 1625, and the Neapolitan Jesuits (who frequently were opposed to the Lynceans), and in particular Fathers Gerolamo Sersale (1584 – 1654), Giovanni Battista Zupus (1589–1667) and Giovan Giacomo Staserio (1565–1635).

Fontana was a fine craftsman and never needed to do anything else for a living. His telescopes reached the courts all over Europe that were interested in scientific and military developments. The quality of his lenses was such that Fulgenzio Micanzio (1570–1654) wrote in a letter to Galileo:

> By continually working on and constructing telescopes it is said that Fontana's achievements reached such a high standard that in matters of the heavens he is a genius. (Micanzio, 1638).[1]

To advertise his telescopes, Fontana used to send maps of the Moon and news of other discoveries he had made by observing the sky from the roof of his house in Naples:

> … after personally manufacturing two [telescopes] of enormous length and attaching them to a wooden support on the top of his house, Fontana regularly observed the planets, which featured in a book titled *Novae Observationes caelestium terrestriumque rerum* [*New Celestial and Terrestrial Observations*] that was published in 1646. (Crasso, 1666: 298).

The *Novae Coelestium, Terrestriumque rerum Observationes, et Fortasse Hactenus non Vulgate a Francisco Fontana Specillis a se Inventis, et ad Summam Perfectionem Perductis, Editae*

(1646) is the only work that Fontana published, although Crasso mentioned a treatise titled *On Fortifications*, but this has never been found. In 1656 Fontana and all his family died from the plague.

However, during his life, and even after his death, Fontana's work received little attention from scholars, apart from rare exceptions like F. Colangelo (1834: 246–268), and there was even open opposition to his ideas. His numerous detractors generally emphasized the superficiality, if not the incorrectness, of his observations and the lack of any optical theory for the functioning of the telescope. His claim to have constructed a telescope with two convex lenses in 1608 was generally considered as unreliable. Thus, on 25 May 1647 Evangelista Torricelli (1608–1647) wrote to Vincenzo Renieri (1606–1647): "I have the book of stupidities observed, or rather dreamed up, in the heavens by Fontana." In his *Almagestum Novum*, the Jesuit Giovanni Battista Riccioli (1598–1671) acknowledged the quality of the instruments constructed by Fontana (1651) but he rejected most of the 'novelties' that Fontana claimed to have observed (Riccioli, 1651). The recent translation from Latin by Beaumont and Fay (2001) now allows us to make an accurate evaluation of Fontana's writings, and this reveals a rather different—and probably more realistic—image of the scientist and of his work.[2]

Figure 1: An etching of Fontana's self-portrait printed in his *New Celestial Observations*. In the oval frame Fontana identifies himself as the inventor of the telescope (Fontana, 1646: [ii]).[3]

2 THE *NEW CELESTIAL OBSERVATIONS*

The *Novae Coelestium, Terrestriumque rerum Observationes, et Fortasse Hactenus non Vulgate a Francisco Fontana Specillis a se Inventis, et ad Summam Perfectionem Perductis, Editae*, or simply the *New Celestial Observations* as we will henceforth refer to it, was published in Naples by Gaffaro in 1646. The title makes an explicit claim that Fontana was the inventor of the instruments used for the observations, and this claim is iterated rather obsessively in several passages in the book. Dedicated to Cardinal Camillo Pamphili (1622–1666), the book opens with four testimonies supporting Fontana's claim. The first is from the Jesuit Giovanni Battista Zupus, who had been a Professor of Mathematics at the Jesuit College in Naples for twenty-seven years. In his declaration Father Zupus asserts that he first used Fontana's telescope in 1614, together with his superior Jacobo Staserio, and that through his own observations he could confirm all the discoveries announced by Fontana:

> I, Jo. Baptista Zupus of the Society of Jesus in the kindly Neapolitan College, Professor of Mathematical Sciences, assert that many, if not all the phenomena, which Dom. Francesco Fontana is bringing to the public domain in print, not once or twice but on several occasions by me and by others of our Society by means of the very optic tubes constructed by the same Dom. Fontana … I assert that he was he who first employed two convex lenses in optical tubes, beginning in the fourteenth year of this century when he displayed for inspection a tube equipped with such lenses both to Jacobo Staserio, my Master, and to me, to the surprise and delight of us both. (Beaumont and Fay, 2001: 7).

A second declaration, by Father Sersale, states that Fontana invented both the telescope and the microscope. The remaining testimonies are two eulogies, one from an anonymous scholar and the other from Ippolito Vigiliis, a monk in Cassino, Reader in Philosophy at the cloister of St Severino in Naples and a member of the Academia degli Oziosi. Vigillis supports the truthfulness of the numerous discoveries made by Fontana, and he also states that Fontana made his own telescope, although he fails to mention when this occurred.

The *New Celestial Observations* includes an etching of the author, and this is shown in Figure 1. The surrounding oval frame contains an inscription where Fontana identifies himself as the inventor of the telescope, and his age as 61. This could either represent Fontana's age in 1646, which implies that he was born in 1585 and invented the telescope at the age of 23 or, as suggested by Favaro (1903), it could be read in reverse as 19, which implies that Fontana was 19 years old when he invented the telescope and that he was born in 1589. Both hypotheses are consistent with the range of the possible years proposed for Fontana's birth.

In the 'Preface to the reader', after recalling once more that he had invented an optical tube with two convex lenses, Fontana explains the motivations behind his book. He complains that various authors, including Michael Florentius Langrenus (1598–1675) and Athanasius Kircher (1602–1680), had circulated papers based on his planetary observations without crediting them to him. The only exception was Giorgio Polacco (1644) who in his *Catholic Treatise against Copernicus* gave credit to his claims. An extensive list of these forged copies, including some not even mentioned by Fontana, is given in Van de Vijver (1971a; 1971b). Fontana (1646: 9) explicitly says that in order to avoid that

> … others reap the glory for themselves of all my hard work ... I wish to quickly collect everything together.

The *New Celestial Observations* contains observations that Fontana made in 1629, along with later observations made mostly in the last two months of 1645 and at the beginning of 1646. However, Fontana (ibid.) considered the material included as incomplete, and warned that "I could not finish for lack of health and time."

The book contains eight treatises. The first is dedicated to the telescope; the next three to his observations of the Moon; the fifth to the planets Mercury and Venus; the sixth to Mars and Jupiter; and the seventh to Saturn and the Pleiades. The final treatise is on the microscope. The observations are accompanied by 27 full-page etchings of the Moon, a larger folded map of the Full Moon (made by Fontana), and 26—mostly full page—woodcuts of the planets based on Fontana's own observations (as he declares in the Preface). This is the first published 'atlas' of the Moon, where Fontana features images of our satellite at nearly every phase of the lunar cycle, a sort of illustrated astronomical book that would become very popular at a later time (cf. Winkler and Van Helden, 1992).

3 THE FIRST TREATISE: THE TELESCOPE[4]

Fontana believed that the concept of the telescope was first proposed by Della Porta and that it was then put into practice and refined by Galileo.[5] Fontana also included verses of the Lyncean Giovanni Faber (1574–1629), the doctor and herbalist to the Pope, who celebrated Galileo as the first scientist of his times:

> Porta holds the first realm; German [i.e. Kepler!], you may have the second;
> your work, Galileo, gives you the third realm of the stars.
> But as far as the heavens are distant from the earth,
> you, Galileo, shine more brightly than the rest.
>
> (Beaumont and Fay, 2001: 11).

This was quite noteworthy as Fontana was close to the Jesuits of Naples, who were notably hostile to Galileo and whose permission was needed for him to publish. Considering Porta as the inventor of the telescope in 1589, makes clear that Fontana's claim to have invented the telescope in 1608 referred exclusively to the telescope made by combining two convex lenses.

Later in his book Fontana comments on the history of the telescope from antiquity up to his era. He rejects the possibility that the ancients already knew of the telescope on the grounds that they never revealed any details of the Moon or the stars. The earliest important telescopic discoveries about the planets and stars were made by Galileo. A detailed list follows:

(1) The Milky Way is made of stars;
(2) The *hazy* stars are composed of multiple stars;
(3) The number of fixed stars is 10 or 20 times greater than that given by Ptolemy;
(4) Jupiter has four satellites;
(5) The Moon is not a perfect sphere;
(6) Saturn consists of three stars; and
(7) Venus has phases.

After Galileo the only significant discovery was made by Langrenus in 1645, with his map of the Moon showing the maria. Langrenus was the first to propose a system of lunar nomenclature, but few of his names have survived to the present day. However, Fontana (1646: 15) adds that Langrenus' map could have been

> … derived possibly from my maps … first done in 1629 … since Langrenus never reveals the designer of his telescope.

Fontana wrote that with his own telescopes he had confirmed all of the above-listed discoveries, i.e. in an apparently 'empty' sky the telescope reveals that there are in fact "… now 3 now 4 …" stars; the Pleiades contained at least 28 stars; nebulae were composed of stars; and the Milky Way contained an infinite number of them.

The difficulty of grinding and polishing lenses in order to give them a perfect spherical shape is then described, including the role played by bubbles and air-holes in the glass. Fontana stresses the importance of possessing a testing tool to check for lens-shape, and he proposed to look at the projected image of a candle as a testing procedure for the quality of the lens (Fontana calls this his first invention). In a chapter titled "Concerning the Astronomical Telescope Invented by the Author", the construction of the author's second invention is described. Fontana clarifies that when he conceived the idea of his telescope he did not know of the book *Dioptrice* by Johann Kepler (1571–1630):

> Although that model seems to be proposed by Johann Kepler in his Dioptrics, Question 86, p. 42 printed in 1611. However, I had in truth no knowledge of this book earlier than the present moment when I am publishing this treatise, and I have received it in return from the aforementioned Johan Baptiste Zupus. It is surprising that it is not recorded that Kepler was the inventor of this device in Germany and myself in Naples; also his method is quite different from the method suggested here … (Beaumont and Fay, 2001: 21).

In the last sentence Fontana seems to doubt the real intentions of Kepler and invites the reader to go directly to the source.

Fontana also describes how to correct inverted images by the use of a third lens with the same radius of curvature (his third invention), apparently ignoring the presence of a similar concept in Kepler's *Dioptrice* and in *Oculus Enoch et Elliae Sive Radius Sidereomysticus* (1645) by Anton Maria Schyrleus de Rheita (1604–1660). An astronomical and terrestrial telescope thought to have been made by Fontana around 1650 is in Luxottica's Museum of Optics in Agordo. It is a terrestrial telescope with an eyepiece containing three lenses, and could be an early implementation of Fontana's third invention.

The last chapter describes how to construct very long telescopes, i.e. with a length of up to 50 palms (i.e. 13.18 metres, since 1 Neapolitan palm corresponds to 0.2637 metres).[6] With such a length the radius of curvature of the lenses was so large that the lenses surface became almost flat and therefore were extremely difficult to work. Fontana describes his solution to the problem by introducing for the first time the concept of the optical meniscus:

> This inconvenience will be avoided, if the glass is figured on one side in a convex shape and on the other side in a concave one. (Fontana, 1646: 23).

Fontana considered this his fourth invention. But he does not mention the problem with chromatic aberration, which severely affects this kind of telescope.

3.1 On Fontana's Telescopes

Some information on Fontana's telescopes can be obtained from the correspondence between the natural philosophers and scholars of his era. The first mention is contained in a letter from Colonna to Federico Cesi (1585–1630), dated 30 November 1629:

> F. Fontana made a telescope of eight palms [2.1 m], with which he shows the Moon and the stars though upside down.

In 1637, when he was trying to sell his telescopes to the Grand Duke of Tuscany Federico II, Fontana contacted Benedetto Castelli (1578–1643), who wrote to Galileo celebrating the virtues of Fontana's telescopes (see Castelli, 1637a, 1637b).

In the following year, Fontana made a 14-palms (i.e. 3.7-m.) telescope. The construction of this very long telescope was documented in a letter written by G.G. Cozzolani to Carlo Antonio Manzini on 11 September 1638, and in two letters that Castelli wrote to Galileo in July 1638. Thus, on 3 July, Castelli (1638a) wrote:

> I am holding a glass of Naples that is for a telescope long fourteen Neapolitan palms … magnifies the object ninety times.

Two weeks later the magnification had become "… 160 times … a monstrosity." (Castelli, 1638c). This telescope was then bought by the Extraordinary Imperial Ambassador in Rome, the Duke of Cremau, Prince Ecchembergh (Del Santo, 2009).

Fontana's grinding and polishing technique still remains unknown as it was only partially disclosed in his book. On 3 January 1638 Fontana wrote to the Grand Duke of Tuscany with the offer to reveal his secret way of working lenses for a reward of 2000 piastres but the Grand Duke declined the offer. This attempt is also recorded in a letter by Castelli (1638d) to A. Santini written in the same year (cf. Arrighi, 1964). In a letter dated 10 July 1638 Castelli (1638b) wrote to Galileo that he thought he had figured out Fontana's secret way of grinding lenses. Apparently Fontana was working only the central part of the lens, as we deduce from Galileo's answer of 20 July 1638 (see Galileo, 1638b).

On 23 October 1639 Fontana directly addressed the Grand Duke of Tuscany proposing a 22-palms (i.e. 5.8-m) telescope (del Santo, 2009). We do not know the Grand Duke's answer, although del Santo suggests that this telescope had actually reached Florence.

3.2 The Genesis of the Astronomical Telescope

Four centuries later the details of the genesis of the Dutch telescope are still unknown, but even more mysterious is the birth of the astronomical telescope, i.e. the one made up with two convex lenses (Van Helden, 1976; 1977a; 1977b; Van Helden et al., 2011). After the publication of *Sidereus Nuncius* by Galileo, in the summer of 1610 Kepler wrote *Dioptrice*, the publication of which followed one year later. Kepler's book was devoted to an explanation of the functioning of the Dutch telescope but also considered all other possible combinations of lenses, including two and three convex lenses. However, these considerations were not inserted in the Dioptrice's section on the telescope and, when discussing image formation, Kepler did not mention the magnification, which is the main characteristic of a telescope. As argued by Malet (2010: 281) "… the idea of turning his theoretical combination of two convex lenses into a working telescope may have never crossed Kepler's mind." A similar doubt was expressed by Fontana, when invited to read carefully Kepler's book. As a matter of fact, Kepler did not make a telescope, and we had to wait as long as 1645 before Schyrleus de Reita manufactured the first 'Keplerian' telescope, apparently on the basis of Kepler's instructions.

In 1655 Johannes Sachariassen (b. 1611) claimed that his father Sacharias Janssen (1585 –1648) was the first to construct a 'long tube' telescope, in 1618, when he attended a Middelburg City Council investigation set up in 1655 to clarify the origin of the telescope:

> In the year 1590 the first tube was made and invented in Middelburg in Zeeland by Sacharias Janseen, and at that time the longest were 15 to 16 inches ... The length of 15–16 inches was in use until the year 1618; then I and my father invented the long tubes which are used at night for seeing the stars and the Moon.

However, Van Helden (1976) and Zuidervaart (2011) have noted several inconsistencies in his declaration and probably the definition of 'long tubes' did not refer to a Keplerian telescope but rather to a Dutch one with a longer focal length (Van Helden, 1976).

The first printed mention of a telescope formed by two convex lenses appeared in *Rosa Ursina sive Sol* (1631) by Christoph Scheiner (1573–1650). When describing how to use a Dutch telescope to project the solar image, he mentioned that a different arrangement for the projection which made use of two convex lenses was also possible:

> If you fit two like [convex] lenses in a tube in the same way, and apply your eye to it in the proper way, you will see any terrestrial object whatever in an inverted position but with an incredible magnitude, clarity, and width. Scheiner, 1631: 130).

Then on page 130 Scheiner (1631) wrote: "… thirteen years ago, I made erect the images intercepted for the most Serene Maximilian, Archduke of Austria." Thirteen years before the publication date was the year 1617; but since *Rosa Ursina* took a four-year period to be printed, it could have been within 1613–1617 (cf. Van Helden, 1976). However, a document of 1616, kept in the Tyrolean State Museum Ferdinandeum, states that

> … the Archduke [Maximilian] acquired an optical instrument of admirable utility but that was giving inverted images; since he wished to see the pictures erect, and this could not be obtained he turned to the Jesuits, who gave him the Professor of Mathematics in Ingolstadt [Christoph Scheiner] as an expert. (Anonymous, 1616).

This was the first document to refer to an astronomical telescope, and it confirms Scheiner's reconstruction and fixes the date at 1616. However, neither this document, nor the *Rosa Ursina* mention Scheiner as the inventor. He was simply reported to have added a lens to a preexisting telescope and rectified the image, for the benefit of Maximilian III. Moreover, neither in *Disquisitiones Mathematicae* (1614), nor in the manuscript *Tractatus de Tubo Optico* (1616), or even in *Oculus hoc est fundamentum opticum* (1619), does Scheiner ever refer to himself as the inventor of the Keplerian telescope. Such an omission would be rather bizarre if he really was the inventor of a new kind of telescope.

Actually, so very little was known of Kepler's telescope that, when Schyrleus de Rheita mentioned it in his *Oculos Enoch et Eliae* (1645)—disregarding altogether the contribution of Fontana—he was generally credited with this inventtion (see King, 1955). However, a very different story was presented by Francesco Fontana in 1646 when he claimed throughout his book to be the first to construct a telescope made with two convex lenses. There are no apparent reasons to question Father Zupus' declaration to have used Fontana's telescope in 1614, since he was still alive when the book was published. Allowing for some time to improve the quality of the lenses, even the year 1608 does not seem implausible as the birth-date of Fontana's telescope, though it is based only on his own word. The improvement in the optical quality of the lenses was probably the decisive factor if we consider that already in 1538 the Italian scholar Girolamo Fracastoro (1478– 1553) wrote:

> If someone looks through two eye-glasses of which one is placed above the other, he shall see everything larger and closely. (Fracastoro, 1538: p18v, section II, cap 8).

4 OBSERVATIONS OF THE MOON

Fontana dedicated three treatises of his *Novae Celestium Observationes* to the Moon. The first is a summary of all of his lunar discoveries; the second presents thirteen observations of the waxing Moon; and the third reports eleven observations of the waning Moon made in January 1646 together with four previous lunar observations made in 1629, in 1630 (two) and in 1640. Fontana considered the results of these earliest observations as less accurate since "… they took place at a time when the optic tube had not reached its present standard of perfection …" and he therefore presents them at the end of the fourth treatise. They were probably obtained with his telescope of 8 palms, while for his last observations he probably used his 12-palms telescope. However, his earliest observations are more interesting since they were the first observations ever performed with an astronomical telescope. Let us now examine these early observations.

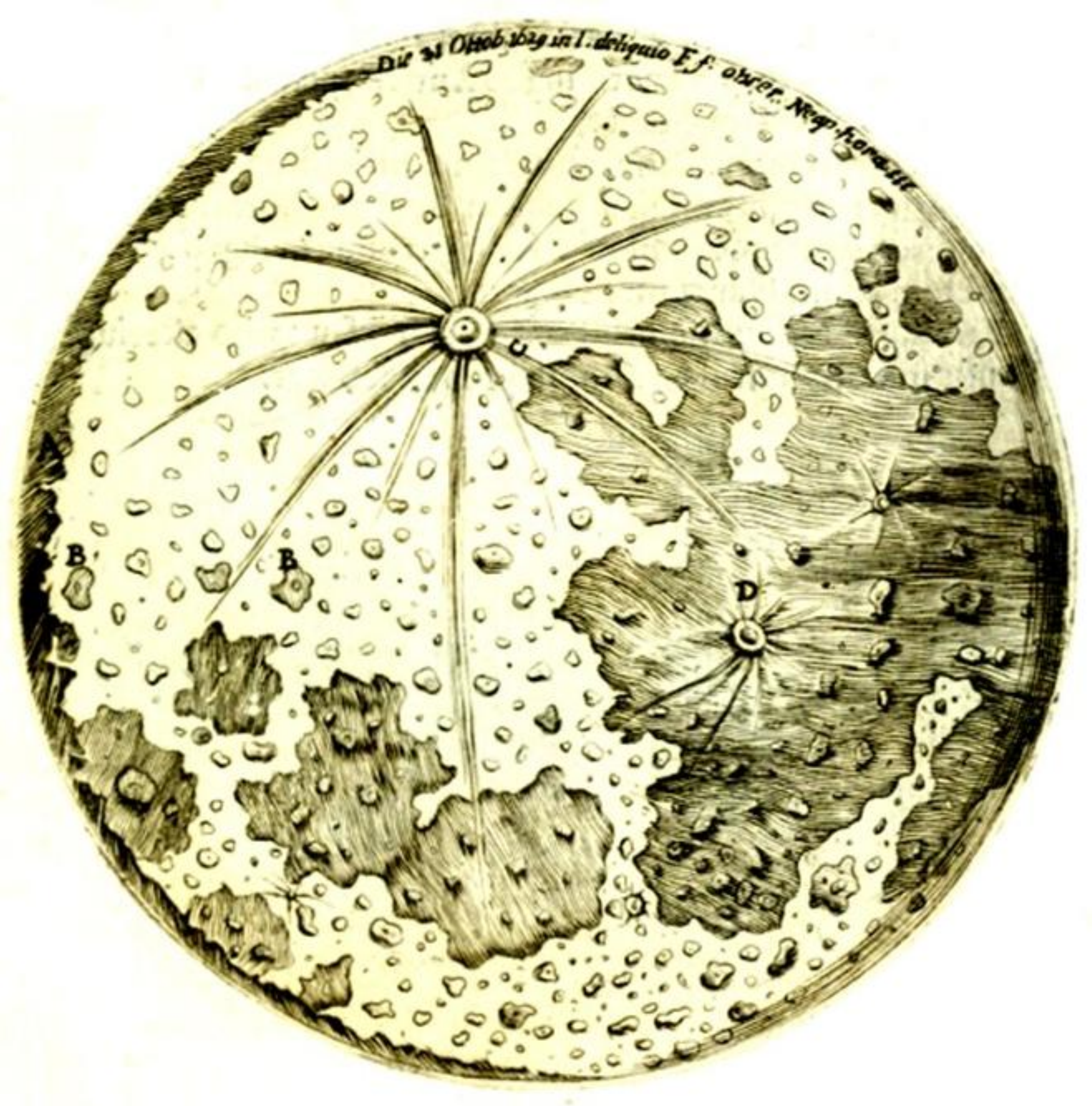

Figure 2: A drawing of the Moon based on observations made on 31 October 1629, three hours after sunset. The actual size of the etching is 10.3 cm. The Moon is shown upside-down with the South at the top and East on the right, as seen in an astronomical telescope. Some features are marked with letters. Letter A highlights that the Moon is not perfectly spherical but is irregular along the limb like an axe blade.[7] Letter B indicates a new, though relatively small, spot. Letter C indicates what we know today as the crater Tycho. This crater was observed (in this position) for the very first time by Fontana, who also saw several rays formed by the material splashed out during the impact, and a central peak, which is a characteristic of large craters. Fontana named Tycho 'Fons Major', i.e. biggest fountain, echoing his own name Fontana (which in Italian means fountain). Letter D marks the crater today known as Copernicus, which was also seen for the first time by Fontana (courtesy: Perkins Library of the Duke University).

4.1 The Lunar Observations of 1629 and 1630

Figure 2 shows Fontana's observation of the Moon made on 31 October 1629 three hours after sunset, probably from the roof of his house in Naples. The quality of this map can be judged by comparing it with those available at about this time, prepared in 1619, 1620 and 1627 by Charles Malapert (1581–1630), Giuseppe Biancani (1566–1624) and Christoforo Borri (1583–1632) respectively (see Figure 3), and with the modern high-resolution image shown in this figure (after Whitaker, 1999). Fontana was definitely the first to draw the true shape of both the Moon's maria and the major craters.

Fontana's etchings of the Moon were circulated around Europe long before they were published in his *Novae Celestium Observationes*. For instance, one of his lunar maps was sent to scholars in Genoa by Castelli, as documented in the letter Renieri wrote to Galileo on 5 March 1638:

> A picture of the Moon has arrived in Genoa, sent here by Benedetto Castelli, with news of

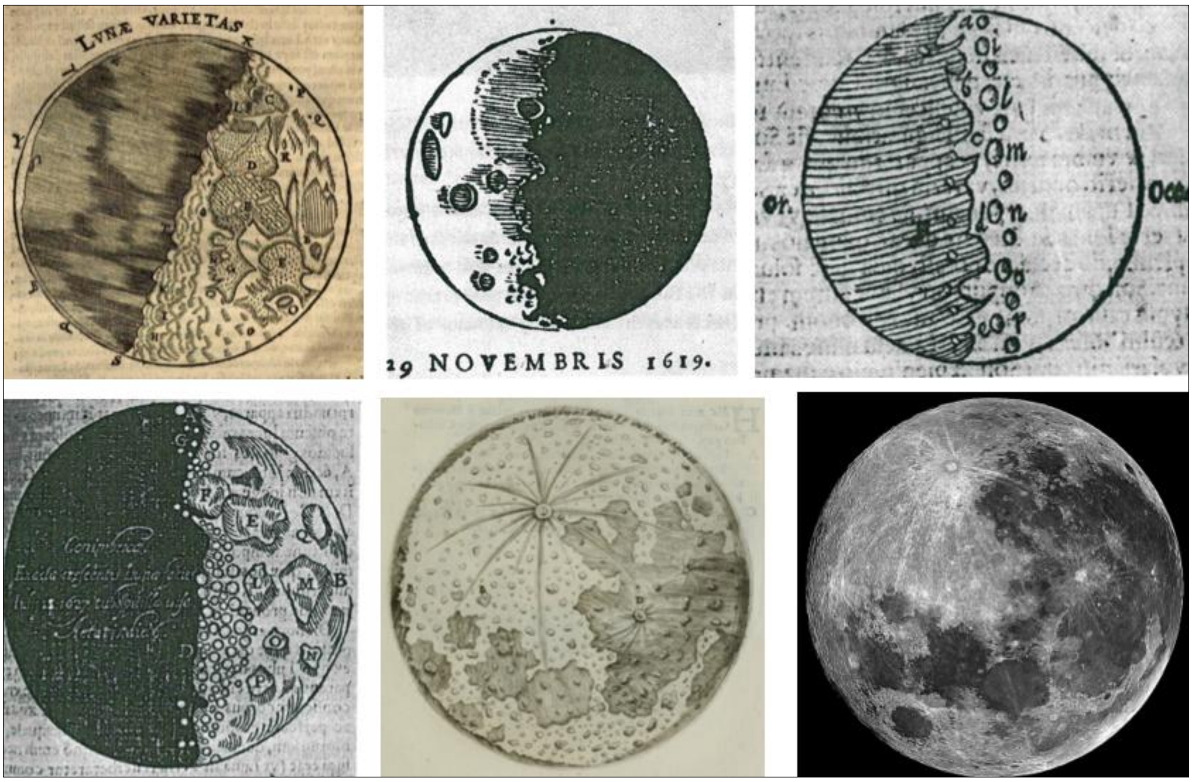

Figure 3: Drawings of the Moon made before Fontana did his first drawing. Top, left to right: Christophe Scheiner (1614), Charles Malapert (1619) and Giuseppe Biancani (1620). Bottom, left: Christoforo Borri (1627). Bottom, centre is Fontana's first drawing (1629), shown upside down, and bottom right is a modern view of the Moon (also shown upside down).

> a new telescope invented by a certain Fontana from Naples showing things more exquisitely than any other.

Then from a letter Gloriosi wrote to Santini on 13 March 1638 (Arrighi, 1964: 444) we learn:

> In Naples there is a person ingenious but has not studied science. His name is Francis Fontana ... I send to you the map of the Moon ... observed also designed by Fontana. These maps have gone to Rome to S. Cardinal Barberino, the Grand Duke of Florence and perhaps to other people that I do not know. (My English translation).

Fontana's lunar maps were reproduced by several authors. According to van de Vijver (1971b), Matthias Hirzgarter (1574–1653) used them in his *Detectio Dioptrica Corporum Planetarum Velorum* (1643); Andrea Argoli (1570–1657) in his *Pandosium Sphaericum*, (1644); Kircher in *De Arte Magna de Lucis et Umbrae* (1646) and Polacco in his *Anticopernicus Catholicus* (1646). And as we have already noted, Fontana suggested that his maps might have been the source of the map that Langrenus (the Royal Cartographer of King Philip IV of Spain) published in 1645, where he provided the first nomenclature of the lunar features, some of which are still in use today. As Fontana explained in his opening address to the reader, his wish to claim priority for the invention of the astronomical telescope was one of his motivations for writing the book.

The observation of 20 June 1630 shown in Figure 4 is of special interest since it records a rare occultation of Saturn by the Moon. Fontana wrote that the occultation took place on 20 June

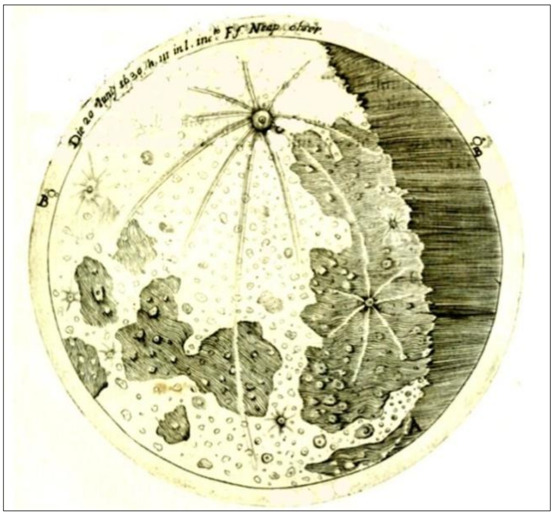

Figure 4: An English translation of the inscription around the Moon reads: "20 June 1630, IIIrd hour of the waxing Moon observed by Francesco Fontana in Naples." Beside the letter B there is the Galilean symbol for Saturn, which marks the position of Saturn both at the start and the end of the occultation. The letter A highlights the presence of a special darker area than the dark surroundings, and the letter C marks the 'Chief Fountain' (the crater Tycho) and one of the rays that joins up with a ray originated from the other 'great fountain' (Copernicus) in the great dark area (Oceanus Procellarum). The diameter of this Moon map is 10 cm.

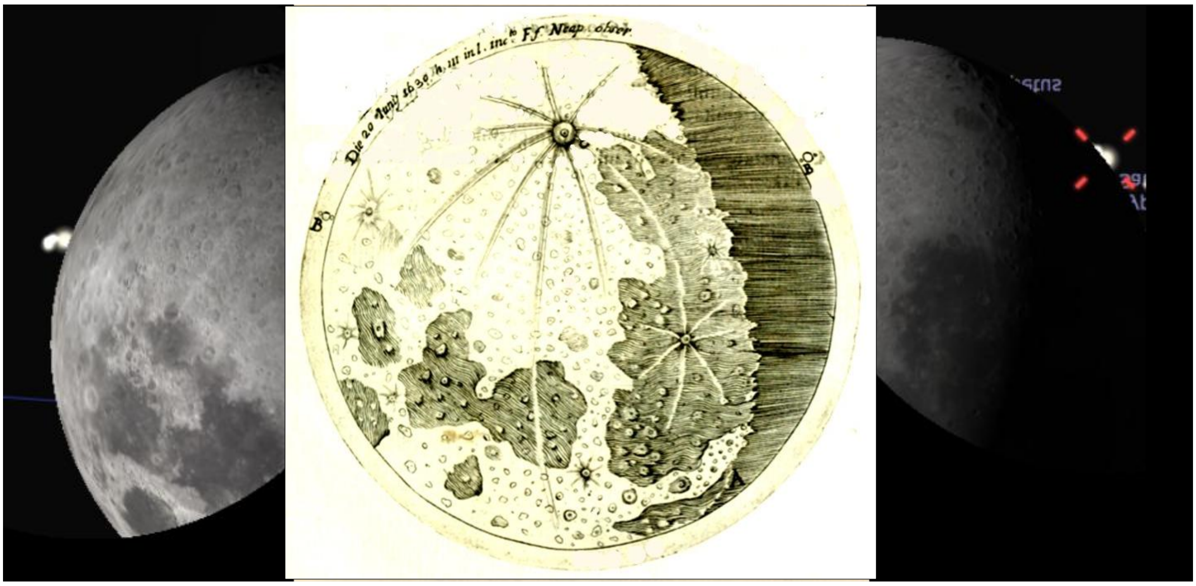

Figure 5: The same as the previous figure, but with the end of the occultation on the left and the start on the right. The occultation is reconstructed with Skygazer 4.5. This shows that the positions marked by Fontana were drawn precisely.

1630, starting about three hours after sunset and lasting less than two hours, but in fact the occultation took place on 19 June, one and a half hours after sunset and lasted less than one hour.

These differences have often been considered as evidence of Fontana's overall inaccuracy. However, these inaccuracies can be explained if we consider the way Fontana recorded his observations. As suggested by Beaumont and Fay (2001), Fontana took sunset as the start of the day, instead of midnight. Thus, the third hour after sunset of 20 June corresponded to the evening of 19 June. In the Skygazer simulation of the event the occultation from Naples started at 22:10:19 (UT) and ended at 22:58:59, for a total duration of about 49 minutes, thus much shorter than the two hours reported by Fontana. Nonetheless, I suggest that Fontana could possibly have used Roman timekeeping. In this system there are 12 hours between sunset and sunrise and the length of the hour over the year and between night and day is variable. The occultation took place almost at Summer solstice, when the night hours are shortest. Adopting a modern astronomical definition of sunset, the end and the start of twilight at the time in Naples were respectively at 20:44 UT and at 1:23 UT, which yields an hour length of 4:39m/12h = 23.25 minutes. It is possible that Fontana used a less strict definition for sunset, such as the civil or the nautical sunset, with the Sun at 6° or 12° respectively, thus getting an average hour slightly longer than 25 minutes and thereby accounting for the length of time reported by Fontana. Moreover, this hypothesis also is consistent with the start of the occultation, which he said occurred three hours after sunset. With sunset at 20:44 UT and a 28-minute-long hour, the occultation would have started around 22:08 UT, in agreement with the Skygazer simulation of 22:10 (UT). Figure 5 reproduces the start and the end of the occultation in our simulation, as well as Fontana's drawing, showing that the positions were accurately drawn in the etching.

The third of Fontana's etchings of the Moon referred to an observation on 24 June 1630, just a few days later than the previous one. Here Fontana noted that the 'Chief Fountain' (Tycho) was nearer to the centre of the Moon, which implied that the Moon was rocking back and forth. In the fourth observation, on 9 June 1640, Fontana noted that Tycho was closer to the centre of the Moon than he had ever seen before. Moreover, the middle of the great marking (Oceanus Procellarum) was at the limb of the Moon, definitively proving the existence of the third motion, i.e. the E-W motion. It is really remarkable that Fontana made these suggestions in the summer of 1630.

Before presenting his observations, Fontana summarized his lunar discoveries in Treatise II. The first chapter opens with a theory about the source of the Moon's light, which he believed came from the Sun, although according to him some feeble light also originated from the Moon itself (which could be seen in the non-illuminated part of the disk). The origin of this secondary light was a quite controversial issue, with Galileo defending the interpretation of its terrestrial origin and the Jesuits taking the opposite view (Molaro, 2013).

In Chapter II the Moon's shape is discussed and reported to be irregular:

> A large number of observations seem to indicate that the Moon is not a perfectly spherical body, but on its surface various irregularities are to be found. (Fontana, 1646: 26. Cf. Note A in Figure 2).

Chapter III describes the lunar markings, which Fontana thought were actual irregularities on the Moon's surface.

Chapter IV is dedicated to lunar movements. As already noted, the observation of the crater Tycho revealed a North-South direction movement which was to be added to the already known shift in an East-West direction. Galileo first described the Moon's libration in depth in a letter dated 7 November 1637 (Galileo, 1637), and he returned to the subject in a letter written to Alfonso Antonini (1584–1657) of Udine on 20 February 1638 (Galileo, 1638a). This letter, which Galileo asked to keep reserved, was only published in 1656, in the Bologna edition of Galileo's works (i.e. after the publication of Fontana's book). It is therefore unlikely that Fontana had read Galileo's letter. Fontana connected the Moon's motions with its rotation, which he assumed to last 27 days, the same as the solar rotation estimated by Scheiner in "The Revolution of the Sun" (Book IV, Part II, Chapter 10) in the *Rosa Ursinae*. It is interesting to note that Fontana argued that the Moon's rotation and North-South motion implied that it could not be a fixed body on the celestial sphere which, according to Aristotle, was moving East-West. The same argument was used later for the other planets, which he found to rotate on their own axes.

Treatise III and Treatise IV contain 13 etchings of the waxing Moon and 11 of the waning Moon, which were meant to show how the lunar features changed with phase. Fontana also remarked that he had been capable of reproducing only one thousandth part of the details that he had seen through his telescopes. Such a detailed lunar atlas has no precedents, and it is the first astronomically illustrated book (cf. Winkler and Van Helden, 1992). Of particular interest is observation N. 10 where, together with the lunar observation of November 1645, Fontana summarized his main planetary discoveries in the four corners of the etching. The label in the round framework recalls that the observations were performed with a "Telescope invented in 1608" (my English translation), where the Italian word 'Thelescopio' is used here for the first and last time.

5 THE FIFTH TREATISE: OBSERVATIONS OF MERCURY AND VENUS

5.1 Observations of Mercury

Two observations of Mercury are presented in Treatise V in which the planet is described as

> … curved like a bow with the concave edge pointing towards the sky and the convex edge turned towards the horizon. (Fontana, 1646: 90).

Thus Mercury revealed its phases conclusively, showing that it was orbiting the Sun. Fontana revealed that these observations were not made by him but rather by Father Zupus with one of his telescopes. In Figure 6 we show woodcuts of the two Mercury observations, together with the Skygazer simulations of the planet seen from Naples on the dates provided. These simulations give a percentage of illumination of about 40% on 23 May 1639 and of about 36% in January 1646, which are quite consistent with the drawings.

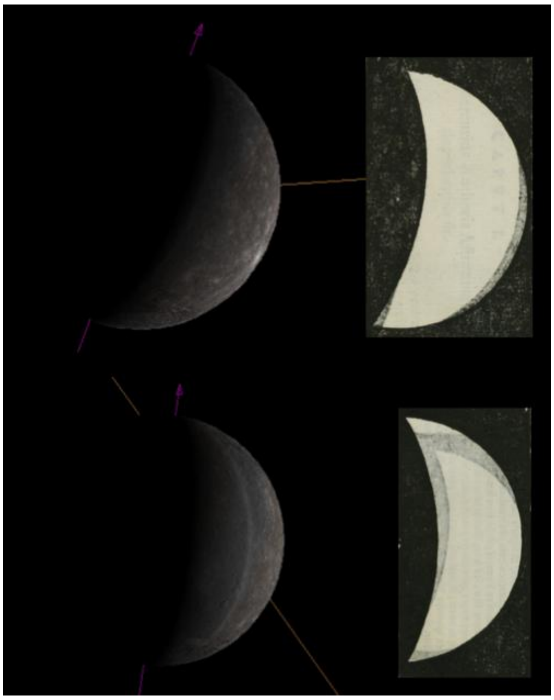

Figure 6: The top images show Mercury as seen from Naples on 23 May 1639. The concave edge pointing towards the sky and the convex edge turned towards the horizon. The bottom images show Mercury on January 1646. The cusps of Mercury's concave side pointed to the sky at a different angle to that seen in the first observation.

In his *Almagestum Novum* Riccioli (1651) ascribed the former observation to Father Zupus and the latter to Fontana. Riccioli also observed Mercury's phases in 1643–1644 and in 1647. He considered the detection of Mercury's phases a very difficult observation because of the small dimensions of the planet. These observations show both the quality of Fontana's telescope and his rectitude in attributing the discovery of Mercury's phases to Father Zupus.

5.2 Observations of Venus

Observations of Venus are shown in six drawings. The first was made on 22 January 1643 and the last on March 1646, which was probably the last observation that Fontana recorded before the publication of his book. His drawings show Venus' phases at their best, and are reproduced in Figure 7. The simulations with Stargazer are also shown beside the drawings, providing illuminated values of 17% and 35%, which are in good agreement with Fontana's drawings. Fontana also noted that the concave side showed an irregular edge with the light appearing a little dimmer near the edge, a phenomenon known as 'terminator shading'. In particular, using these two observations Fontana thought that Venus had an oval shape and that therefore the change in its appearance implied that it was rotating around its axis.

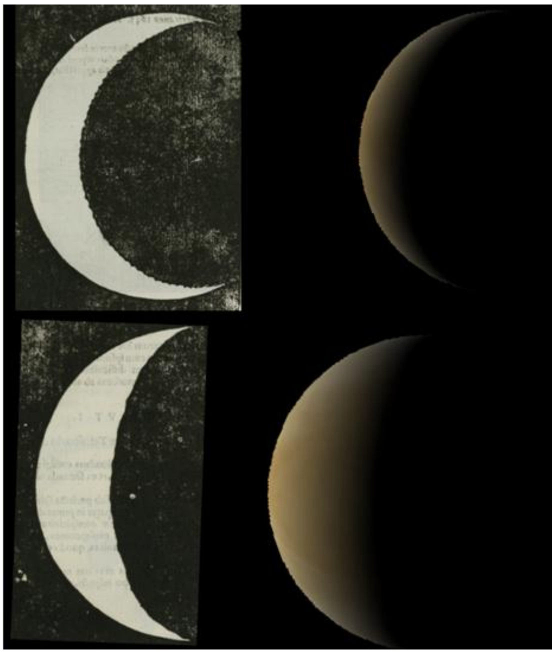

Figure 7: The top images show Venus on 22 January 1643. The illumination was only 17%, matching very well Fontana's observations. The bottom images show Venus on March 1646. The illumination is 35%, the same as in the drawing. Fontana noted also that the brightness was unequally distributed with the light appearing dimmer near the concave edge, an effect known today as 'terminator shading'.

The remaining four observations, obtained between 11 November 1645 and 22 January 1646, besides confirming the phases also reported the presence of two Cytherean satellites:

> This is a new discovery not yet published in my opinion. But it is true that they do not always appear, but only when Venus is shimmering … These little dots were ... not always seen in the same situation on Venus, but they moved back and forth like fish in the sea. (Fontana, 1646: 91).

This claim launched a controversy that would last for more than one hundred years, and a detailed account of this research is provided by Kragh (2008). According to Kragh (ibid.), Riccioli said he had never observed the moons and Christiaan Huygens (1629–1695) in 1659—three years after making his observations—concluded that there were no moons. On the other hand, Giovanni Domenico Cassini (1625–1712) claims to have seen a moon in 1672 and in 1686, but never again (Kragh, 2008). James Short (1710–1768) saw a luminous object close to Venus on 3 November 1740 (ibid.) and A. Mayer on 20 May 1759 (ibid.). This issue was resolved only when the 1761 transit of Venus did not reveal any moon (see Woolf, 1959). It is a point of curiosity, therefore, that in the same year (i.e. 1761) the moons of Venus reputedly were seen 19 times! An explanation in terms of optical reflections in the telescope was published in the *De Satellite Veneris* (1765) by the Jesuit Maximilian Hell (1720–1792), and in 1881 William Frederick Denning (1848–1931) provided a similar explanation (cf. Kragh, 2008).

It is very likely that Fontana's telescope was affected by some light reflection, particularly when observing a bright object such as Venus, which also was reported responsible for the presence of rays.

In fact, in commenting on the third observation of 15 November 1645 Fontana noted that

> Two starlike points of that same subdued reddish colour were seen, one at each of Venus' cusps, almost adjoining them. Although this appearance of Venus, if it is a sphere and receives its light from the Sun, might be an optical illusion, yet this is how it really looks. (Fontana, 1646: 96).

Finally, in commenting on his fifth observation Fontana said that a little globe or spot was facing the concave edge of the *real* Venus. The word 'real' is literally 'more true', and Beaumont and Fay (2001) commented that Fontana suspected that the little globe could be an optical illusion. In retrospect, it seems that this wrong prediction influenced the negative judgement reserved for Fontana by astronomers over the years.

6 THE SIXTH TREATISE: OBSERVATIONS OF MARS AND JUPITER

6.1 Observations of Mars

Fontana observed a gibbous Mars with a 'black cone', like a hollow in the middle of the planet. This was probably Syrtis Major, a marking recorded a few years later by Huygens (1659) and Robert Hooke (1635–1703; Hooke, 1666). Figure 8 shows Fontana's undated observations of Mars made in 1636, and his observation of 24 August 1638. While in the former drawing there is no evidence of phase, the latter shows a gibbous Mars. This feature of Mars was also seen by Castelli (1638c) with Fontana's telescope, as recorded in his letter to Galileo of 17 July 1638.

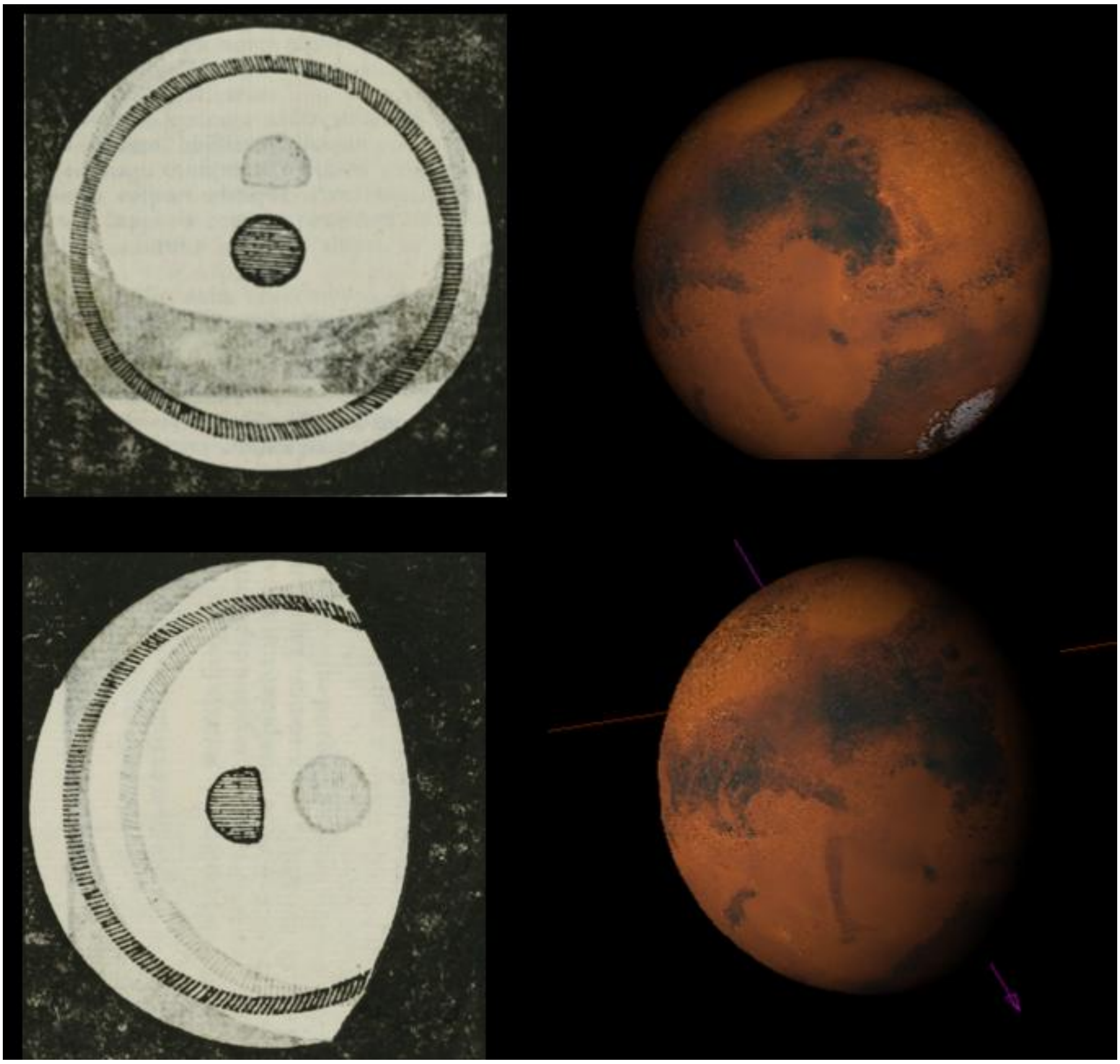

Figure 8: An undated observation of Mars of 1636 (top), and the observation of 24 August 1638 (bottom). In the former Mars is perfectly round, and in the latter it is gibbous. On the right are the Stargazer simulations. In 1638 the illuminated fraction of Mars was 83.3%, as the drawing suggests. The dark spot at the center changed quickly and it could not be reproduced without an hour. Note that Fontana also reported the presence of a ring, which did not exist.

At that date the illuminated fraction of Mars was 83.3%, as the drawing suggests. The dark marking at the center of the disk changed quickly, and since the time of the observation was not provided we have not attempted to reproduce its position. Note that Fontana reported also the presence of a ring which does not exist. From the quick motion of the dark marking Fontana deduced that Mars rotated. The book is not very clear on this point, as in both drawings the dark marking is approximately in the same position. However, a letter dated 11 September 1638 from Cozzolani to Manzini revealed some of the discussions inspired by Fontana's observations long before their publication:

> … in the center of Mars there is a prominence as a black velvet ending in cone shape and around there are two circles or two bands ... and everything is mobile, since you do not look in the same place ...

On 17 July 1638 Castelli (1638c) wrote to Galileo that he had seen a gibbous Mars through one of Fontana's telescopes. Three days later Galileo (1638b) answered, saying how beautiful this observation was, and in a letter to an unknown correspondent dated 15 January 1639 he wrote:

> As to the planet Mars it was observed that being at the square with the Sun, it is not seen perfectly round, but rather flared, similar to the Moon of 12 or 13 days, which from the side opposite to that touched by the solar rays it remains unilluminated, and consequently not seen, what I have said should have happened when Mars was seen superior to the Sun.

6.2 Observations of Jupiter

Fontana presented eight observations of Jupiter dating between 1630 and 1646. The planet was found to be perfectly spherical, but on the globe he noticed, already in 1630, some bands which persisted in subsequent observations. The observation of these bands was independently confirmed by Father Zupus with a different telescope. Fontana also observed the bands with different telescopes to be sure of their existence.

Sometimes Fathers Niccolo Zucchi (1586–1670) and Daniello Bartoli (1608–1685) are credited with having also seen Jupiter's bands in 1630 (Riccioli, 1665; cf. Graney, 2010), but there is no proven documentation for this and we think that the sources are the observations by Fontana and Father Zupus. Indeed, they were the only ones with access to telescopes capable of observing the Jovian bands. According to a letter written by Torricelli on 10 February 1646, Castelli saw Jupiter's bands from Rome in 1632 (see del Santo, 2009).

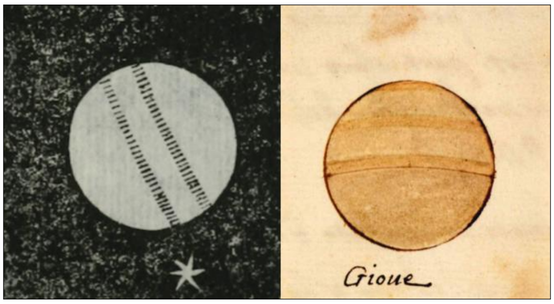

Figure 9: On the left is a woodcut showing Fontana's observations of Jupiter in 1630. The star is one of Jupiter's moons and together with the bands marks the plane normal to the axis of rotation of the planet. On the right is a watercolour of Jupiter showing three bands that was attached to Fontana's letter of 1639 that he sent to the Grand Duke Ferdinand II dé Medici (Courtesy: Archivio di Stato di Firenze, fondo MM, busta 514,fas.1,c 64v).

The bands were "… not more than three not fewer than two …" (Fontana, 1646: 101) and sometime they were seen as convex curves, sometime concave, and also as straight lines. The bands were thought to be circular clefts with some hollow spots on them. From the changes in shape of the bands Fontana deduced that the planet was rotating, and this implied that the planet had an independent existence and was not attached to the revolving heavens. Moreover, these new features implied a flaw in the perfection of the Aristotelian skies. When in 1639 Fontana approached the Grand Duke proposing a telescope of 22 palms (i.e. 5.8 m) as a demonstration of the superiority of his telescopes he attached a watercolour painting showing his discovery of the bands on Jupiter, and this is shown in Figure 9.

In the field of view of Jupiter Fontana noted the persistence of five stars that he suggested could be moons:

> It can be shown that they are not fixed stars for the reason that fixed stars always keep the same positions relative to each other, as all Astronomers agree. But these are seen to behave differently. Also some fixed stars would be visible in the vicinity of Mars too, which is nearer to Jupiter in the order of the planets, and many more around Saturn, the nearest planet to the realm of fixed stars, but the opposite is the case. (Fontana, 1646: 108).

For an observer the argument provided by Fontana is rather naive, since it would seem that he did not realize that he was looking at different regions of the sky:

7 THE SEVENTH TREATISE: OBSERVATIONS OF SATURN AND THE PLEIADES

7.1 Observations of Saturn

Fontana presented a set of seven observations of Saturn which he said appeared in his telescope like the full Moon to the naked eye. The dates are not always reported but there appear to be three groups. The first observation was made on 20 June 1630 when the planet had been eclipsed by the Moon, as we have already discussed. The drawing depicts Galileo's rendering of the planet as three perfectly spherical stars with the middle one about two times larger than the outer ones.

The second drawing does not list the year, but it looks similar to the third, which was made in 1634. Fontana noted that the shape of the planet changed considerably. The central body was oval and the two stars seemed to be "… embracing the planet itself on either side." (Fontana, 1646: 115). Also in the next observations of 1636 these were seen in the form of the "… crescent moon and touching its globe …" (Fontana, 1646: 116), which this time was perfectly spherical. It is quite possible that the different appearance of the planet was linked to improvements to his telescope as it evolved from 8 palms long to 14 palms (i.e. from 2.1 to 3.8 m).

The fifth observation does not include a date but as noted by Beaumont and Fay (2001) it must have been close to the last two observing sessions on 3 and 12 December 1645. The two satellite stars appeared more distant from the central body and

> … they have on either side something in the nature of handles forming a triangular shape which seems attached to the middle of a perfect spherical body. (Fontana, 1646: 117).

The observation on 3 December is very similar, but with the triangular shape of the handles becoming more oval and curved, and in those of 12 December the satellite stars are becoming smaller and more distant. The last observation of 12 December is shown in Figure 10 together with our simulation for the same day. From the simulation it is possible to appreciate how the overall proportions and the tilt of the disc were accurately drawn by Fontana. The description of the planet during the last three observations shows how close he came to revealing the real nature of the planet.

Fontana's thoughts regarding the changing shape of Saturn can be deduced from a letter by Gloriosi dated 21 September 1638 about Fontana's observations where he says that the cause is likely the change in the position of Saturn with respect to the Sun. From the same letter we also know that the regions within the 'handles' were seen by Fontana to be empty sky. The true form of Saturn finally was revealed by Huygens (in 1659), and he admitted to having been inspired by Fontana's observations (Huygens, 1888: 535, 558).

Also for Saturn, as for the other planets and the Moon, Fontana concluded that the planet was moving freely in the sky, and therefore it was not attached to an Aristotelian celestial sphere.

Around Saturn on several occasions Fontana seems to have seen further moons away from the planet. As suggested by Beaumont and Fay (2001) it is possible that Fontana saw Titan and Iapetus, since they were relatively bright. Huygens (1888) discovered Titan on 25 March 1655, and on 12 December 1645 it was visual magnitude 8.23 and about 3 arcminutes from Saturn so it should have been within reach of Fontana's telescope.

7.2 Observations of the Pleiades

Fontana also presented his observations of the Pleiades. With one observation alone his telescope revealed 29 new stars. We recall that Galileo was able to see some 40 stars in the same field. However, no discussion or comparison is made here, apart from Fontana's remark that he believed the stars to be 'countless'.

8 THE EIGHTH TREATISE: THE MICROSCOPE

In the opening pages of his book Fontana inserted a testimonial from the Father Sersale who stated that he had used Fontana's microscope since 1625:

> I Jerome Sirsalis, Jesuit in the College of Naples, wish to bear witness to all that around the year 1625 in the house of this most illustrious gentleman, Francesco Fontana, the glory of his Neapolitan homeland, I saw a microscope, and after a short space of time, a telescope constructed by him with great skill from two convex lenses, so that such outstanding inventions, perceived by his divine genius, deserve to be reported. (Beaumont and Fay, 2001: 6).

In this section of the book Fontana (1646: 143) describes an instrument "… by which the smallest and virtually invisible things are so magnified that they can clearly and distinctly be examined …", made in 1618 (his fifth invention). Colonna informed Cesi of the new invention by his friend Fontana on 17 July 1626 (cf. Freedberg, 2002). Fontana (1646: 145) did not pretend to be the first inventor of the microscope since it "…could have been invented earlier elsewhere by someone else."

Fontana then presents a detailed description of ten observations as an example of what he observed with the microscope. He describes a cheese mite, a flea, an ant, a fly, several unknown animals, a spider, the sand, a human hair, material at the base of the window, and other things. As an example, his description of the cheese mite is provided below:

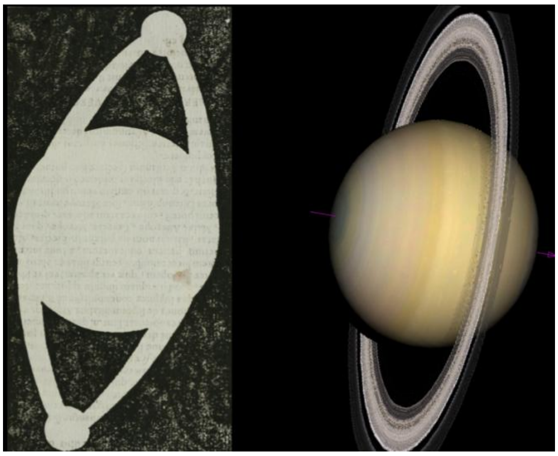

Figure 10: On the left is Fontana's observation of 12 December 1645, and on the right is a simulation of the planet as seen from Naples on the same date. The axis of the simulation has been slightly adjusted by 10 degrees to match the drawing. The disk/body ratio and the tilt of the rings is rather well reproduced in Fontana's drawing (after Fontana, 1646).

> The dust produced by cheese. This dust when placed under the microscope does not present the appearance of dust but of a remarkable living creature. It has eyebrows, lightly drawn as though painted with a brush, in like manner huge globes of eyes manifestly somewhat black, giving out a cheerful light. It is armed with little nails and claws, and seems to-be equipped with eyes. The entire appearance of its body too, in colour outstandingly exquisite, ennobles the tiny form of the animal, never before seen. To see it also – which cannot be done without marvelling – amounts to this: it crawls, feeds and definitely chews as well as moves itself; it seems equal in size to a human nail, its back is all rough and covered with scales, embellished with various star-like feat-

> ures, protected by thick and shaggy bristles, with such wondrous artfulness that you might have said that Nature, the creator of such a work, was born along with it, grew up with it, and even breathing with it, draws breath herself. (Beaumont and Fay, 2001: 126).

Federico Cesi and Francesco Stelluti (1577–1652) in their *Apiaria* of 1625 provide the first description of the anatomy of bees based on microscopic observations. *Apiaria* was a gift to Pope Urban VIII and bore an attached engraving by Matthaeus Greuter (1564–1638) entitled the 'Melissographia', reproducing three bees as seen under the microscope. The arrangement of the bees referred to the trio of bees on the crest of the Barberini Family.

The word 'microscope' was coined by Giovanni Faber in 1625, and the first printed microscopic illustrations were published five years later in the translation of the Latin poet Aulus Persius Flaccus by Stelluti, *Persio Tradotto in Verso Sciolto e Dichiarato* (1630). On page 52 there is a reproduction of three bees that closely resemble those in Greuter's 'Melissographia'. We note that on page 47 Stelluti writes that the bees were "… observed and drawn by Francesco Fontana …", thus confirming that Fontana had a major role in the first microscopic observations of bees. In his letters of 1626 to Cesi, Colonna refers to Fontana as a friend of the bee (see Gabrieli, 1989).

The invention of the microscope also is unclear (Rezzi, 1852; Zuidervaart, 2011). Galileo made explicit mention of his microscope in the *Saggiatore*, which was written in the period 1619–1622 and published in 1624, but he could have invented the microscope a few years earlier. On 23 September 1624 Galileo sent an instrument that he referred to as an 'occhialino' to Cesi with instructions on how to use it to see things close up (Zuidervaart, 2011). In the same year, Abraham Kuffler (1598–1657) and his brother Aegidius provided Cesi with a microscope made by Cornelis Drebbel (1572–1633) (ibid.). Like the telescope, the microscope also can have two optical configurations and it is quite possible that Fontana was the first to conceive of a compound microscope made only with convex lenses.

9 FONTANA AND HIS TELESCOPES IN CONTEMPORARY PAINTINGS

The *Allegory of Sight* and *Allegory of Sight and Smell* by Jan Brueghel the Elder (1568–1625) were painted in 1617 and around 1618 respectively, and show very sophisticated silver telescopes made with seven and eight draw tubes. It has been suggested that these are Keplerian telescopes (Molaro and Selvelli, 2011; Selvelli and Molaro, 2009). This is deduced from the length of the telescopes which likely exceeded two meters, and from the boxy shape of the eyepiece which was made to help the eye to be positioned precisely at the focus of the convex lens. As we have seen, in those years Fontana was the only one able to work two convex lenses in an accurate way to manufacture a Keplerian telescope. The telescopes in J. Brueghel The Elder's paintings belonged to the collection of scientific instruments of Albert VII (1559–1621), Archduke of the Southern (or Austrian) Low Countries. Albert VII was the brother of Emperor Rudolf II (1552–1612) in Prague, the protector of Kepler and Tycho, and the brother of Maximilian III (1558–1618) who, as we have seen, had a Keplerian telescope around 1616. All three Hapsburg brothers were ruling Catholic Europe, to which Naples and the Kingdom of Spain belonged. The Viceroys in Naples also were fond of astronomy and of the military applications of the telescope, and they were in possession of Fontana telescopes, as documented in the letter of Colonna to Cesi of 30 November 1629. According to Crasso (1666: 298; my translation),

> Fontana made telescopes for all the courts and nobles around Europe which when obtained one of his telescopes conserved it together with the most precious things.

Thus, it is quite possible that a preferential circulation of scientific instruments took place within the Catholic countries, and that Fontana's instruments reached the far courts in northern Europe even before other places in Italy.

Brueghel's series of paintings was preceded only a few years earlier by another series of 'senses' painted by the Spaniard Jusepe de Ribera (1591–1652), who in his *The Sight* chose a telescope for the first time. We note here that the sitter in *The Sight* by Ribera bears a close resemblance to the self-portrait made by Fontana for his book. *The Sight*, depicted by the young Ribera under the influence of Velasquez, is shown here in Figure 11, where a man is holding a sophisticated telescope. Ribera's painting is not dated, but according to Mancini (1956) it was executed during the end of the Roman period of the painter, therefore some time between 1613 and 1616. The canvas was commissioned by an unknown Spaniard, who has now been identified by Longhi (1966).

Earlier, the *Allegory of Sight* was attributed to Velasquez. Ribera was definitely in Rome in 1611, and possibly arrived in 1608, and in May 1616 he moved to Naples where in November he married the 16-year old daughter of the painter Giovanni Bernardino Azzolino (1598–1645). Such a quick acclimatization to Naples suggests that Ribera was familiar with the town and he could have visited it before. It must be recalled that Pedro Téllez-Girón y Velasco, the Third Duke of Osuna (1574–1624), was the Spanish Ambas-

Figure 11: Jusepe Ribera's 114 × 89 cm oil on canvas, the *Allegory of Sight* painted around 1615 (courtesy: Franz Mayer Museum, Mexico City).

sador in Rome when Ribera was in Rome, became the Viceroy in Naples in 1616 (the same year that Ribiera moved to Naples), and was a patron of Ribera from the early days, probably appointing him as a court painter. In my view, the idea that the *Allegory of Sight* could have been painted or finished in Naples is also suggested by the marine landscape depicted in the window, which is similar to what could be seen from a window of a house in Naples.

The series of the five senses shows a caravaggesque naturalism with the figures represent-

Figure 12: On the left is the self-portrait published by Fontana in 1646, but showing his likeness in 1608. On the right is the head of the sitter in *The Allegory of Sight* painted by Ribera around 1615.

ed with high contrast in the tradition of tenebrism painting. The two faces on the self-portrait by Fontana and the anonymous sitter in Ribera's painting are shown next to one another in Figure 12.[8] The shape of the head and the characteristics of the face and of the gaze are strikingly similar. One main difference between the two portraits lies in the hair. However, Fontana in 1646 presented himself as he looked in 1608 (i.e. almost 40 years younger), and the simplest way to look younger is by adding hair. Anyway, the possible Fontana in the painting by Ribera should be a few years older. Also, the ears are different, but it must be considered that Fontana's self-portrait cannot be compared to those of one of the most talented painters of his times. Thus, although it is generally believed that Ribera took his models from everyday life, it cannot be excluded that for the specific subject of the *Allegory of Sight* Ribera took inspiration from the figure of Fontana, who by this time was already a renowned telescope-maker. The difference between the expression of profound reflection in the *Allegory of Sight* with the drinker in the *Sense of Taste* has already been noted (Pérez Sanchez, 1992). A telescope decorated with gold is not something that can be associated with a man from the street since at that time it was very precious and was a symbol of power. We admittedly prefer the possibility that the man in Ribera's portrait could be the inventor of the *astronomical* telescope.

10 NOTES

1. Unless it is otherwise stated, I am responsible for all of the English translations in this paper.
2. Beaumont and Fay's translation has been distributed privately, and for this study I used the copy in the Paris Observatory Library.
3. This figure, and all others from Fontana (1646) are taken from a copy of this book that is in the Perkins Library at Duke University, Durham, North Carolina, USA.
4. In the following Sections I use English translations of the original titles listed by Fontana.
5. The first mention of the theory of the telescope is in Book 17 in Della Porta's (1589) *Magic of Nature*, which in Chapter 10 says: "Concave lenses make distant objects clearly visible, convex lenses near objects [smaller?] …" (Beaumont and Fay, 2001: 11).
6. The size of the 'palm' varied throughout Italy. Although in Naples 1 palm was reportedly equal to 203.1 mm according to Riccioli and 218.0 mm according to others, in this paper I have adopted the value of 263.7 mm, suggested by del Santo (2009).
7. Fontana (1646: 41) wrote "The border of the illuminated part was not perfectly circular, but was an irregular shape, like an axe." Fontana was the first to note the irregular shape of the Moon. We recall that in the *Sidereus* Galileo mentioned the presence of mountains and estimated their heights. He was surprised not to see an irregular lunar limb. He also postulated the presence of a lunar at-

mosphere.

8. Two other portraits of Fontana are reproduced by Crasso (1666) and Terracina (1822), but probably both were derived from Fontana's self-portrait.

11 ACKNOWLEDGEMENTS

This work could not have been possible without the translation from Latin together with very useful annotation by Sally Beaumont and the late Peter Fay who are warmly acknowledged. I also thank Elisabetta Caffau (Paris Observatory Library) for providing access to the Beaumont and Fay translation; Simone Zaggia for his help in the use of Stargaze; Pierluigi Selvelli for useful comments about the history of the telescope; Chiara Doz for helping with the literature search; and the Perkins Library at Duke University for providing access to a copy of Fontana's book (1646). Finally, thanks go to Simonetta Fabrizio and Gabriella Schiulaz for helping improve the English; Albert Van Helden for his invaluable referee's comments; and Dr Clifford Cunningham and Professor Wayne Orchiston for editing and formatting this paper.

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Professor Paolo Molaro was born in Artegna (UD), Italy in 1955. He completed a Ph.D. at the International School for Advanced Studies in Trieste with Denis Sciama and since 1987 has been a researcher at the Astronomical Observatory of Trieste which he directed during 2000–2003. His main field of research is the low metallicity Universe, either of extremely metal-poor stars or of primeval galaxies. Paolo is a member of the Particle Data Group for primordial nucleosynthesis. He is also Project Scientist of the high resolution spectrograph ESPRESSO that has just seen the 'first light' at the ESO-VLT in a search for other Earth-like planets and possible variation in funda-mental physical constants. In 2012 he succeeded in detecting the Rossiter-McLaughlin Effect during the transit of Venus, and in 2014 he observed the Earth transiting the Sun as seen from Jupiter. As far as the history of astronomy is concerned, Paolo found the first painted telescope in a painting by J. Brueghel the Elder. He even found a possible new portrait of the young Galileo.

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THE ORIGIN AND DEVELOPMENT OF EXTRAGALACTIC RADIO ASTRONOMY: THE ROLE OF THE CSIRO'S DIVISION OF RADIOPHYSICS DOVER HEIGHTS FIELD STATION IN SYDNEY

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Abstract: Initial post-war developments in non-solar radio astronomy were inspired by Hey, Phillips and Parson's report in 1946 of an intense source of radio emission in Cygnus. This so-called 'radio star' was unique, and questions immediately were raised about its true nature. But it did not remain unique for long. Observing from Sydney, John Bolton, Gordon Stanley and Bruce Slee followed up the Cygnus discovery with more radio star detections, beginning what would evolve into a long-term multi-faceted research program and one of the mainstays of the CSIRO's Division of Radiophysics. But more than this, these early discoveries in England and in Sydney opened up a whole new field of investigation, extragalactic radio astronomy, which has remained a major area of investigation through to the present day.

This paper focusses on the early years of this program when the observations were carried out at Dover Heights Field Station in Sydney, and the ways in which new developments in instrumentation that allowed a major expansion of the program eventually led to the closure of Dover Heights and the founding of the Fleurs Field Station.

Keywords: radio astronomy, field stations, Dover Heights, 'radio stars', discrete sources, sea interferometers, John Bolton, Richard McGee, Bruce Slee, Gordon Stanley, Kevin Westfold

1 INTRODUCTION

Towards the end of 1945 and in early 1946 pioneering solar radio astronomy was carried out by staff from the Division of Radiophysics (henceforth RP) at a number of WWII radar facilities in Sydney (Orchiston et al., 2006). Some of these soon became RP field stations (Orchiston and Slee, 2017), and one of these was situated at Dover Heights in the eastern suburbs of Sydney. This 5-ha facility was located on a 79-m cliff top overlooking the Tasman Sea, 5 km south of the entrance to Sydney Harbour (see Figure 1). The site offered two concrete blockhouses, a WWII radar antenna and direct access to water and power (Figure 2). Despite its suburban location and the presence of a nearby road, it proved a radio-quiet site at the wavelengths the RP scientists were interested in.

From the start, three young RP staff members would form the nucleus of a team that for the next eight years would investigate non-solar radio emission at Dover Heights. They were John Bolton, Gordon Stanley and Bruce Slee, and all three would go on to build international reputations in radio astronomy. The leader of the group was John Gatenby Bolton (1922–1993; Figure 3; Robertson, 2017), who was born in England and after graduating from Cambridge University served in the Royal Navy. In 1946 he joined RP, and was assigned to the Dover Heights Field Station. He later served as Professor of Radio Astronomy at the California Institute of Technology (Caltech) in the USA and inaugural Director of the Owens Valley Radio Observatory before returning to RP as Director of the Parkes Radio Observatory. He remained at RP until his retirement. Gordon James Stanley (1921–2001; Figure 4; Kellermann et al., 2005) was born in New Zealand and trained as an engineer. In early 1944 he began working at RP, and in 1954 joined Bolton at Caltech, becoming the second Director of the Owens Valley Radio Observatory. He then set up a company specialising in sensor technology. Owen Bruce Slee (1924–2016; Figure 5; Orchiston, 2004; 2005) was born in Ade-

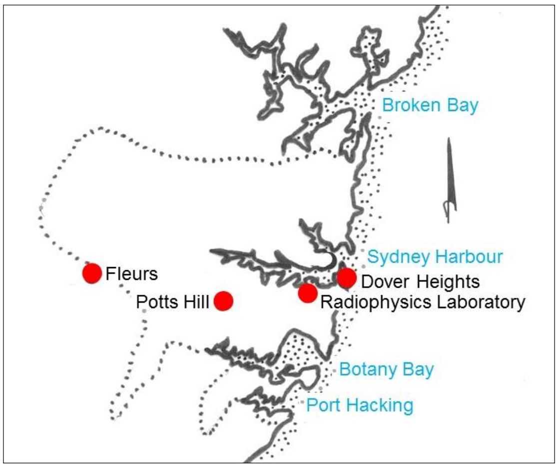
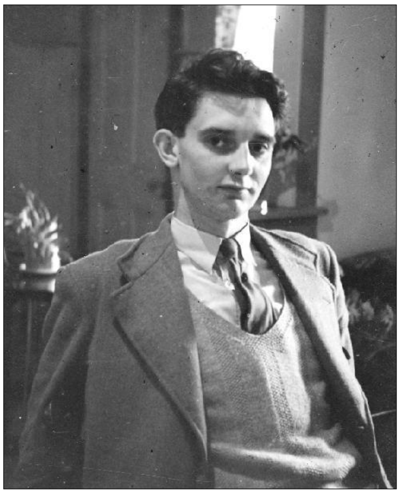


Figure 1: Radio astronomy localities in the Sydney region mentioned in text. The dotted outline shows the current approximate boundary of Greater Sydney. Scale: from Fleurs to Dover Heights is 48 km (map: Wayne Orchiston).

Figure 2: A view looking north showing the Dover Heights radar station in the foreground, and beyond it North Head (where there also was a radar station) and the entrance to Sydney Harbour. The radar antenna on the roof of the cliff-side blockhouse was used initially for solar radio astronomy, then it was removed and the Yagi antennas used by Bolton, Stanley and Slee were installed on the roof of the blockhouse (courtesy: CSIRO Radio Astronomy Image Archive (henceforth CRAIA) B81-1).



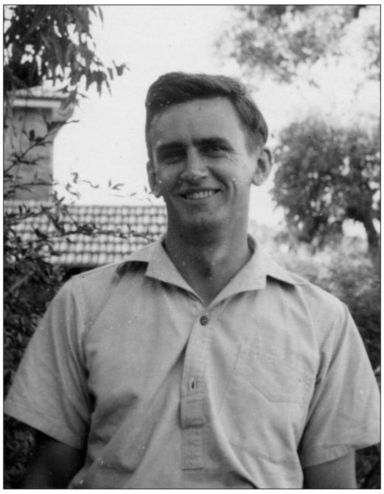


Figure 3 (left): John Bolton in 1948 (courtesy: Bolton family). Figure 4 (centre): an undated photograph of Gordon Stanley (courtesy: Stanley family). Figure 5 (right): Bruce Slee in 1947 (courtesy: Bruce Slee).

laide, and trained as a radar technician. After serving at a number of different radar stations during the War and independently discovering solar radio emission (Orchiston and Slee, 2002a), he joined RP and apart from a short period in England he remained at RP and its successor, the Australia Telescope National Facility, until his retirement.

Although these three scientists were the mainstay of the source survey work at Dover Heights, they were joined for short intervals by other scientists, who will be introduced at the appropriate spots in the following narrative.

2 THE EARLY SEA INTERFEROMETERS AND DETECTION OF THE FIRST 'RADIO STARS'

In early 1947 February, Bolton and Stanley installed two different Yagi arrays at Dover Heights in order to study solar radio emission. One consisted of a 100 MHz 2-Yagi array (Figure 6), and the other a 200 MHz 4-Yagi array (Figure 7). Bolton and Stanley succeeded in detecting solar bursts in March and April (see Payne-Scott et al., 1947), but solar activity declined during May and by June had all but ceased. It was at this stage that Bolton and Stanley decided they would "… conduct an empirical search for radio sources …" (Bolton, 1982: 350).

In order to do this the two arrays were set up facing due east, with the Yagis positioned horizontally. The plan was to use each array as a sea interferometer, the principle of which is clearly explained by Pawsey and Bracewell (1955: 62):

> The simplest method of realising a twin-wave interferometer is that employing a single aerial on a cliff overlooking the sea. The beam is directed horizontally towards the place where the source being studied [or searched for] will rise or set and interference is produced between the direct ray and one reflected from the sea in a manner similar to the interference fringes produced by Lloyd's mirror in optics.

This is illustrated in Figure 8.

After correcting for refraction, curvature of the Earth's surface, and in some circumstances tidal variations, the commencement of the interference fringes pinpointed the position of a source as it rose over the eastern horizon, while the ratio of fringe maxima to minima provided a measure of source size, *W*, via the formula

$$W = (\lambda / \pi h)\sqrt{3R}, \qquad (1)$$

where *R* is the ratio of the received power (above the extrapolated background level) at the maxima and minima of the interference pattern, *h* is the height of the antenna above sea-level and λ is the wavelength (for details see Bolton and Slee, 1953; Stanley and Slee, 1950).

Almost immediately Bolton and Stanley were successful in their quest:

> On the first night of observation a cable broke on the 200 MHz aerial … [but] The 100 MHz equipment which was directed towards the north-eastern horizon gave a sea interferometer pattern of a source in Cygnus which was clearly that previously seen by Hey. (Bolton, 1982: 350).

In his account of this initial detection, Stanley (1994: 509) was a little more circumspect: although "Cygnus appeared on the first record … it took some days until we could be perfectly sure, as the system was erratic." The fringe pattern, meanwhile, indicated a source size of less than 8 minutes of arc, although Bolton and Stanley (1948b: 31) were careful to stress that this "… is an upper estimate and the source may well be effectively a point." Over the next three months Bolton and Stanley observed the Cygnus A source (as it became known) at 60 MHz (with a 2-Yagi array), 85 MHz (with a single Yagi), 100 MHz and 200 MHz, using converted radar receivers in each instance, with no notable modifications apart from the introduction of a 2-stage preamplifier in the 200 MHz set (Bolton and Stanley, 1948a). The majority of the observations were obtained at 100 MHz (a frequency free from man-made interference), and these revealed an approximate position for the source of R.A. 19h 58m 47 ± 10s and Dec. +41° 47 ± 7′, a position devoid of any obvious optical correlates (ibid.) Meanwhile observations at the four different frequencies provided useful spectral data.

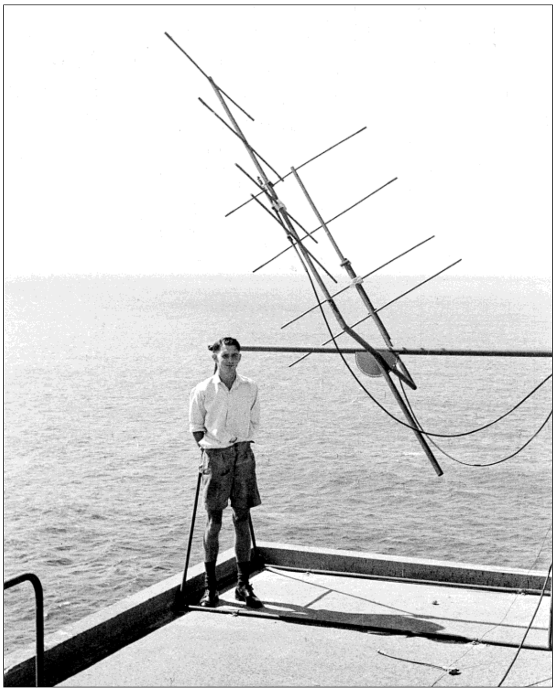


Figure 6: John Bolton and the 100-MHz twin Yagi antenna on the roof of the blockhouse at Dover Heights. The two elements could be positioned horizontally, pointing to the eastern horizon, to form a sea interferometer (courtesy: CRAIA, B1031-7).

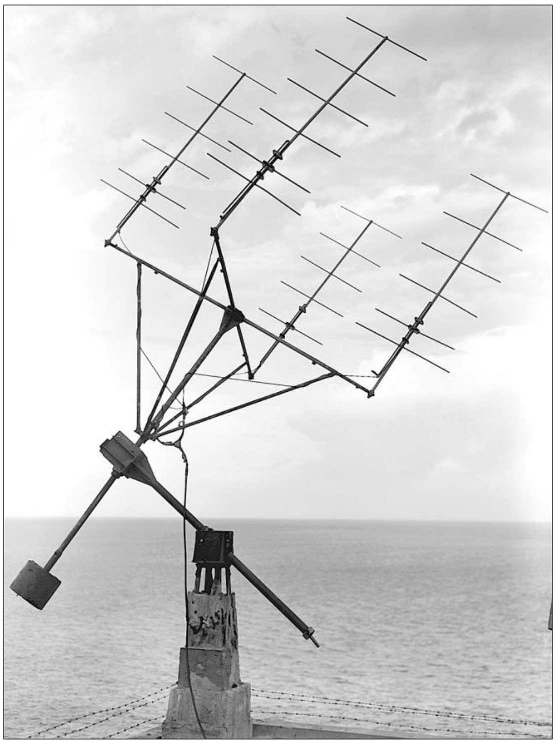


Figure 7: The 200 MHz 4-element Yagi array on the roof of the blockhouse at Dover Heights (courtesy: CRAIA B1165-2).

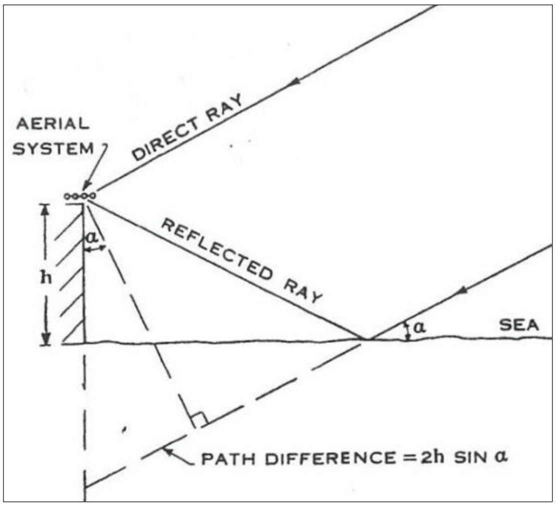


Figure 8: A schematic diagram of the sea interferometer. The cliff-top aerial combines the direct signal with the signal reflected from the sea to create an interference pattern. These two signals produce maximum intensities when their path lengths differ by an even number of half-wavelengths and minimum intensities when path lengths differ by an odd number of half-wavelengths. The reflected signal simulates an imaginary aerial, spaced from the real aerial at a distance equal to twice the height of the aerial above sea-level. The difference in path length between the direct and reflected signals is given by $2h \sin\alpha$, where h is the height of the aerial above sea-level and α is the angle of incidence of the reflected signal to the sea surface, corrected for the curvature of the Earth and atmospheric refraction of the signal (after Stanley and Slee, 1950: 236).

One of the features that Bolton and Stanley (1948b: 312–313) noted was that

> The radiation consists of two components, one constant and the other showing considerable variation over short and long periods … The periodicity of the variations decreases with decreasing frequency. No close correlation has been found between short-period variations on frequencies as close as 85 and 100 Mc./s., but the general activity of the variable component shows good correlation on different frequencies.

This variable component had already been reported by Hey et al. (1946) and was non-solar and non-terrestrial in origin, but what Bolton and Stanley (1948a) found particularly interesting was the fact that it was virtually absent at 200 MHz. A typical record obtained at 100 MHz is reproduced here as Figure 9, where the constant and varying components are both evident.

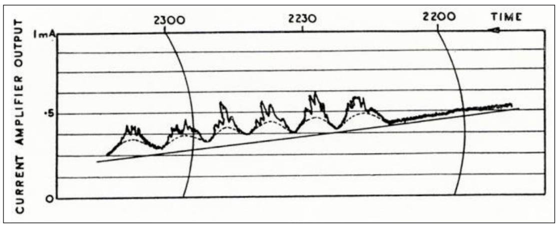


Figure 9: The interference pattern for Cygnus A recorded at 100 MHz after 10 pm on the evening of 19 June 1947 at Dover Heights. The strength of the signal decreases (towards the left) as the source rises higher above the horizon (after Bolton and Stanley, 1948b: 60).

The dashed sine wave helps clarify this.

While analysing their Cygnus A observations, Bolton and Stanley continued their search for other sources at 100 MHz, "… over about one quarter of the celestial sphere." (Bolton, 1948: 141). On 6 November 1947, immediately after having written up their Cygnus A results, they detected a second source, Taurus A, and within the next two months five additional sources. Some information on these is in Table 1.

In the *Nature* paper reporting these discoveries, Bolton (1948) comments on the difficulties associated with obtaining precise positions, and also notes that as in the case of Cygnus, the new sources do not appear to be associated with any notable stellar objects. He further suggests that the emission from these sources derives from a combination of three different components:

(a) A 'base-level' due to free-free transitions in the interstellar medium, as proposed by Henyey and Keenan (1940);
(b) Emission from individual stars in regions of high star-density;[1] and
(c) "A contribution from individual discrete sources, which may be distinct 'radio-types' and for which a place might have to be found in the sequence of stellar evolution." (Bolton, 1948: 142).

With the benefit of hindsight, these conclusions would prove to be naïve and premature. But the true nature of the 'radio stars' would only be revealed when precise source positions were available, and given the geographical circumstances at Dover Heights (and adjacent coastal New South Wales sites), this was an insurmountable challenge.

Bolton and Stanley's solution was to seek a location where the risings *and* settings of the sources could be observed without interruption, and after considering various options in New South Wales they settled on the Northland region of New Zealand (Figure 10). A simple 4-Yagi array operating at 100 MHz was mounted horizontally on an ex-Army radar trailer, and at the end of May 1948 it was shipped to Auckland. For the next three months, Bolton and Stanley carried out sea interferometer observations, first from Pakiri Hill (Figure 11) and later from Piha, near Auckland, at what could be considered RP's two most easterly field stations (for details see Orchiston, 1993; 1994; Robertson et al., 2014). Apart from the advantage of recording rising and setting times, the two New Zealand cliff-tops were considerably higher than Dover Heights (at 279 m, 265 m and 79 m, respectively), and offered horizontal beamwidths of 12° as opposed to 30° at Dover Heights (Bolton and Stanley, 1949). As a result,

> Despite the foul weather at Leigh [i.e. Pakiri

Table 1: Radio sources detected at Dover Heights up to 1 February 1948 (adapted from Bolton, 1948: 141).

Source	Position		Flux at 100 MHz (Jy)	Size	Type
	R.A.	Dec.			
Cygnus A	19h 59m	+41° 47′	6000	< 8′	Variable
Taurus A	05h 13m	+28°	1000	<30°	Variable?
Coma Berenices A	12h 04m	+20° 30′	1500	<15′	Constant
Hercules A	16h 21m	+15°	200	< 1°	
8.48			200		Constant
5.47			300	< 1°	Constant
Centaurus A			1000	<15′	Variable?

> Hill], all the NZ records were of a much higher quality than those at Dover Heights and this had a lot to do with the identifications. Also, in hindsight, custom had corrupted our thinking. Had we constructed the simplest of east-west interferometers, we could have detected Cygnus A much more easily at Dover Heights. (Stanley, 1994: 509).

To illustrate his point, Figure 12 compares Taurus A fringe patterns at Dover Heights and Pakiri Hill, where the fringe amplitude $P_{max} - P_{min}$ is given by:

$$P_{max} - P_{min} = 4P_o \qquad (2)$$

and if

$$P = 2P_o\,[1 - \cos(4\pi h \sin\alpha/\lambda)] \qquad (3)$$

then

$$P_{max} - P_{min} = 2P/[1 - \cos(4\pi h \sin\alpha/\lambda)] \qquad (4)$$

where P is the power received by the antenna, P_o is the power received with the same antenna in space, h is the height of the antenna above mean sea-level, α is the altitude of the source and λ is the wavelength (Bolton and Slee, 1953: 421–422).

Because of these improved fringe patterns the New Zealand fieldtrip was a resounding success, and the observations there provided more precise positions for Cygnus A, Taurus A, Centaurus A and Virgo A. Bolton and Stanley (1949) first wrote up the Taurus A result, noting that the Crab Nebula (NGC 1952) lay within the error box of the source position. Then in a paper published in *Nature*, Bolton et al. (1949: 101) discussed all four sources, reporting that "… three [of these] sources correspond within limits of experimental error to positions of certain nebulous objects." They confirmed the association of Taurus A with the Crab Nebula, an expanding shell of the AD 1054 supernova (see Stephenson, 2004), and linked Centaurus A with NGC 5128, a well-known nebula featuring a distinctive dark 'lane' (Robertson et al., 2010), and Virgo A with M87 (NGC 4486), an unusual nebula accompanied by a conspicuous blue jet. Most astronomers identified these last two objects as extra-galactic nebulae, so it is interesting that Bolton, et al. (1949: 102) used the presence of associated radio sources to question their true nature:

> Neither of these objects has been resolved into stars, so there is little definite evidence to decide whether they are true extra-galactic nebulae or diffuse nebulosities within our own galaxy. If the identification of these objects with the discrete sources of radio-frequency energy can be accepted, it would tend to favour the latter alternative, for the possibility of an unusual object [NGC 5128] in our galaxy seems greater than a large accumulation of such objects at a great distance.

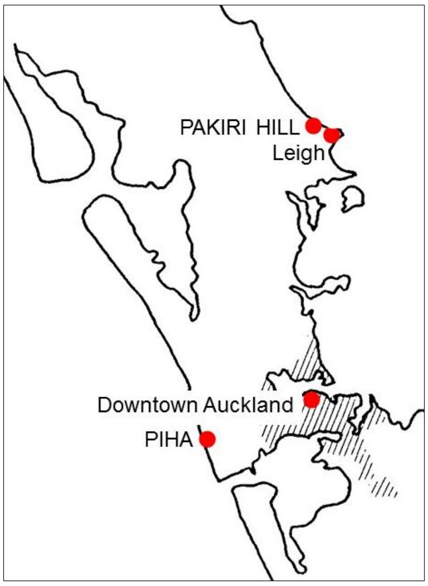


Figure 10: A map showing Auckland city and suburbs (stippled), and Pakiri Hill and Piha, where the RP observations were made (map: Wayne Orchiston).

Figure 11: The mobile radio telescope on the Greenwood farm at Pakiri Hill in June 1948. The cabin mounted on the trailer could swivel in azimuth to observe sources rising at different declinations along the horizon (courtesy: Stanley family).

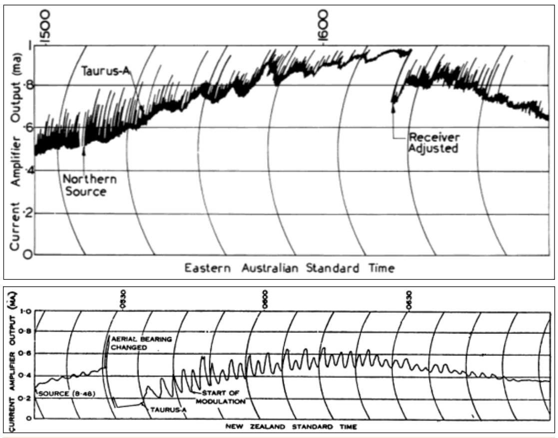


Figure 12: A comparison of Taurus A interference fringes obtained at Dover Heights (top) and Pakiri Hill (bottom) (courtesy: CRAIA, B1651-2; after Bolton and Stanley, 1949: 141).

Redshifts would soon resolve this issue leaving only the identity of the Cygnus A source in doubt, and although the derived New Zealand position of R.A. 19h 58m 14s and Dec. +40° 36′ was an improvement on the Dover Heights value (Stanley and Slee, 1950), it would take several more years and even more precise positions before an optical correlate would emerge (see Bolton, 1955; Robertson et al., 2014). Meanwhile, upon reflection and with the benefit of hindsight, Bolton (1982: 352) would later assert that

> The identification of the Crab nebula was a turning point in my own career and for non-solar radio astronomy. Both gained respectability as far as the 'conventional' astronomers were concerned. (cf. Orchiston and Slee, 2006).

One other interesting outcome of the New Zealand field trip was a resolution of the enigmatic intensity fluctuations that were so conspicuous a feature of Cygnus A (e.g. see Figure 13). While Bolton and Stanley were in New Zealand, Slee remained at Dover Heights and carried out complementary observations. A comparison of their Cygnus A records revealed that the anomalous source variations

> … were not intrinsic to the source but were probably scintillations caused by diffraction in the intervening medium, with the diffraction scale size less than 2000 km (the projected spacing between Leigh and Dover Heights).

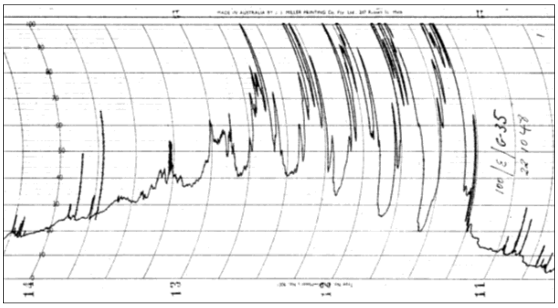


Figure 13: An example of the variable interference fringes exhibited by Cygnus A (courtesy: CRAIA, B1639-2).

> We did not get the opportunity to announce this important result [at the time] because we tried first to enlist the aid of the Cambridge Radio Astronomy group to perform some experiments with baselines up to a few hundred km in order to define the scale size with some precision. Cambridge and Jodrell Bank performed the experiment and published the results (scale sizes were 5-10 km) without acknowledgement. (Slee, 1994: 523).

Many years later, Bolton (1982: 352) mentioned how at the 1950 URSI meeting Bernard Lowell "… very graciously apologised for the form of this publication, for he had not been told of our prior work!" Soon after the publication of the Cambridge and Jodrell Bank papers in *Nature* the initial results of the Dover Heights group appeared in print, where Stanley and Slee (1950) favoured an ionospheric explanation (cf. Bolton et al., 1953).[2] They noted that intensity fluctuations also were associated with a number of other sources, particularly Centaurus A, but that "The degree and incidence of fluctuation … is considerably less than that of the Cygnus source …" (Stanley and Slee, 1950: 246).

After returning from New Zealand and while analysing their newly-acquired data, Bolton and Stanley continued their Dover Heights source survey, with assistance from Slee. Seven new discrete sources were detected during 1948.

3 LARGER YAGI ARRAYS AND THE SEARCH FOR MORE SOURCES

Early in 1949 staff from the RP workshop installed a 9-Yagi array on top of the blockhouse at Dover Heights (see Bolton and Westfold, 1950), which replaced the small 2-Yagi and 4-Yagi antennas that had been used there previously. This new radio telescope (Figure 14) operated at 100 MHz and had a beamwidth of 17°. It comprised three pairs of three Yagis on the one equatorial mounting that could, when required, be readily converted into an altazimuth mounting suitable for sea interferometry observations.

This new antenna was used to survey galactic radio emission between galactic latitudes +60° and –60° and longitudes 140°and 40°, an area of the sky that

> … includes the portion between the galactic centre (*l* = 330°) and Monoceros (*l* = 200°), which cannot be observed from northern latitudes. (Bolton and Westfold, 1950: 19).

Bolton and newcomer to the Dover Heights group, theoretician Kevin Westfold (1921–2001), also were quick to point out that their 100 MHz survey was close in frequency to the earlier surveys carried out by Hey et al. at 64 MHz and Reber at 160 MHz thus enabling

> … a complete picture of the noise distribution over the whole celestial sphere to be constructed. Such a picture will undoubtedly be of

> value in studying correlation between radio-frequency and optical data and possibly in deducing the form of the Galaxy. (ibid.).

While they were indeed able to plot the all-sky distribution of radio emission at 100 MHz (Bolton and Westfold, 1950: 30), from our viewpoint the more interesting outcome of this survey was the discovery of six new discrete sources. As a result, by the end of October 1949 Stanley and Slee (1950) were able to cite 18 different sources detected at Dover Heights between 1946 and 1949. These are listed in Table 2 in chronological order of discovery, and it is illuminating to compare some of the values given here with those in Table 1. This is particularly so of the source fluxes, and also of positions listed for Cygnus A, Taurus A, Virgo A and Centaurus A, where the benefits of the New Zealand field trip are in evidence. However, Stanley and Slee stressed that the positions entered for most other sources were approximate only, and this is borne out by referring to the positional error boxes published in their paper, and reproduced here in Figure 15.

One benefit of the sea interferometer technique is that the interference fringes could provide values or upper limits for the angular widths, *W*, of sources (see the second-last column in Table 2), via formula (1).

A particularly interesting source is 5.47, one of the 1947 sources listed in Table 1, and entered in Table 2 simply as ‘Centaurus’ (it is the first of the two unspecified ‘Centaurus’ sources). Stanley and Slee (1950: 241) discuss its status:

> One example of a possible temporary source is 5.47 … Some 10 records of this source at rising were obtained in November and December 1947. No further records were taken until June 1948, when no trace of the source could be found. Subsequent attempts to obtain records with higher sensitivity have also failed. There have been several other cases when small sources have been detected during systematic surveys—sometimes on several nights in succession—and attempts to secure additional confirmation at a later date have not succeeded … A much longer period of observation, however, will be necessary before the existence of temporary sources can be established beyond doubt.

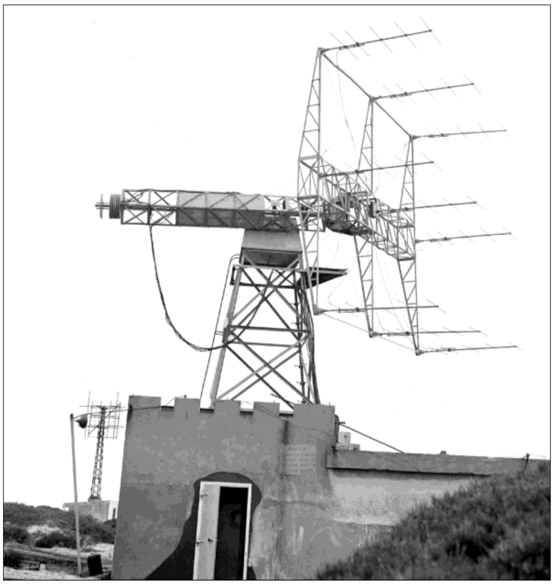


Figure 14: The 100 MHz 9-Yagi array installed on the roof of the blockhouse at Dover Heights in early 1949 and set up in sea interferometer mode (courtesy: CRAIA, B1830-2).

The other interesting discussion in Stanley and Slee's 1950 paper relates to the spectra of the sources. Using observations made at 40, 60, 85, 100 and 160 MHz, they plotted the spectra of Cygnus A, Centaurus A, Virgo A and Taurus A, and these are shown here in Figure 16.

Table 2: Discrete sources detected at Dover Heights as at 4 November 1949 (after Stanley and Slee 1950: 238).

Source	Position		Flux 100 MHz (Jy)	Size (Arc min)	Comments
	R.A.	Dec.			
Cygnus A	19h 58m 14s	+40° 36′	12500	<1.5	Amplitude variations
Taurus A	05h 31m 30s	+22° 01′	1850	< 6	Possibly the Crab Nebula
Virgo A	12h 28m 06s	+12° 41′	1250	< 5	Possibly M87
(Centaurus)			800	< 30	
Centaurus A	13h 22m 20s	–42° 37′	1850	< 7	Possibly NGC 5128
Hercules A	16h 50m	+05°	200	< 30	
Taurus C	04h 38m	+28°	300	< 15	
Taurus B	05h 32m	+24°	600	< 30	
Fornax A	03h 11m	–36°	200	< 15	
Serpens-Cauda A	18h 43m	+05°	300	< 15	
(Centaurus)			200	< 30	
(Leo)	11h 52m	+17°	100	< 30	
Scorpius A			200	< 30	
Serpens-Cauda B	18h 11m	–15°	200	< 30	
Sextans A	09h 55m	–05°	200	< 30	
(Colomba-Caelum)	05h 01m	–36	200	< 30	
Puppis A	08h 18m	–42°	300	< 30	
Pictor A	05h 18m	–44°	300	< 30	

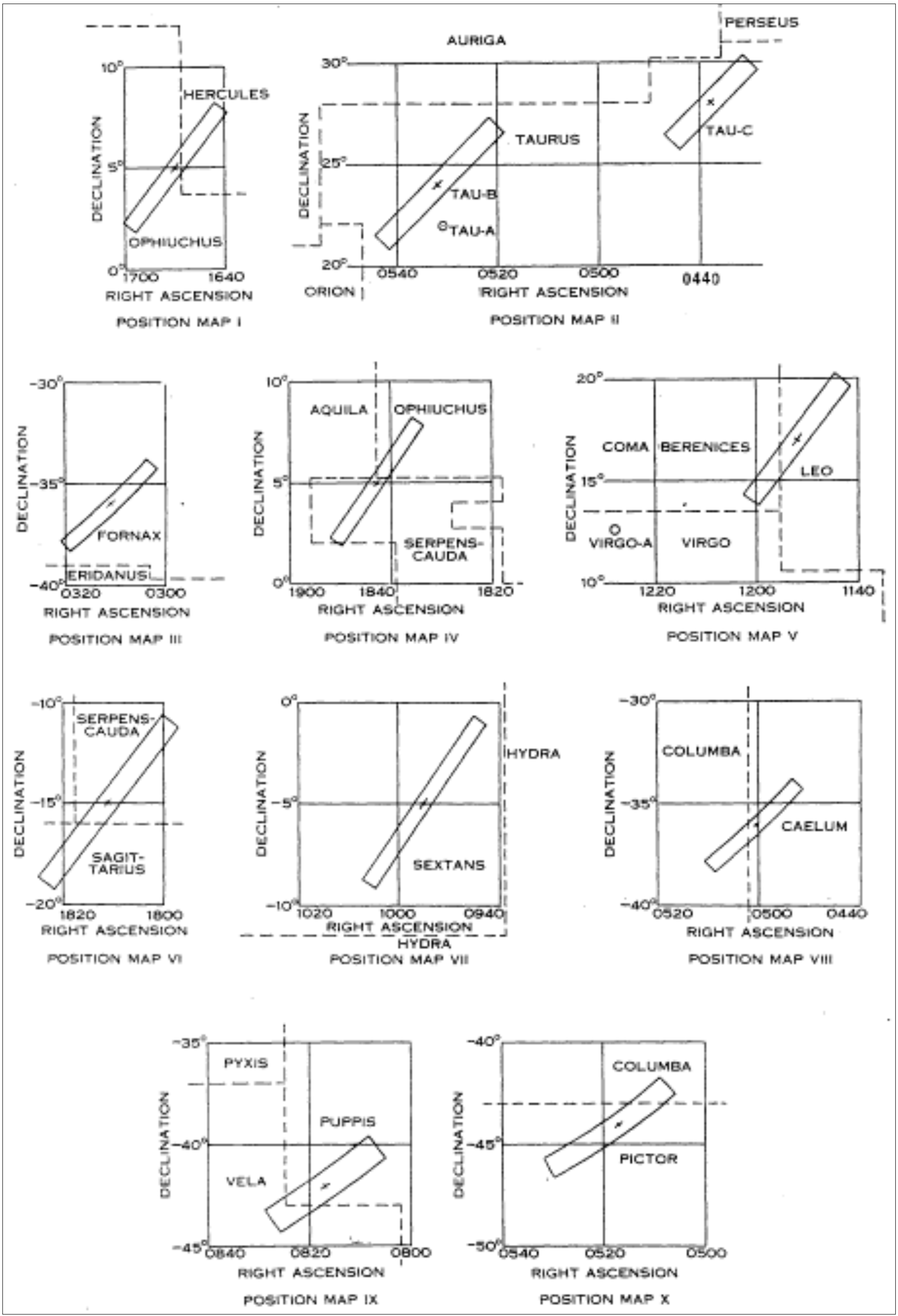


Figure 15: Positional error boxes for those sources listed in Table 2 that were discovered at Dover Heights in 1948 and 1949 (after Stanley and Slee, 1950: 240).

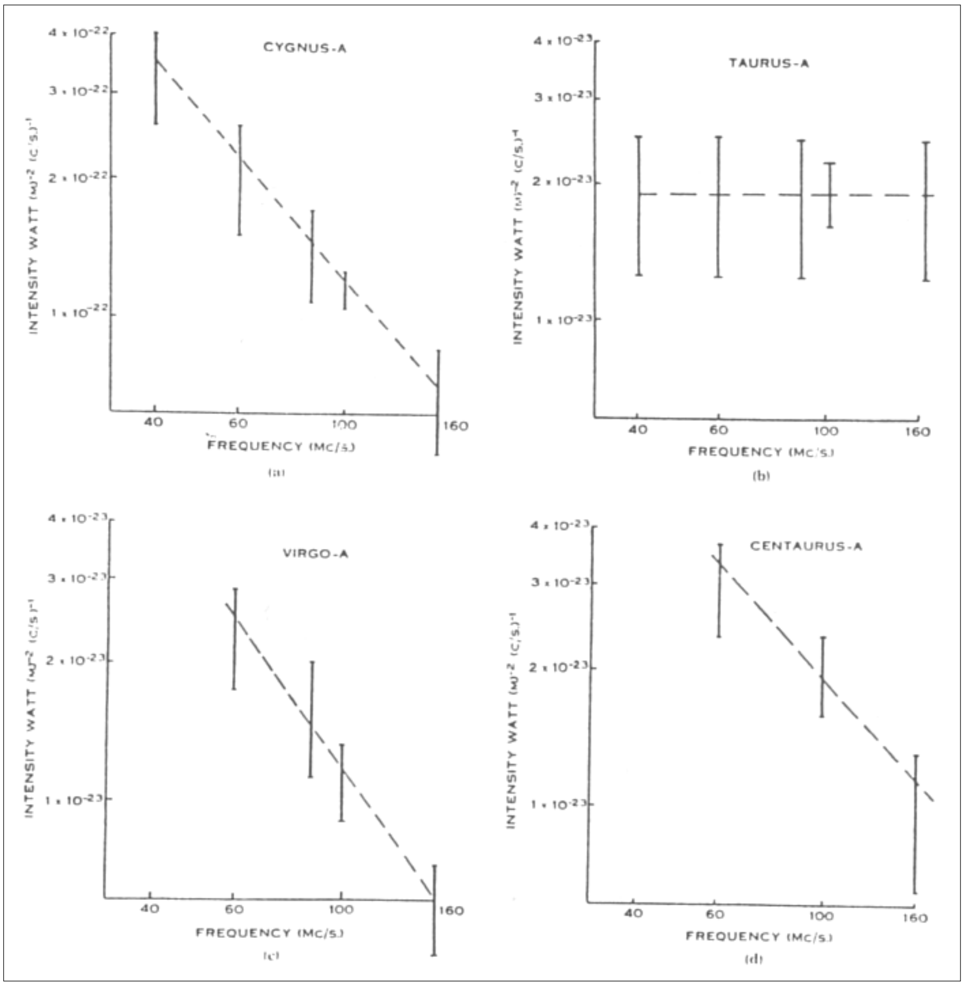


Figure 16: Spectral plots for Centaurus A, Cygnus A, Taurus A and Virgo A (after Stanley and Slee, 1950: 243).

The first three sources display typical non-thermal spectra that are associated with synchrotron radiation, but of course at the time this emission mechanism was unknown to radio astronomers (e.g. see Ginsburg and Syrovatski, 1965). Meanwhile, Taurus A reveals what at the time appeared to be a flat spectrum, "… consistent with "thermal" radiation from an optically thin shell." (Stanley and Slee, 1950: 242). In hindsight, we now know this interpretation to be wrong, and that the four data bars can just as easily accommodate a non-thermal spectrum but with a quite different gradient to that found for the other three sources. This is consistent with the non-thermal emission that is characteristic of a supernova remnant.

John Bolton spent most of 1950 overseas, and Stanley and Slee were left to carry on the radio astronomy at Dover Heights. Slee (1994: 525) continued his "… methodological study of the diurnal and seasonal behaviour of the scintillation phenomenon …" using Cygnus A, Taurus A, Virgo A and Centaurus A, and he and Stanley also constructed a 16-ft (4.9-m) parabolic dish that initially was mounted on the gun-laying trailer used on the New Zealand expedition (Figure 17), and later was relocated to the equatorial mounting on the blockhouse. This instrument was used to observe the stronger sources at frequencies between 100 and 400 MHz (Figure 18) in order to investigate their spectra (Bolton 1982; Stanley, 1994), but no searches for new sources were carried out.

A new source survey only became possible in 1951, after Bolton's return from overseas, when a new 8-Yagi array was constructed by the RP workshop staff, and installed on an ex-WWII radar altazimuth mount at Dover Heights (Figure 17). Soon after, it was extended to a 12-Yagi array, still on the same mount (Figure 19). Nine of the twelve Yagis were cannibalised from the earlier 9-Yagi array. This new radio telescope, which also operated at 100 MHz, was only possible because its "… cost was very small and [it] needed no special budgetary allocation." (Stanley, 1994: 512).

The 12-Yagi array was used during 1951 and 1952 to carry out what would prove to be the last major source survey at Dover Heights, and by far

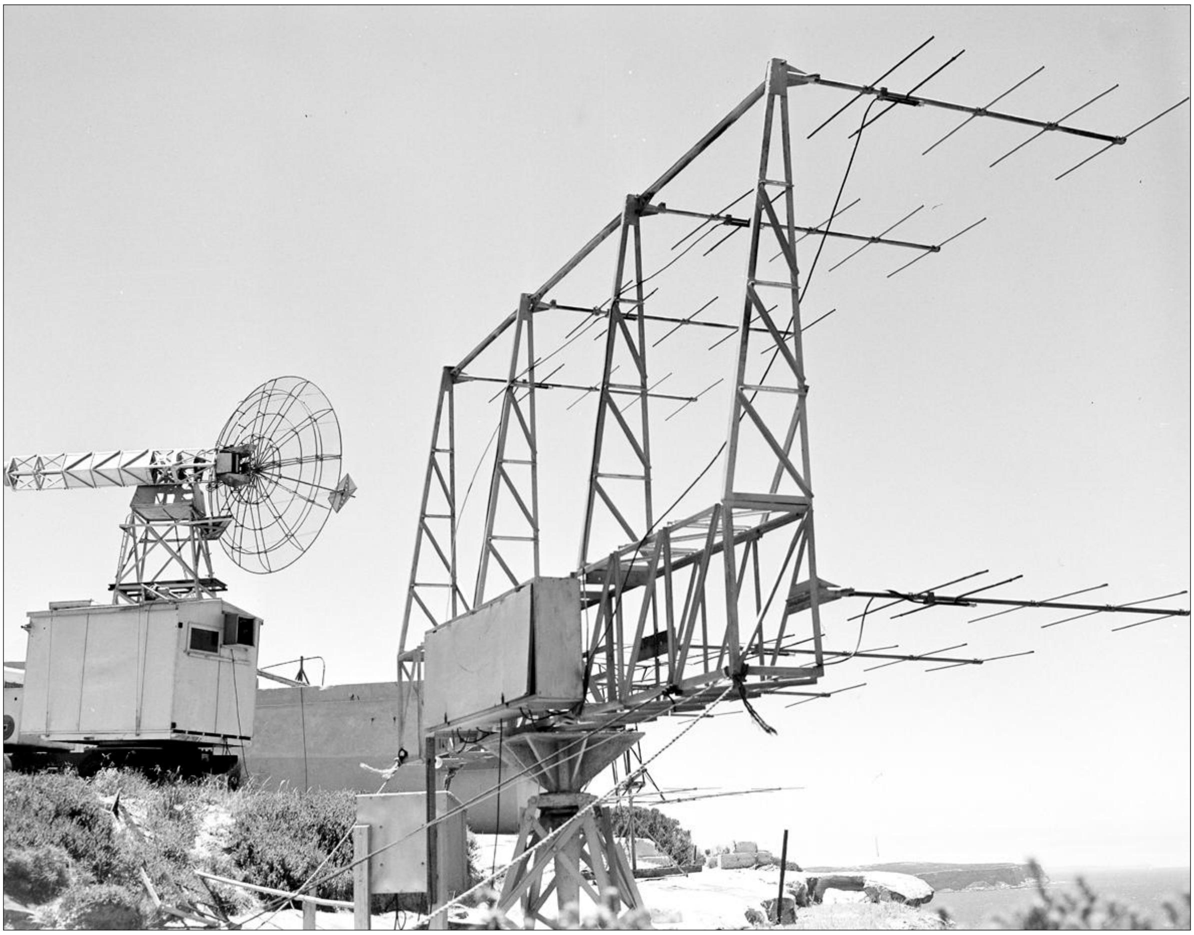


Figure 17: On the left is the 16-ft parabolic dish mounted on the gun-laying trailer and used as a sea interferometer, and in the foreground is the short-lived 8-Yagi array (courtesy: CRAIA B2650-6).

Figure 18: Gordon Stanley with two of the receivers used with the 16-ft parabola (courtesy: CRAIA, B2650-1).

most successful one. With the benefit of improved electronics and a beamwidth of just 12°, this survey produced a total of 104 sources (Figure 20; Tables 3a-3e). However, not all of the reported sources were of equal standing: while those in Tables 3a, 3b and 3c were well established, and Bolton, Stanley and Slee were reasonably confident of those in Table 3d despite some degree of confusion, the 19 sources in Table 3e were not so clear cut. They report that this table

> … contains sources for which a considerable degree of confusion exists in our observations and the particulars given are only reliable provided the observations have been correctly interpreted. (Bolton et al., 1954a: 112).

In hindsight, this level of scepticism was fully justified, for few of these 'sources' appear in the later 85.5 MHz surveys carried out by Mills, Slee and Hill at Fleurs Field Station (see Hill et al., 1958; Mills and Slee; 1957; Mills et al., 1958; 1960).

Another interesting development relating to discrete sources which occurred in 1951 was the construction of a prototype 2-element azimuth interferometer at Dover Heights. Bolton and Slee

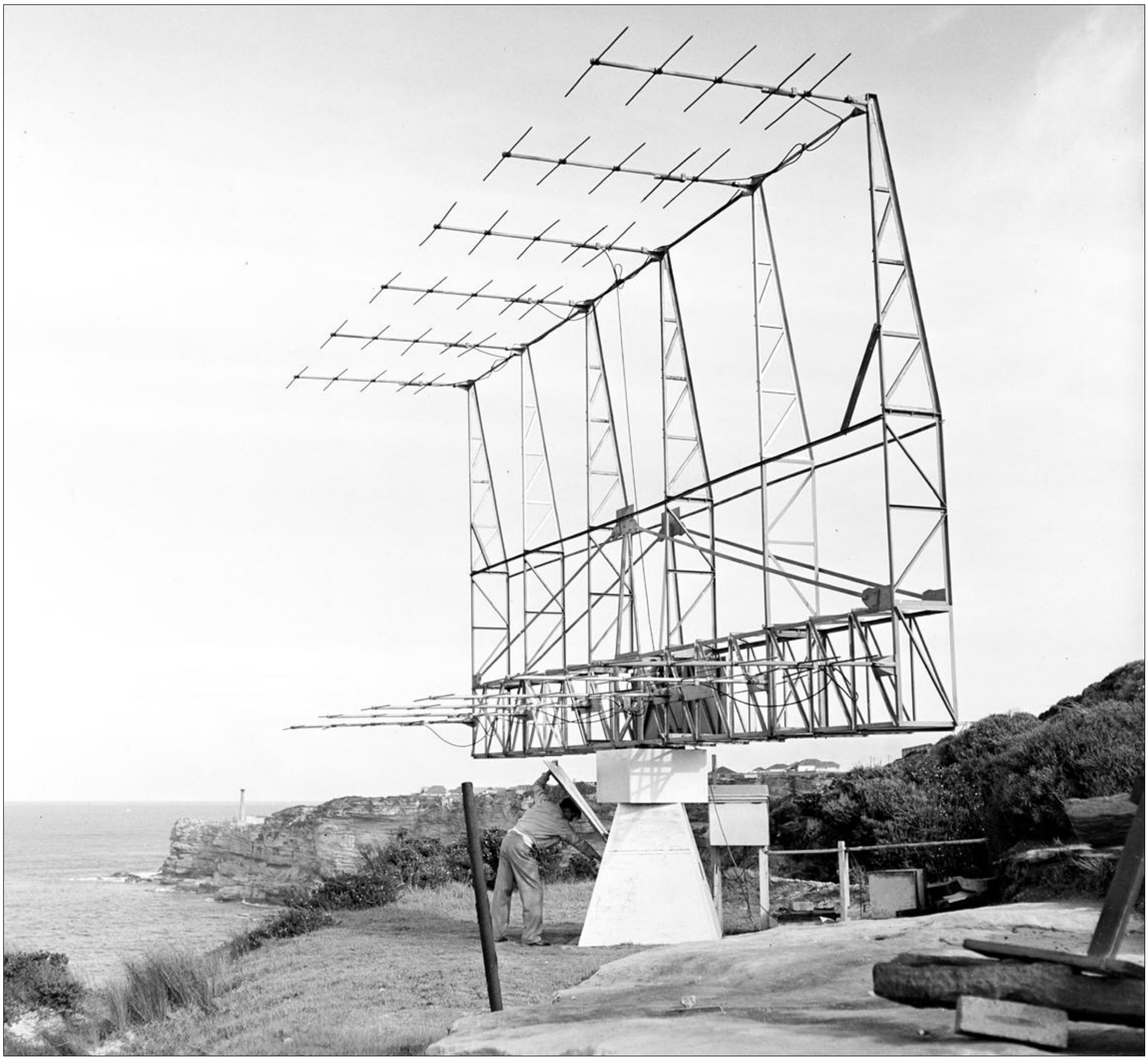


Figure 19: The Dover Heights 12-Yagi array, completed in 1952 (courtesy: CRAIA, B2763-5).

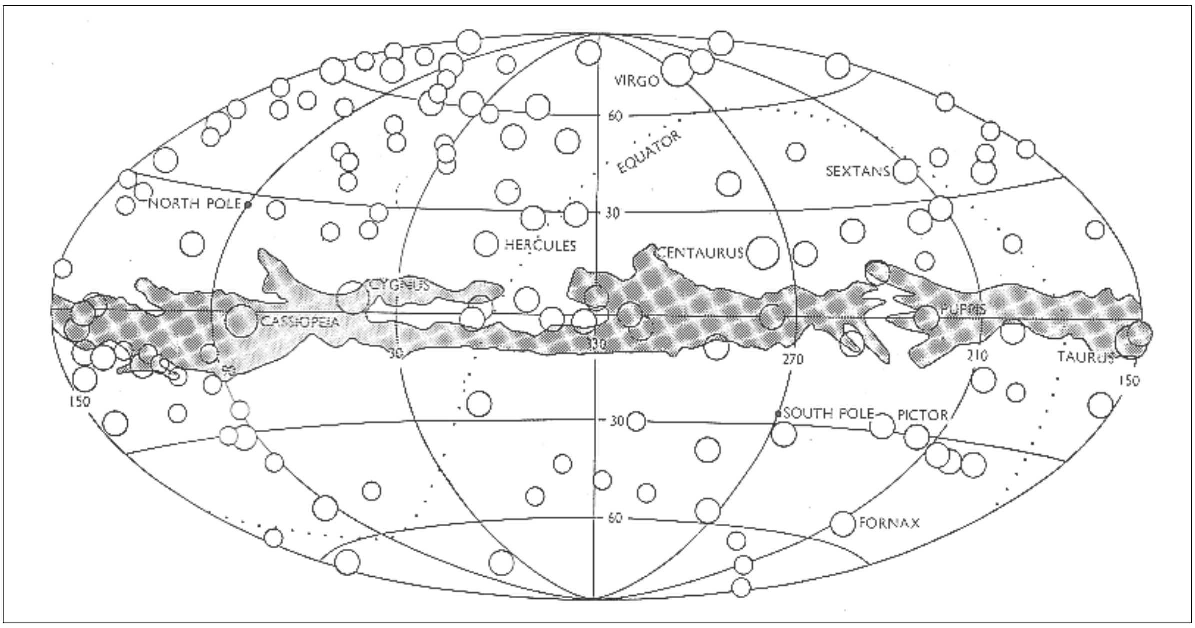


Figure 20: The distribution of discrete sources detected with the 12-Yagi array (courtesy: CRAIA).

Table 3a: Well-known bright sources recorded during the 12-Yagi array survey in 1952 (after Bolton et al., 1954a: 113).[3]

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Numbers	Comments
	R.A.	Dec			
10	03h 17m	–37° 15′	240	M03-3	Fornax-A
2	05h 31m	+22°	1850	M05+2, R05.01	Taurus-A
21	08h 20m	–42° 30′	180	M08-4, S08-4	Puppis-A
26	09h 16m	–12°	280	M09-1A, S09-1	Hydra-A
4	12h 28m	+12° 30′	1250	M12+1, R12.01, S12+1	Virgo-A
6	13h 22m	–42° 45′	1800	M13-4, S13-4	Centaurus-A
7	16h 49m	+06°	400	M16+0, R16.01	Hercules-A
1	19h 58m	+40° 30′	12000	M19+4, R19.01, H.B.19, S20+x	Cygnus-A

Table 3b: Other well-established sources recorded during the 12-Yagi array survey in 1952 (after Bolton et al., 1954a: 114).

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Numbers	Constellation
	R.A.	Dec			
71	01h 56m	–40°	50	M02-4	Phe
97	02h 36m	–03°	50	M02-0	Cet
62	02h 04m	–10°	70	M02-1	Cet
40	03h 09m	+41°	80	M03+4, H.B.6, R03.02	Per
8	04h 30m	+31°	300	M03+4, R04.01	Per
76	05h 08m	+46°	70	H.H.9, M05+4	Aur
22	05h 09m	–43° 30′	250	M05-4, S05-4	Pic
99	08h 08m	–06°	60	M08-0	Mon
86	09h 16m	+46°	70	H.B.12, R09.01, M09+4	Lyn
50	10h 20m	–43° 30′	80	M10-4	Vel
56	11h 38m	–15°	50	M11-1	Crt
28	13h 35m	–60°	700	M13-6, S13-5	Cen
80	15h 10m	+11°	60	M15+1	S Cp
81	16h 36m	+41°	80	M16+4, R16.03	Her
27	16h 10m	–61°	800	M16-8	TrA
120	18h 16m	–08°	150	M18-0	SCd

Table 3c: Sources recorded during the 12-Yagi array survey in 1952 for which no confusion exists, but which have not been documented by other observers (after Bolton et al., 1954a: 115–116).

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Numbers	Constellation
	R.A.	Dec			
35	00h 58m	+15°	70	(M00+1)	Psc
38	00h 40m	–02°	70		Cet
73	00h 11m	–08°	60		Cet
83	00h 23m	–29°	50		Scl
92	01h 38m	+32°	60	(R01.01)	Tri
41	01h 30m	+28°	40	(R01.01)	Tri
95	02h 02m	+15°	50		Ari
53	03h 00m	+03°	90		Cet
39	04h 06m	+10°	60		Tau
69	05h 12m	–25°	70		Lep
52	06h 26m	–06°	70		Mon
70	08h 57m	–25°	70		Pyx
96	09h 51m	+08°	70	(M09+0)	Leo
98	10h 42m	00°	120		Sex
102	10h 07m	–29°	70		Ant
15	11h 42m	+18°	90		Leo
30	12h 19m	+05°	140		Vir
65	13h 08m	+30°	100	(M13+2)	Com
111	13h 58m	–25°	80		Hya
49	15h 30m	+20°	80		SCt
79	14h 05m	+10°	70		Boo
64	15h 58m	+03°	80		SCt
74	15h 20m	–02°	50		SCt
114	16h 44m	–43°	150		Sco
58	17h 44m	–20°	200	M17-2A	Oph

68	17h 43m	–31°	120	M17-2B	Sco
17	17h 08m	–34°	150		Sco
23	18h 45m	+08°	120	M19+0	Aql
11	18h 39m	+02°	270		Aql
48	19h 18m	+16°	200		Aql
75	19h 33m	–17°	80	S19-2	Sag
66	19h 34m	–46°	80	M19-5	Tel
33	20h 00m	+25°	70		Vol
113	20h 57m	–25°	90	S21-3	Cap
63	21h 22m	–20°	70		Cap
89	22h 26m	–05°	50		Aqr
61	23h 30m	–14°	50		Aqr

Table 3d: Sources recorded during the 12-Yagi array survey in 1952 for which some confusion exists, but which are believed to be fairly accurate (after Bolton et al., 1954a: 116).

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Number	Constellation
	R.A.	Dec			
54	00h 56m	+03°	60		Cet
105	00h 27m	–20°	50	S00-1	Cet
57	00h 37m	–40°	70		Phe
107	02h 00m	–25°	50	(M01-2)	For
72	02h 22m	–47°	70		Phe
100	04h 20m	–16°	50	(S04-2)	Eri
91	06h 20m	+36°	60	(R06.01)	Aug
67	06h 41m	–20°	70	(M07-2)	CMa
90	07h 16m	+36°	60		Gem
94	07h 00m	+20°	60		Gem
103	07h 14m	–33°	70		Pup
84	08h 00m	+48°	70	H.B.11, R08.01	Lyn
82	10h 30m	+43° 30′	60	(M10+4)	UMa
87	11h 42m	+31°	100	(M11+3A)	LMi
59	15h 04m	+43°	60	(M14+4)	Boo
44	14h 43m	+30°	60	(M14+2)	Boo
88	17h 45m	+24°	80		Her
55	17h 23m	+20°	70		Her
116	18h 00m	–44°	90		CrA
106	21h 53m	–16°	80		Cap
118	21h 52m	–33°	50		PsA
60	22h 30m	–14°	60		Cap
77	23h 07m	+05°	40		Psc
108	23h 18m	–17°	50		Aqr

Table 3e: Sources recorded during the 12-Yagi array survey in 1952 for which considerable confusion exists (after Bolton et al., 1954a: 117).

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Number	Constellation
	R.A.	Dec			
109	01h 35m	–12°	40		Cet
47	03h 08m	–16°	60		Eri
122	04h. 46m	–30°	60	(M04-03)	Cae
121	05h 48m	–17°	70	(M06-1), (S06-1)	Lep
32	07h 00m	+15°	60		Gem
93	09h 56m	+28°	70		Leo
19	09h 40m	00°	40		Sex
119	09h 08m	–42°	100		Vel
101	10h 46m	–20°	50		Hya
123	11h 00m	–32°	50	(M10-3)	Hya
78	13h 26m	+10°	40		Vir
110	14h 54m	–29°	100		Hya
112	15h 48m	–34°	140		Lup
51	17h 12m	+10°	150		Oph
36	18h 47m	+12°	100		Aql
31	21h 13m	+20°	100		Vul
117	21h 30m	–42°	50	(M21-4)	Gru
45	22h 24m	+04°	50		Peg
115	23h 32m	–29°	50	(S23-2)	Scl

(1953: 431–432) explain the basics of this new system:

> In this system two aerials spaced along the cliff edge are used. The spaced aerials produce a second set of interference fringes at right angles to the normal sea interference fringes. The two aerials are connected to the receiver alternatively in and out of phase, thus switching the azimuth fringe system through half a fringe width. A synchronous rectifier at the receiver output detects only signals due to sources or irregularities in the background distribution smaller than the angular separation of the azimuth fringes.

Figure 21: In the foreground is one of the two Yagi arrays of the azimuth interferometer (courtesy: CRAIA).

One of the two 4-element Yagi arrays is shown in the foreground in Figure 21, and although the two Yagi arrays were just 15-m apart, "To our surprise we recorded a large number of sources … which did not appear on the sea interferometer." (Bolton, 1982: 355). Amongst the sources detected was Puppis A, which Baade and Minkowski were able to associate with a supernova remnant. Although further research was carried out on some of the extended sources, unfortunately no attempt was made to plot the numerous discrete sources that did not show up on the sea interferometer records.

4 THE 'HOLE-IN-THE-GROUND' ANTENNA AND THE 400 MHz SOURCE SURVEY

4.1 Introduction

The sea interferometers used in the aforementioned source surveys offered both advantages and disadvantages (see Stanley, 1994), but if Dover Heights was to remain at the forefront of international research on discrete sources new ways had to be found to increase the resolution of the radio telescopes based there. The alternatives were to develop interferometry further or to construct a radio telescope with a large parabolic antenna. As we have seen the 8-Yagi was constructed at Dover Heights in 1951 and the 12-Yagi array would soon replace it, but in the interim Bolton, Stanley and Slee also decided that they would construct a new antenna of relatively large aperture and innovative design, the so-called 'Hole-in-the-Ground' Antenna, or HitGA (see Orchiston and Slee, 2002c, d).

4.2 The Original HitGA

This was Bolton's brainchild, and was inspired in part by the Jodrell Bank 66.4-m (218-ft) above-ground fixed antenna that was constructed in 1947 and later used with great success by Hanbury Brown and Hazard (see Hanbury Brown, 1984). After the simple Yagi arrays and the small parabolic dish they had previously employed at Dover Heights, the new antenna would not only offer Bolton, Stanley and Slee increased resolution but also a means of escaping the various problems associated with sea interferometers (B. Slee, pers. comm., 2001).

As a lunchtime exercise, in the second half of 1951 John Bolton and Bruce Slee, with some assistance from Gordon Stanley and Kevin Westfold, excavated a 72-ft (21.9-m) diameter parabolic depression in the sand near the cliff top at Dover Heights (Bolton, 1982; Slee, 1994 and pers. comm., 2001). They employed shovels for the excavation work, and a wheel-barrow to dump the spoil round what would become the rim of the antenna. A crude wooden jig was used to approximate the parabolic shape. The excavations took about three months, and when it was finished metal strips from packing cases were stretched across the surface and pegged in place, to improve the reflectivity. A mast supported by guy-ropes was installed at the centre of the dish to carry the dipole, which was connected to a modified ex-WWII 160 MHz receiver (Slee, 1994).

This new radio telescope was completed in late 1951 (Figure 22), and observations were carried out through into early 1952, resulting in a map of galactic radio emission along the galactic plane. The resulting isophote plot clearly showed the Sagittarius A source, now identified with the Galactic Centre (see Figure 23), but at the time this result was not published.

In a bid to improve the resolution and fill a gap in other all-sky continuum surveys a decision was then made to expand the aperture of the antenna to 80 ft (24.4 m) and to use an operating frequency of 400 MHz.

4.3 The Final HitGA

Extending the original antenna involved further excavation (Slee, pers. comm., 2001), and a wooden jig constructed in the RP Workshop was

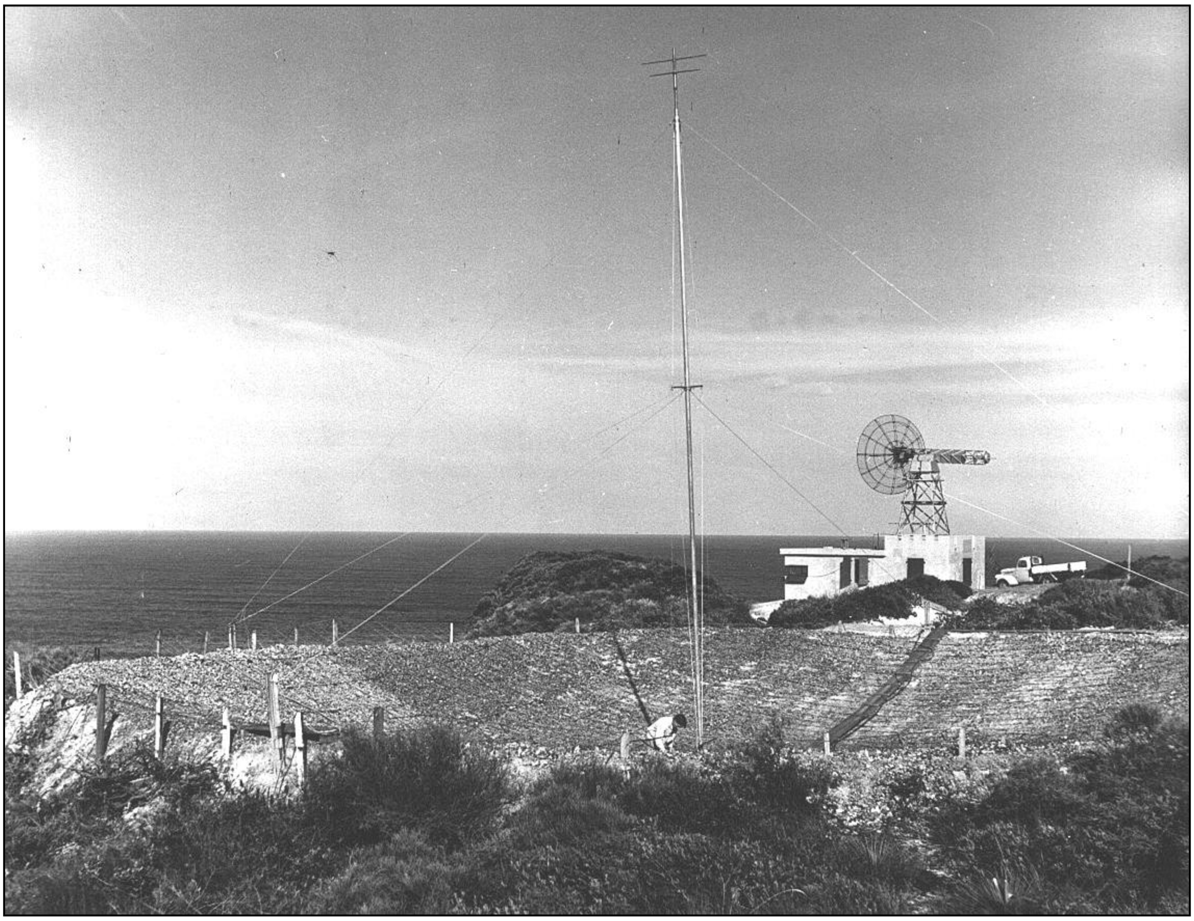


Figure 22: The 72-ft HitGA in June 1952, with the WWII blockhouse and the 4.9-m parabolic dish in the background (courtesy: CRAIA, B 2763-1).

used to finalize the parabolic form of the concrete surface (a photograph of this is included in Bolton, 1982 as Figure 10). The concrete surface was coated with 12.7-mm wire mesh, and the full aperture was only reached by cantilevering the periphery of the expanded dish beyond the rim in-fill using a base of aluminium tubes and annular tension wires (see Figure 24).

A 7.6-cm diameter aluminium central mast was installed to carry a conical dipole and plane reflector, but on this occasion a Dicke switch (which proved particularly troublesome—Bolton, 1982: 356−357) and preamplifier were situated at the very top of the mast. Meanwhile, the second stage of the 400 MHz superheterodyne receiver was located at the base of the mast in a water-tight wooden box (Figure 25) that would float should water accumulate in the antenna after rain (but a plug in the centre of the dish and a drainage system leading towards the cliff edge normally prevented this from happening—Slee, pers. comm., 2001). Connected to this were the detector, an amplifier, and the chart recorder, all of which were located in a small instrument hut adjacent to the southern rim of the dish (Figure 26). Centaurus A served as "… a convenient daily reference for calibrating the overall sensitivity of the aerial and receiver." (McGee and Bolton, 1954: 986).

Construction of the new HiTGA took about six months (B. Slee, pers. comm., 2001), resulting once again in a transit instrument, but this time with a focal length of 12.2 m (40 ft) and an angular resolution of 2°. The position of the aerial mast was maintained by nylon guy ropes, but could be altered in the north-south plane to allow

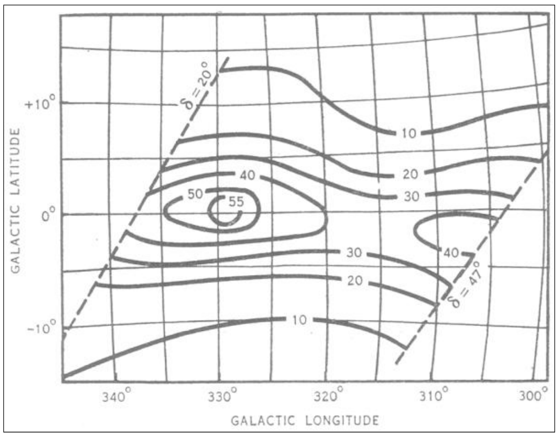


Figure 23: Isophotes of 160 MHz emission obtained with the prototype HitGA, showing the Sagittarius A source (after Bolton et al., 1954b: 98).[4]

Figure 24: The enlarged concrete-coated 80-ft HitGA in September 1953, with Gordon Stanley using a theodolite to record the position of the aerial mast (courtesy: RAIA B3150-2).

strips of the sky adjacent to the zenith to be observed. Whenever the mast was realigned it was important to measure its precise position, and this was accomplished with a theodolite. For this purpose, a platform was constructed adjacent to the western margin of the dish, and this contained position markers for the tripod legs that supported the theodolite. This arrangement is illustrated in Figure 24, taken when Gordon Stanley was busy using the theodolite (ibid.).

The first research project carried out with the new antenna was a survey of part of the southern sky at 400 MHz, modelled on the earlier one achieved with the prototype dish at 160 MHz, and this was to occupy the remainder of 1952 and through into 1953. Most of the observing and data reduction was carried out by a new member of the Dover Heights group, Richard (Dick) X. McGee (1921–2012), assisted from time to time by Bolton, Slee and Stanley who were otherwise engaged in an-all-sky survey at 110 MHz and in a detailed investigation of selected sources using the Dover Heights 12-Yagi array (Bolton, 1982). It also should be mentioned that in mid-1953 Bolton temporarily left radio astronomy when he transferred to RP's Cloud Physics group.

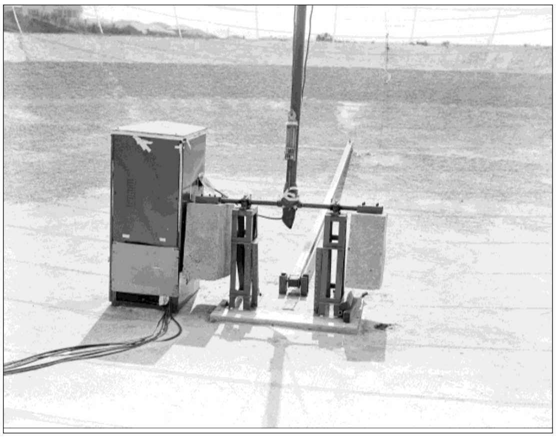


Figure 25: A close up of the water-tight box containing the second stage of the 400 MHz receiver located at the centre of the 80-ft HitGA (courtesy: CRAIA, B3150-5).

The primary effort of the 400 MHz survey

> … was concentrated on the Milky Way in the zone of declinations from –17° and –49° ... The Milky Way was observed on one fixed declination per day, changes in Right Ascension occurring as the rotation of the Earth swept the aerial beam across the sky. In a preliminary survey observations were made at intervals of 1° in declination. Later, in order to cover the more interesting regions in greater detail, intervals of ½° were used. The record obtained at a particular declination was repeated until features of the variation of equivalent temperature with sidereal time were either satisfactorily reproduced or revealed as spurious and discarded. (McGee et al., 1955: 353).

The main account of the survey was published by McGee et al. (1955) in the *Australian Journal of Physics*, but only after an abbreviated version had appeared in *Nature* (McGee and Bolton, 1954).

As Figure 27 illustrates, the most important outcome of this survey was the clear delineation of Sagittarius A, the strong source at *l* = 327.9° and *b* = –1.0° or R.A. 17 hr 42 min and Dec. –28.5° (1950), which McGee, Slee and Stanley correctly identified with the nucleus of our Galaxy. We should note in relation to Figure 27 that in a footnote added when their paper was in press, McGee et al. (1955: 349) pointed out that the conspicuous contour 'bulges' that extend obliquely from *l* = 348°, *b* = –23° to *l* = 341°, *b* = –7° and also from *l* = 318°, *b* = –17° to *l* = 310°, *b* = –3° were not real: they were artefacts generated by the coma that is associated with this type of antenna system.

Earlier investigations had already shown

> … that the contours of radio brightness ascend to a rather broad peak close to the calculated position of the galactic centre. (McGee et al., 1955: 347),

but there was considerable confusion about the location and nature of the radio source and the authors of the HitGA survey were happy to report that their research "… clears up this confusion to a large extent and indicates considerable detail in the fine structure of the Milky Way." (McGee et al., 1955: 348). This is precisely what

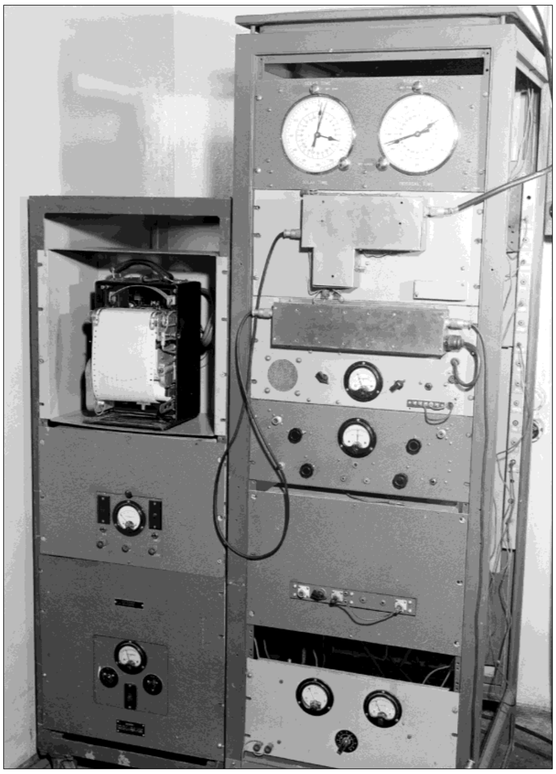


Figure 26: The receiver and chart recorder located in the hut beside the 80-ft radio telescope (courtesy: CRAIA, B3150-4).

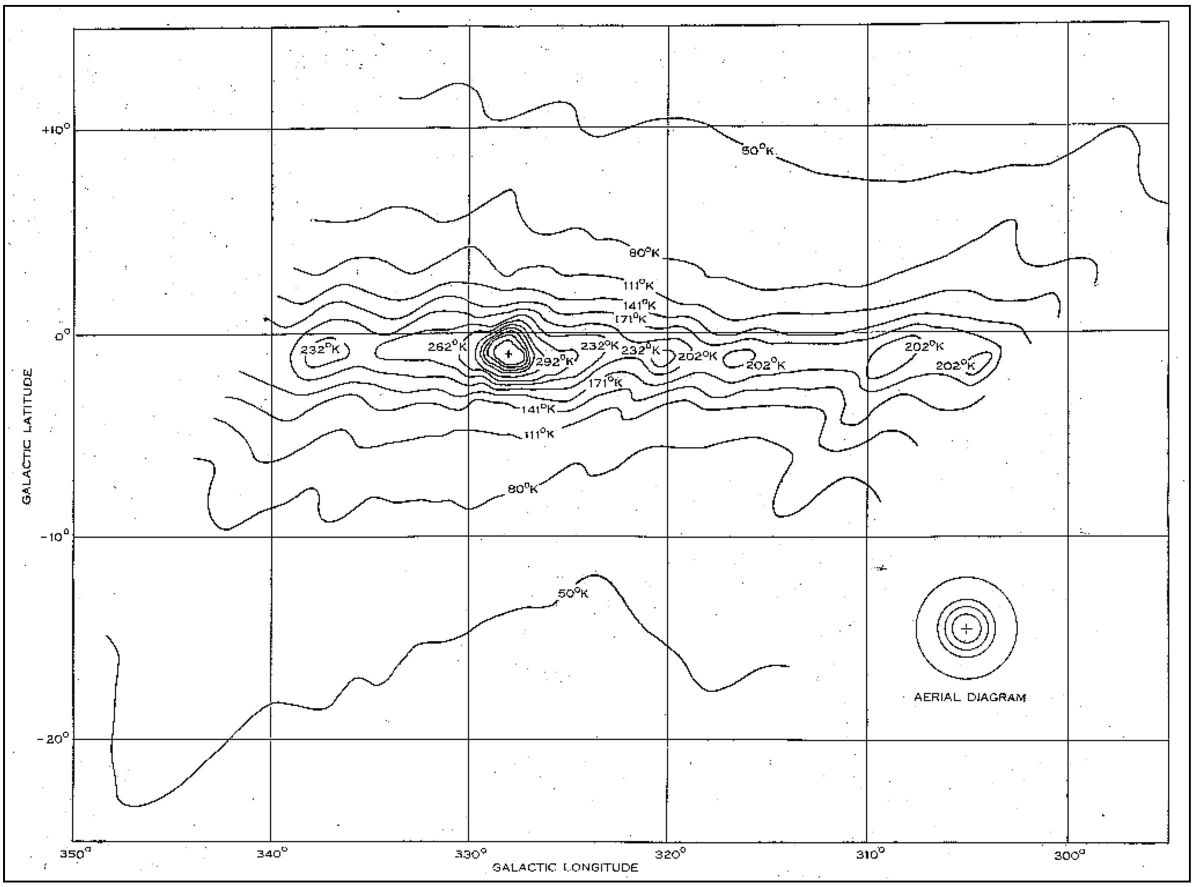


Figure 27: Contour plots at 400 MHz showing the strong emission source associated with the Galactic Centre (after McGee et al., 1955: 356).[4]

Table 4: Discrete sources observed at 400 MHz (adapted from McGee et al., 1955: 359–364).

Constellation	Position (1950)		Flux (Jy)	Notes and Comments
	R.A. (hr min)	Dec. (°)		
Fornax	03 20±1	–37.25 ± 0.5	140	
Pictor	05 09±1 05 16±1	–42.75 ± 0.5 –45.0 ± 0.5	150	Two maxima of approximately equal intensity, slightly spread.
Puppis-Vela	08 24±2 08 35±2	–43.2 ± 1 –45.1 ± 1	150	The first of these is Puppis A and it is superimposed on an extended source with peak intensity at the second position listed.
Antlia	09 59±1	–28.5 ± 0.5	90	Only one observation of this was obtained.
Vela	10 41±1	–43.7 ± 0.5	200	
Centaurus	13 22.5	–42.75 ± 0.1	600	Centaurus A.
Lupus	15 04.1	–30.9 ± 0.5	60	
Ara	16 34±1	–47.7 ± 0.5	230	Associated with an HII region?
Scorpius	17 04±1	–44.4 ± 0.5	260	
Scorpius	17 13±1	–38.1 ± 0.5	330	Associated with an HII region?
Scorpius	17 23±1	–35.0 ± 0.5	510	Associated with an HII region?
Sagittarius	17 42±1	–28.5 ± 0.2	1640	Sagittarius A, associated with the Galactic Centre.
Sagittarius	17 59±1	–21.5 ± 0.5	280	Associated with an HII region?
Sagittarius	18 07±1	–19.6 ± 0.5	360	

Walter Baade would have hoped for when he first suggested this project to the Sydney radio astronomers (McGee and Bolton, 1954). An interesting consequence of this work was that the International Astronomical Union subsequently agreed to adopt the Sydney position of Sagittarius A as the location of the Galactic Centre, thereby re-calibrating the datum point of the galactic co-ordinate system (Bolton, 1982).

Apart from the Galactic Centre result, another important outcome of the 400 MHz survey was the detection of a number of other discrete radio sources. Even though

> … there was not the same attention given to establishing their presence as was given to checking the features in the central region of the Milky Way. (McGee et al., 1955: 359, 362),

this resulted in a list of 14 different sources (see Table 4, which includes Sagittarius A).

As one brief investigation that formed part of the 400 MHz survey, trial polarization measurements were taken in two different areas of the sky, but McGee et al. (1955: 359) found that

> … at regions centred in R.A. 16 hr 54 min, Dec. –42.75° and R.A. 17 hr 55 min, Dec. –23.5° plane polarization of the radiation at 400 Mc/s is less than 2 per cent.

After the 400 MHz sky survey, the HitGA was used for just one further research project: a search for the 327 MHz deuterium line, which would be expected to show up as an absorption feature in the region of the Galactic Centre. In a paper published in *Nature*, Gordon Stanley and a U.S. Fulbright Fellow, Robert Price (1956) reported on their unsuccessful search. This project was carried out in 1954, and employed a receiver centred on 327.369 MHz, with a filter bandwidth of 16 kc/s and a spacing of 48 kc/s between the filters. The observations were made in the area of the Galactic Centre and in the region of the galactic plane at $l = 220^\circ$ by

> … automatically scanning with the receiver through 200 kc/s as the direction of the galaxy passed through the antenna. Such methods failed to detect any radiation. In the later records graphical integration was performed to increase the sensitivity. (Stanley and Price, 1956: 1221).

These latter observations also failed to reveal deuterium emission.

5 DISCUSSION

5.1 The Demise of Radio Astronomy at Dover Heights

The search for the deuterium line spelled the death knell for radio astronomy at Dover Heights, and although Bolton (1982) and Stanley (1994) had plans for other more ambitious antennas there, including a second HitGA that could be used with the first one as an interferometer (B. Slee, pers. comm., 2001), these did not eventuate.

Instead, the focus of RP's non-solar research turned to the Potts Hill (Wendt et al., 2011) and Fleurs (Orchiston and Slee, 2002b; Orchiston et al., 2015: 7–11) Field Stations, and it was at about this time that the RP radio astronomers realized that

> … more and more sophisticated instruments would be necessary. The days of hasty improvisation were over – more and more planning would be required and much more money would be needed for capital expenditure. Little did we realize how large these sums would become. (Bowen, 1984: 96).

Thus, the sea interferometers that had been the mainstay of the Dover Heights field station for much of its existence would soon be replaced by spaced interferometers, grating arrays and cross-type radio telescopes at other RP field stations (see Orchiston and Slee, 2017).

5.2 The Dover Heights Site Today

Radio astronomy ceased at Dover Heights at the end of 1954 (Bolton, 1982), but for a while RP's Cloud Physics group made use of the site. Finally, in 1959, the field station was closed, and most of the site was converted into Rodney Reserve (Figure 28), complete with a football field. From all accounts, the HitGA was simply filled with spoil and then grassed over. Today it lies not far north of the northern goal post, about where the 'N' of RODNEY is located in Figure 28.

Until 2003 there were no scientific relics at Rodney Reserve to serve as a reminder of this site's remarkable scientific past, apart from a rusting mounting near the cliff-top (Figure 29) that originally supported the 8-Yagi array and later the 12-Yagi array (shown here in Figure 17). In 2003, when the first author of this paper was employed as the Archivist and Historian at the Australia Telescope National Facility, one of his projects was to design an interpretive display panel about radio astronomy at Dover Heights and a scaled-down replica of the 8-Yagi antenna that graced the site in 1951 (see Orchiston et al., 2003) and install these at Rodney Reserve, along with a commemorative plaque about the site that already existed (Figure 30). The historic precinct shown as the inset in Figure 28 was officially opened on 20 July 2003 by Professor the Honorable Dame Marie Bashir, Governor of New South Wales, during the Sydney General Assembly of the International Astronomical Union.

During the ensuing 13 years the display panel suffered damage and fading, and in 2017 it was replaced by an updated version (Figure 31) prepared by Dr Jessica Chapman from CSIRO Astronomy and Space Sciences. Meanwhile, the 8-Yagi replica antenna continues to grace the site (see Figure 32), and is a fitting reminder of the amazing scientific contribution that the Dover Heights Field Station made in the early days of Australian radio astronomy.

6 CONCLUDING REMARKS

The Dover Heights Field Station is famous in world radio astronomy. More than any other site it was associated with the discovery of the true nature of 'radio stars'—that they were discrete sources of radio emission, and most of them were at extragalactic distances.

This paper merely provides an overview, and the full drama of the research by John Bolton, Gordon Stanley and Bruce Slee on discrete sources is detailed in the recent biography of Bolton by Robertson (2017) and in a paper by Robertson, Orchiston and Slee that was published in 2014. In that paper, we suggested that the identification of optical correlates for Centaurus A, Taurus A and Virgo A marked

> … an extraordinary development [in astronomy]. The discovery of the two extragalactic objects did not diminish the importance of the *Nature* letter—on the contrary it raised some profound questions. What was the mechanism responsible for this prodigious output of radio energy? If two of the strongest radio sources were distant galaxies could some of the fainter sources be even more distant? Might the fledgling field of radio astronomy be able to 'see' much further out into the Universe than traditional astronomy? (Robertson et al., 2014: 301–302).

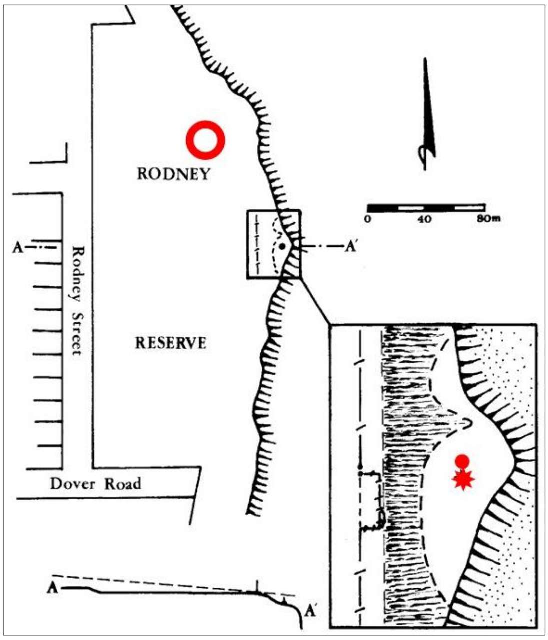


Figure 28: A plan of Rodney Reserve showing the locations of the 80-ft HitGA (red circle, to scale), the rusting antenna mounting (red dot), replica 8-Yagi array (red star) and the 'alcove' in the fence-line with the interpretive display panel and commemorative plaque. The A–A′ transect (bottom left) shows that the replica antenna is invisible from houses located along Rodney Street (map: Wayne Orchiston).

Woody Sullivan (2009: 324) also comments on the seminal place of these observations in the annals of radio astronomy:

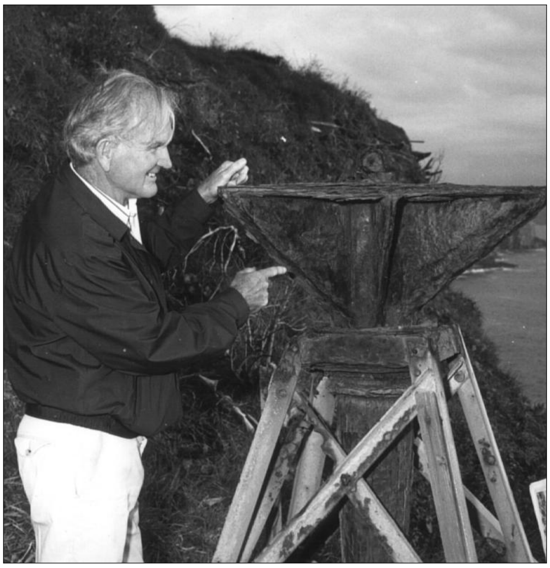


Figure 29: An undated photograph showing Bruce Slee examining the rusting mounting (courtesy: CRAIA).

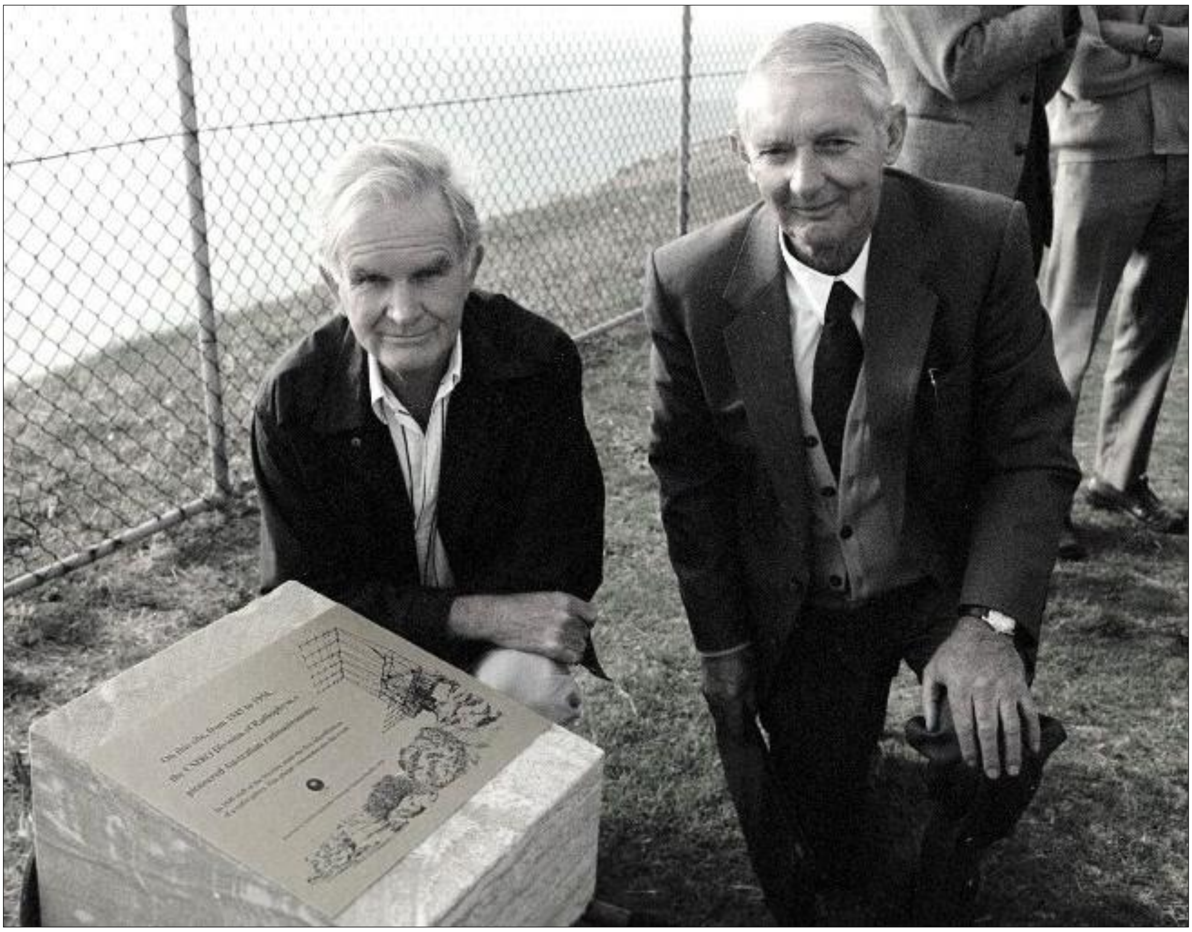


Figure 30: Bruce Slee (left) and John Bolton (right) and the commemorative plaque at Rodney Reserve in 1989 (courtesy: CRAIA, N15506-4).

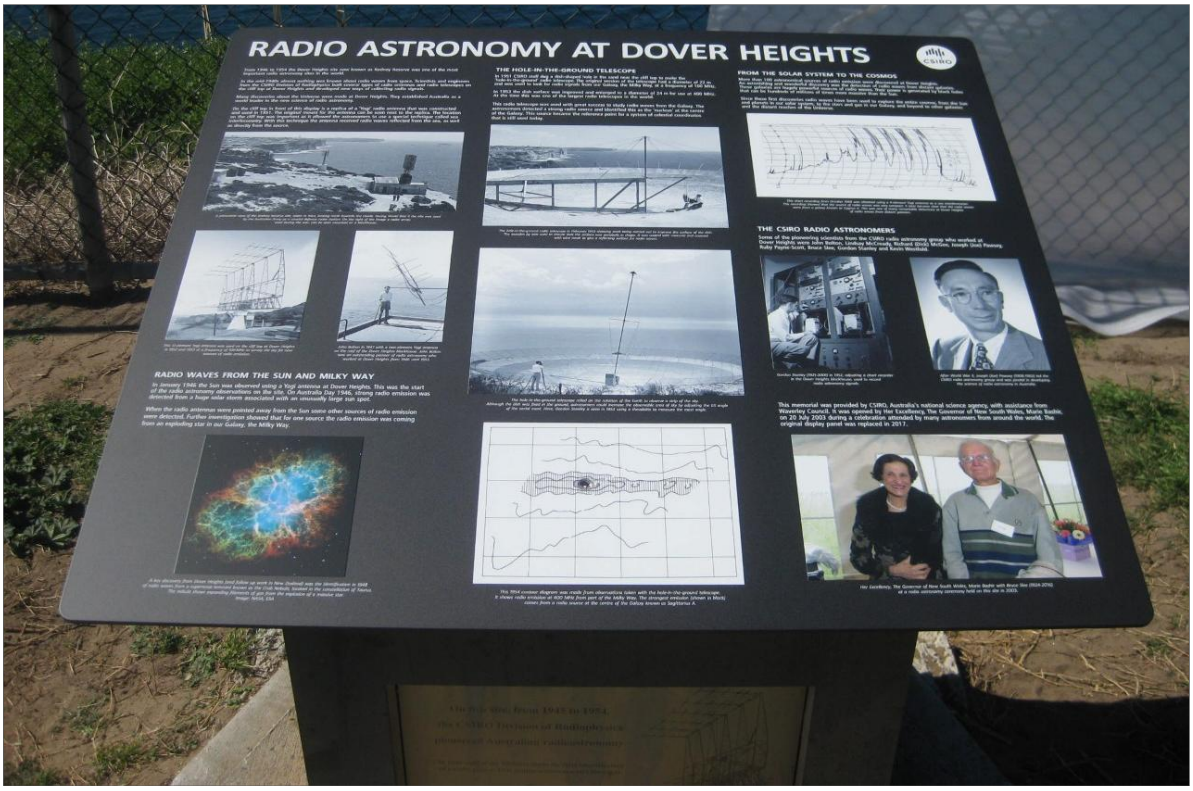


Figure 31: The new interpretive display panel installed at Rodney Reserve in 2017 (courtesy: Dr Jessica Chapman).

> The short paper [in *Nature*] by Bolton, Stanley and Slee (1949) was one of the most important in early radio astronomy, presenting a first plausible link between "galactic noise" and traditional astronomy.

Indeed, we would go further and suggest that although Bolton, Stanley and Slee would go to build international reputations in radio astronomy, none of them "… would produce another paper to rival the importance of their 1949 *Nature* letter." (Robertson et al., 2014: 302).

As we documented in that paper, this research at Dover Heights on the first 'radio stars' launched an ambitious program to detect discrete sources at frequencies from 40 to 400 MHz that would span almost eight years and involve a succession of Yagi arrays and ultimately the remarkable HitGA. Back in 2001 one of the authors of this paper (WO) asked Bruce Slee for his overall assessment of the HitGA, and after pondering a moment he was moved to reply:

> It certainly was a lot of hard work digging it out—all those blisters—but the research output certainly justified the physical input! (Slee, pers. comm., 2001).

This is a fitting reflection on an era long gone (see Orchiston and Slee, 2017; Robertson, 1992; Sullivan, 2009), when ingenuity, dedication and minimal financial outlay could produce significant astronomical results. Today's radio astronomy, with its sophisticated multi-million dollar arrays, is a very different world!

Arguably, one of the most important scientific contributions made by the HitGA to international radio astronomy was to show isophote details of the Sagittarius A discrete source that marks the site of the centre of our Galaxy. Through the paper published in *Nature* by McGee and Bolton (1954) this discovery reached a wide audience but, because of the journal it was published in, the earlier detection of this source by Piddington and Minnett (1951) at Potts Hill Field Station was not so well known. This interesting interplay of personalities, politics and publications is discussed further by Orchiston and Wendt (2017).

In ending this paper we can do no better than to repeat our earlier evaluation of Dover Heights. This field station launched a whole new branch of astronomy, extragalactic radio astronomy, which

> … would revolutionise astronomy in the second half of the twentieth century. The detection of increasingly-distant radio galaxies and then the discovery of quasars in the 1960s led to an expansion in the size of the known Universe by almost two orders of magnitude. Extragalactic radio astronomy revealed a Universe populated by objects undergoing violent, energetic processes on a scale previously unimaginable to 'traditional' optical astronomers. (Robertson et al., 2014: 302).

7 NOTES

1. Dr James Lequeux (pers. comm, December 2017) mentioned that even in 1954, when he began working in radio astronomy, scientists still believed that stars were responsible for most of the radio emission observed in our Galaxy.
2. We now know that the solar wind is responsible for these scintillations.
3. In Tables 3a to 3e (inclusive), in the second-last column, the 'H.B.' sources refer to Hanbury Brown and Hazard, 1953: 125; the 'M' sources to Mills, 1954: 282–287; the 'R' sources to Ryle, Smith and Elsmore, 1950: 514; and the 'S' sources to Shain and Higgins, 1954: 140.
4. Note that positions in this figure are shown in the old galactic co-ordinates.

Figure 32: The rusting old antenna mount (on the left) and beside it the scaled-down replica of the 8-Yagi antenna (photograph: Harry Wendt).

8 ACKNOWLEDGEMENTS

We are grateful to the late Dr Bruce Slee, Dr Jessica Chapman and Dr Harry Wendt (University of Southern Queensland) for providing information and photographs used in this paper; to Dr Wendt and Dr James Lequeux (Paris Observatory) for reading and commenting on the manuscript; and to CSIRO Astronomy and Space Sciences for access to images in the Radio Astronomy Image Archive.

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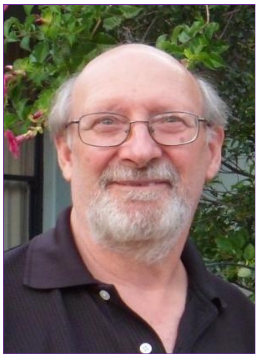

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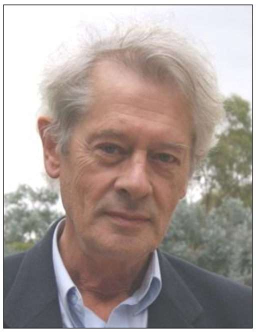

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Wayne Orchiston. He also recently published a full-length biography of John Bolton, titled *Radio Astronomer: John Bolton and a New Window on the Universe* (2017, NewSouth Publishing), which nicely complements his earlier book *Beyond Southern Skies – Radio Astronomy and the Parkes Telescope* (1992, Cambridge University Press).

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THE CONTRIBUTION OF THE GEORGES HEIGHTS EXPERIMENTAL RADAR ANTENNA TO AUSTRALIAN RADIO ASTRONOMY

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Abstract: During the late 1940s and throughout the1950s Australia was one of the world's foremost astronomical nations owing primarily to the dynamic Radio Astronomy Group within the Commonwealth Scientific and Industrial Organisation's Division of Radiophysics based in Sydney. The earliest celestial observations were made with former WWII radar antennas and simple Yagi aerials attached to recycled radar receivers, before more sophisticated purpose-built radio telescopes of various types were designed and developed.

One of the recycled WWII antennas that was used extensively for pioneering radio astronomical research was an experimental radar antenna that initially was located at the Division's short-lived Georges Heights Field Station but in 1948 was relocated to the new Potts Hill Field Station in suburban Sydney. In this paper we describe this unique antenna, and discuss the wide-ranging solar, galactic and extragalactic research programs that it was used for.

Keywords: Australia, radio astronomy, experimental radar antenna, solar monitoring, H-line survey, 1200 MHz all-sky survey, Sagittarius A, 'Chris' Christiansen, Jim Hindman, Fred Lehany, Bernie Mills, Harry Minnett, Jack Piddington, Don Yabsley

1 INTRODUCTION

In 2003 the IAU Working Group on Historic Radio Astronomy was formed, and one of its challenges was to identify and research radio telescopes that made important contributions to radio astronomy prior to 1961. One such Australian radio telescope was based on an experimental radar antenna (Figure 1) that originally was located at Georges Heights Radar Station, overlooking the entrance to Sydney Harbour.

During WWII the Council for Scientific and Industrial Research's[1] Division of Radiophysics (henceforth RP) was involved in the development of radar (Bowen, 1984), and following the war one its main areas of research was radio astronomy.

At the end of WWII Dr Joe Pawsey (1908–1962; Figure 2; Lovell, 1964), the dynamic Head of Radio Astronomy at RP, decided to set up a number of field stations in or near suburban Sydney. By the early 1960s these field stations and associated remote sites had mushroomed in number, eventually totalling twenty-one. Their geographical distribution is shown in Figure 3, which also includes the Radiophysics Laboratory, located in the grounds of the University of Sydney (where high frequency solar and lunar observations were made in the late 1940s). These field stations were a special feature of RP radio astronomy, and one of the reasons for Australian pre-eminence in radio astronomy during the two decades following WWII (see Orchiston and Slee, 2017). For those of us who worked at RP in the early 1960s, the field stations bring back fond memories,[2] and with the close down of the field stations and remote sites following the commissioning of the 64-m Parkes Radio Telescope in November 1961 (Robertson, 1992) the nature of Australian radio astronomy changed forever (see Sullivan, 2017).

The experimental radar antenna that is the subject of this paper started its radio astronomical 'career' at Georges Heights Field Station (site

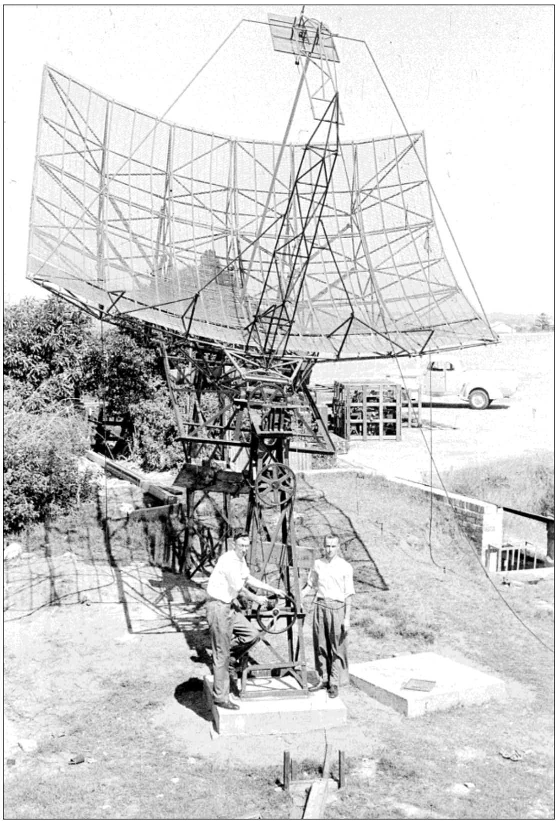

Figure 1: The Georges Heights experimental radar antenna. Posing in the photograph (left to right) are Joe Pawsey and Don Yabsley (courtesy: CSIRO Radio Astronomy Image Archive—henceforth CRAIA, B1031-9).

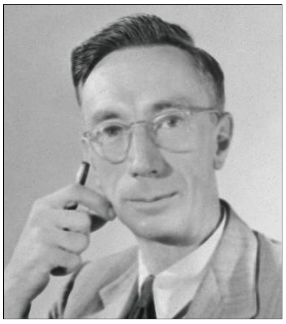

Figure 2: Dr Joseph Lade Pawsey (courtesy: CRAIA).

8 in Figure 3), when this military facility was taken over by RP at the end of the War, but less than three years later it was transferred to the Potts Hill Field Station (site 16 in Figure 3). Let us now examine the role that this historic radio telescope played in international radio astronomy.

2 THE ABORTIVE 1947 SOLAR ECLIPSE EXPEDITION

One of the key challenges for the early researchers was the low resolution of the existing radio telescopes, which prevented the determination of precise positions of the sources of solar radio emission. Some early progress was made by McCready et al. (1947) using a sea interferometer, but it was soon realised that solar eclipses offered a more sophisticated method of establishing the locations of different radio-emitting regions in the solar corona (see Hey, 1955). In 1946, the Canadian radio astronomer, Arthur Covington, used the partial solar eclipse of 23 November to accurately measure the time—hence position projected onto the solar disk—when radio emission at 2,800 MHz was masked by the passage of the Moon's disk (Covington, 1947). Sander (1947) also used this same eclipse to examine the distribution of radiation across the Sun's disk at 9,428 MHz. Although Dicke and Beringer (1946) were the first to observe a solar eclipse at radio frequencies, it was Covington who first showed that strong emission was associated with a sunspot group that was occulted during an eclipse.

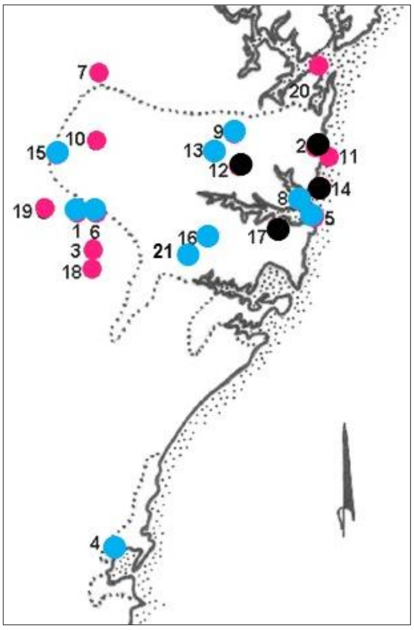

Figure 3: Radio astronomy localities in the Sydney-Wollongong region; the dotted outlines show the current approximate boundaries of Greater Sydney and Greater Wollongong. Key. Field stations: blue; remote sites: red; other sites: black. 1 = Badgerys Creek, 2 = Collaroy, 3 = Cumberland Park, 4 = Dapto, 5 = Dover Heights, 6 = Fleurs, 7 = Freeman's Reach, 8 = Georges Heights, 9 = Hornsby Valley, 10 = Llandilo, 11 = Long Reef, 12 = Marsfield (ATNF Headquarters), 13 = Murraybank, 14 = North Head, 15 = Penrith, 16 = Potts Hill, 17 = Radiophysics Laboratory (Sydney University grounds), 18 = Rossmore, 19 = Wallacia, 20 = West Head, 21 = Bankstown Aerodrome. For scale: from Dapto (site 4) to Dover Heights (site 5), as the crow flies, is 88 km (map: Wayne Orchiston).

These promising results inspired Joe Pawsey to plan RP's first eclipse expedition: to observe a total solar eclipse from Brazil on 20 May 1947. In a proposal from the Chief of the Radiophysics Division, Dr E.G. ('Taffy') Bowen (1946) to the Chief Executive of the C.S.I.R., Dr F.W.G. White, the rationale for this expedition was outlined: a solar eclipse offered an ideal opportunity to measure the apparent diameter of the solar disk at different frequencies. Pawsey (1946c) explained why this was important:

> A quantitative theory concerning the steady component of radiation has now been advanced by D.F. Martyn. This assigns a distribution of intensity over the disc of the sun which changes radically with the frequency of observation. An interesting prediction is that, in the region of 600 Mc/s, the radiation should be intense near the edge of the sun and weak in the centre, so that the sun should appear as a bright ring and not a disc. Such a distribution gives an intensity variation during the eclipse markedly different from that from a disc. The part of the theory dealing with intensity distribution over the surface is as yet unsupported by experiment and it appears that eclipse observations provide a sound method of verification. This quantitative verification is an extension of Bowen's suggested measurement of the apparent diameter of the sun's disc.

This was Radiophysics' first international venture, and was a major undertaking. Despite the cost being around £6,000, the proposal received Government approval on 13 November 1946, and Joe Pawsey, Lindsay McCready (1910–1976) and Don Yabsley were selected as the proposed members of the expedition.

What was needed on short notice was a versatile radio telescope that functioned simultaneously at 200, 600 and 1,200 MHz. The COL radar antennas used at the radar stations around

Sydney were totally unsuited, because they were 'permanent' fixtures, were not capable of tracking the Sun throughout the day, and could not be used effectively over the required frequency range.

Pawsey and others from RP then visited the Georges Heights Radar Station, which occupied an attractive strategic position on Middle Head (Figure 4) overlooking the entrance to Sydney Harbour and during WWII was home to a number of different radar antennas (see Figure 5). After carefully evaluating these, they settled on the experimental radar antenna shown in Figure 1, a 16 × 18-ft (4.9 × 5.5-m) section of a parabola that was on a crude mounting. This could track the Sun—after a fashion—throughout the day, but more importantly, it could operate successfully over the frequency range 200–1,200 MHz.

The idea was to construct 200, 600 and 1,200 MHz receivers for it, and then ship this antenna to Brazil, along with two separate single crossed Yagi antennas that also could make total power measurements, and at the same time measure polarization at 100 and 200 MHz (Pawsey, 1946a).

The radio astronomers at Cambridge University group also planned to send an expedition to Brazil, but upon learning about RP's expedition they decided to cancel theirs (Ratcliffe, 1946). It was only after this occurred that Pawsey's group

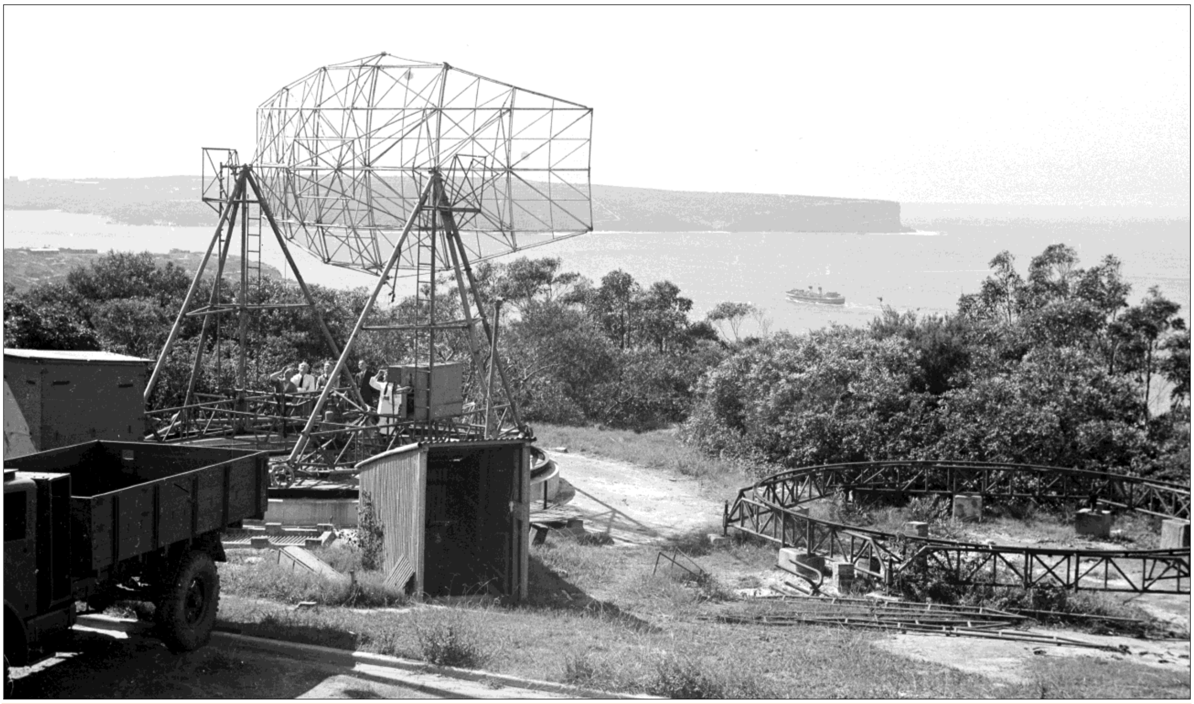

Figure 4: A photograph showing the commanding view of the entrance to Sydney Harbour from the Georges Heights Radar Station. North Head is shown, and below it a Manly ferry. The suburb of Manly is at the head of the inlet on the left, just off of the photograph (courtesy: CRAIA, B2736-3).

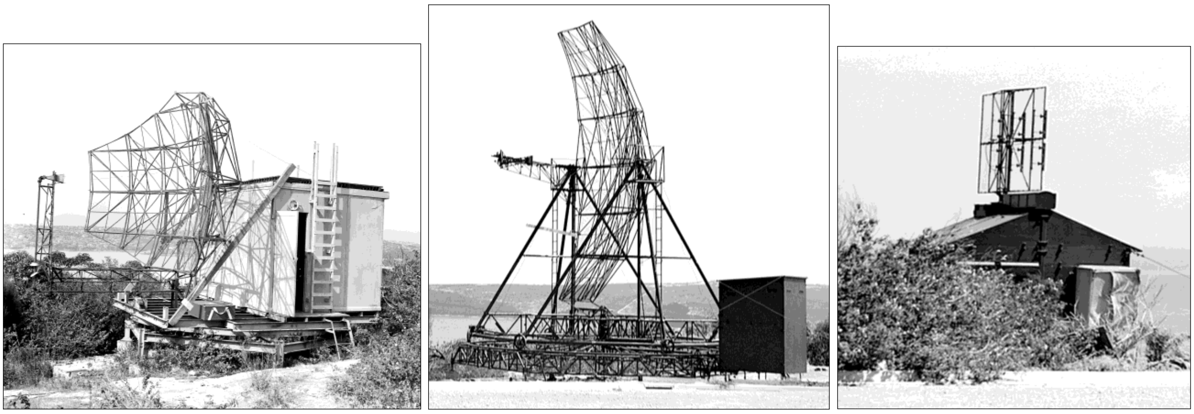

Figure 5: Three of the five different WWII radar antennas at Georges Heights when this radar station was taken over by RP as a radio astronomy field station. The other two antennas are shown in Figures 1 and 4. After a careful evaluation of each antenna—e.g. see the RP staff assessing the antenna in Figure 4—they chose to use the antenna in Figure 1 for radio astronomy (courtesy: CRAIA, B1507-4, B1362).

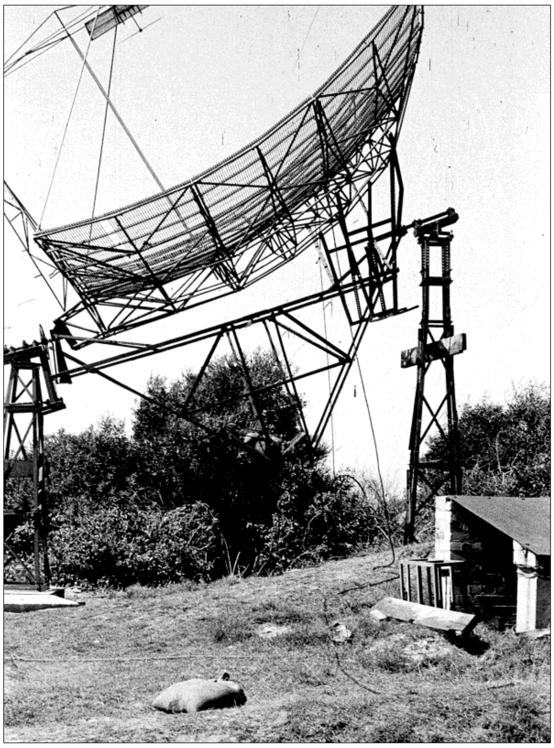

Figure 6: A side elevation view showing the antenna's simplistic mounting (courtesy: CRAIA, B1031-12).

realised that they had seriously underestimated the amount of time required to make the Georges Height antenna operational at three frequencies and get it and the other equipment to Brazil in time. Unfortunately, the 3-ton consignment had to be shipped via London, and the transit time plus delays in customs would see it arrive in Brazil after the eclipse! So in December Pawsey (1946b) reluctantly wrote to Ratcliffe, informing him that the RP expedition had been abandoned, and apologizing for having disrupted Cambridge's initial plans.

For further details of RP's planned Brazil eclipse expedition see Wendt et al. (2008a).

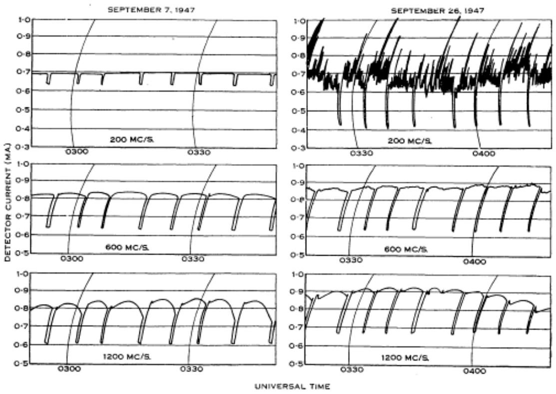

Figure 7: Chart records for 200, 600 and 1,200 MHz obtained at Georges Heights on 7 and 26 September 1947. Note the extensive 200 MHz burst emission on 26 September. The distinctive 'picket fence' nature of the chart record is clearly illustrated in the 600 and 1,200 MHz plots (after Lehany and Yabsley, 1949: 55).

3 SOLAR MONITORING AT GEORGES HEIGHTS FIELD STATION

The regretted cancellation of the Brazil expedition opened the way for RP to convert the Georges Heights facility into a field station—although it would turn out to be short-lived (see Orchiston, 2004b). More importantly, it allowed the experimental radar antenna to be developed as a radio telescope for regular solar monitoring at 200, 600 and 1,200 MHz, thus significantly expanding the frequency-coverage of RP's solar program, which at the time focussed on work carried out at 60, 100 and 200 MHz by Ruby Payne-Scott (Goss, 2013; Goss and McGee, 2009) and Don Yabsley at Dover Heights Field Station.

One major impediment, however, was the primitive mounting (see Figure 6). Because the antenna was not driven, the only way it could be used for solar observations was to place it ahead of the Sun, let the Sun drift through the beam, hand-crank the antenna ahead of the Sun again, and repeat the process throughout the day. This tiresome procedure produced a distinctive 'picket fence' chart record (Figure 7), and although it was far from ideal it would produce useful results. So Pawsey's team decided to live with the existing mounting for the time being, instead of making time-consuming and costly modifications. These would come later—as we shall see.

Joe Pawsey assigned two young RP researchers to carry out solar observations with the Georges Heights radio telescope. They were Fred Lehany and Don Yabsley, and like others in Pawsey's fledgling Radio Astronomy Group they were radio engineers, and had little—if any—knowledge of astronomy (see Sullivan, 2017). Consequently, Pawsey's group studied 'cosmic noise' and 'solar noise', and initially found it challenging to try and reconcile their observations with accepted astronomical theory and practice. They were engineers, not astronomers, and even the term 'radio astronomy' would only be coined in 1948 (Sullivan, 2009). It would then take nearly a decade before optical astronomers began to openly accept their radio colleagues as 'astronomers' (see Jarrell, 2005).

Fred Lehany (1915–1994) was born in New Zealand, and had an M.Sc. degree from the University of Otago, in Dunedin. During WWII he was employed by Amalgamated Wireless (Australasia) Ltd. (AWA), and between 1945 and 1948 he worked at RP as a Senior Research Officer, before transferring to the National Standards Lab—where he eventually assumed the post of Director. Thus, his involvement in radio astronomy research was short-lived, and his Georges Heights involvement

> … came about in a typical 'Pawseyian way', before I knew what was happening … there was an observing program and … Yabsley and I were a suitable pair to share not only the week days but also the weekend duty … (Lehany, 1978).

Yabsley (1986) later pointed out that Lehany's special contribution was

> … the provision of a cavity filter at the input of both the 600 MHz and 1200 MHz mixer receivers, thereby suppressing the unwanted image frequency and higher frequency bands using harmonics of the local oscillator for frequency conversion. Thus each of these receivers was essentially monochromatic and this feature facilitated the achievement of accurate calibration of flux densities. He was also responsible for providing the matched hot loads used to perform the calibration.

Lehany's youthful companion, Donald Yabsley (ca 1922–2003), joined RP as an Assistant Research Officer in 1944 after completing a combined B.Sc./B.Eng. at the University of Sydney, and he worked on the radio-navigation LORAN project (Yabsley, 1978). Immediately after the War he carried out solar observations in collaboration with Ruby Payne-Scott at Dover Heights, and in 1947 he transferred to Georges Heights. There he was responsible for designing and building the triple-feed system (see Figure 8) that allowed the ex-radar antenna to operate simultaneously at 200, 600 and 1200 MHz.

Meanwhile, assisting Lehany and Yabsley between June and August 1947, mainly during the development of the receivers and feed systems and operational testing of the antenna, was a young Technical Assistant named Bruce Slee (1924–2016; Figure 9). Later Slee would establish an international reputation through his work at Dover Heights, Fleurs, Parkes and Culgoora (see Orchiston, 2004; 2005a).

A frequent visitor to Georges Heights during the developmental phase was Lindsay McCready, one of RP's receiver experts, who monitored the development of the three new receivers. Slee (pers. comm., 2002) also recalled that Ruby Payne-Scott and Joe Pawsey were occasional visitors.

By August 1947, the equipment was fully operational (see Figure 10), and in the first instance solar monitoring was carried out for about two hours daily, from 18 August until 30 November. Although a considerable number of short-duration bursts were detected at 200 MHz, these were usually absent at 600 and 1200 MHz. The only notable exception to this general pattern occurred on 4 October 1947, when a conspicuous outburst was recorded at 600 and 1200 MHz and

> … the intensity levels at both frequencies increased to thirty times their normal value and remained high for approximately ten minutes … (Lehany and Yabsley, 1949: 58; cf. Lehany and Yabsley, 1948).

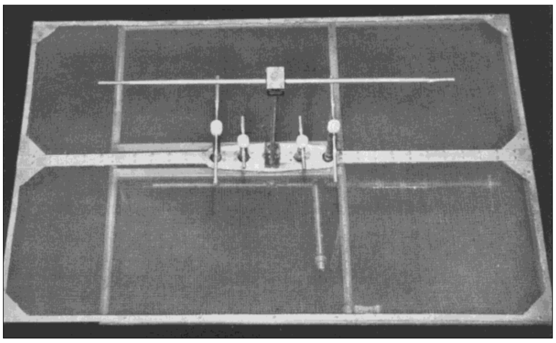

Figure 8: The prime focus assembly showing the different dipoles for 200, 600 and 1200 MHz (courtesy: CRAIA).

Despite the rudimentary state of their astronomical knowledge, Lehany and Yabsley (1949: 60) postulated that the emission at 600 and 1200 MHz was

> … compatible with the thermal radiation expected from the solar atmosphere at these frequencies. It is considered that the variations in intensity … are at least partly due to the magnetic fields of the sunspots raising parts of the effective radiating shells into the corona …

Clearly Lehany and Yabsley were well on the way to becoming astronomers—even though Lehany (1978) later was quick to admit that he had little intrinsic interest in the discipline!

Accompanying the 4 October 1947 outburst was corresponding burst activity at 200 MHz and (on the basis of Dover Heights records) at 60 and 100 MHz (see Figure 11). About twenty-five minutes after the end of the outburst at 600 MHz there was a further period of activity, characterized by a succession of intense bursts of short-duration. As Figure 11 shows, some correspond-

Figure 9: Bruce Slee in 1947, one year after he joined RP as a Technical Assistant. During WWII Slee was a radar technician, and he independently discovered solar radio emission while based near Darwin (courtesy: Bruce Slee).

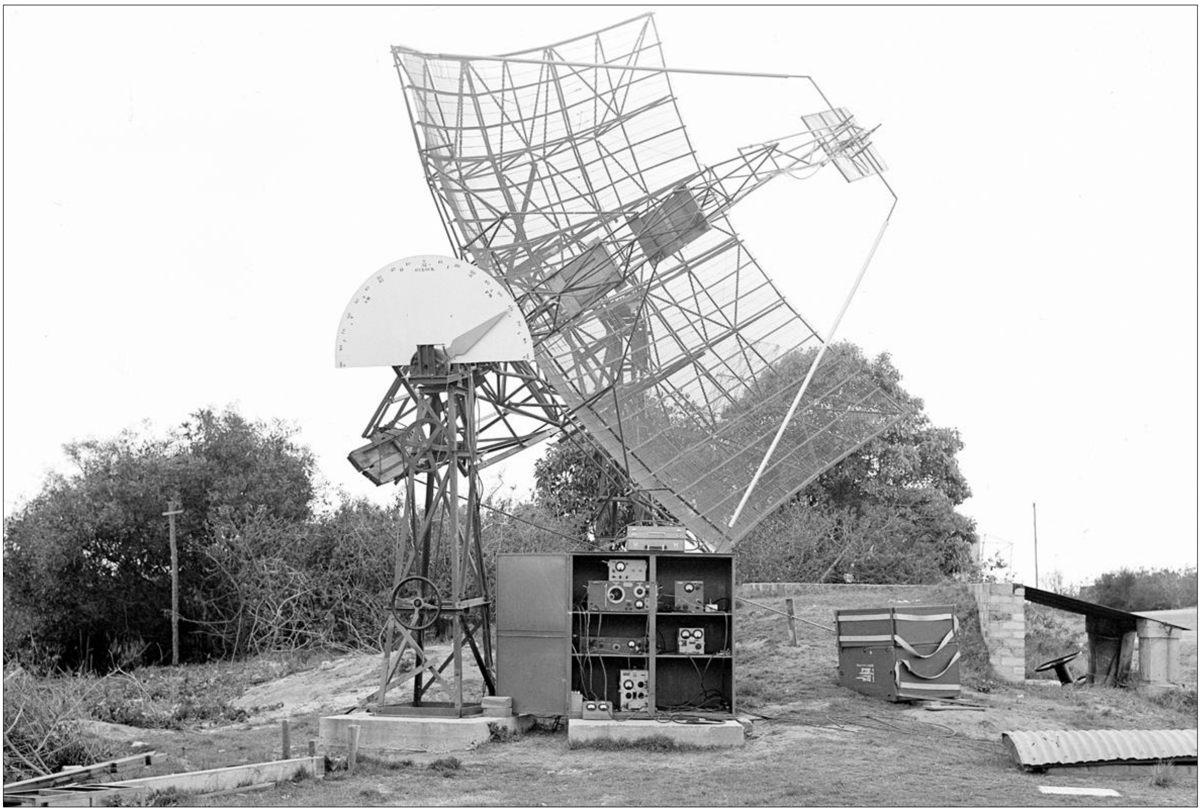

Figure 10: A view of the Georges Heights radio telescope, set up for solar monitoring at three frequencies. Note the large white semi-circular indicator used for tracking the position of the antenna and the newly-installed receiver box adjacent to the antenna. Also obvious is the wheel that was used to crank the antenna ahead of the Sun during observations (courtesy: CRAIA, B1164).

ing burst activity was also recorded at 60 MHz and 200 MHz, but these bursts were conspicuously absent at 1200 MHz. At the time of the initial outburst, the ionospheric recording station at Mt Stromlo recorded a short-wave radio fade-out.

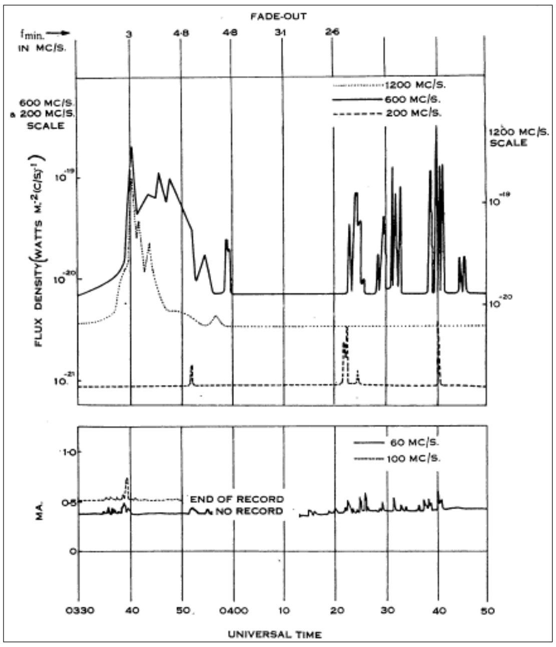

Figure 11: The 4 October 1947 outburst and subsequent bursts at 60, 100, 200, 600 and 1200 MHz. (after Lehany and Yabsley, 1949: 58).

The 4 October 1947 event (now classed as a comparatively rare spectral Type II outburst) was anomalous, and for much of the monitoring period, Lehany and Yabsley (1949: 48) found that

> At 600 Mc/s. and 1200 Mc/s., the received intensity was normally steady on any one day but underwent long-period variations over a range of about two to one. The radiation received when the sun was almost free of sunspots corresponded to an effective black-body temperature of 0.5 million °K [*sic*] at 600 Mc/s. and 0.1 million °K [*sic*] at 1200 Mc/s. As sunspots appeared, the temperature rose and showed marked correlation with sunspot area.

Thus, the general flux variations with time were correlated with sunspot area (see Figure 12).

During mid-1948, the Georges Heights Field Station also was used as a test-base for two portable 10-ft (3.05-m) dishes[3] that would be used to observe the 1 November 1948 partial solar eclipse from Rockbank in Victoria and Strahan in Tasmania. Sadly, this eclipse was the death-knell for Georges Heights as an RP Field Station, for a decision was made to transfer the ex-radar antenna to the Potts Hill Field Station where it would be used to observe the eclipse.

4 THE NOVEMBER 1948 PARTIAL SOLAR ECLIPSE

The Potts Hill Field Station (Figure 13; Davies, 2008; Wendt et al., 2011b) was founded in 1948. It is shown as site 16 in Figure 3, and was located beside Sydney's main water reservoir in what, at that time, was an outer southwestern suburb of Sydney.

Apart from the relocated Georges Heights radio telescopes, by November 1948 the Potts Hill Field Station boasted a single Yagi antenna that was used by Alec Little to observe the Sun at 62 MHz, a 44-inch (1.1-m) solid metal dish with 9,000 and 24,000 MHz receivers relocated from the 'Eagle's Nest' observing precinct atop the Radiophysics Laboratory in the grounds of the University of Sydney, and a 10-ft (3.05-m) wire-mesh dish that later would be employed by for solar and galactic research at 1,210 MHz.

The principal incentive for the consolidation of solar astronomy at Potts Hill was the 1 November 1948 partial eclipse of the Sun. In the late 1940s the angular resolution of radio telescopes was poor, and observations of total and partial solar eclipses offered an elegant way of pinpointing the positions of localized regions responsible for solar radio emission and also of determining the distribution of radio brightness

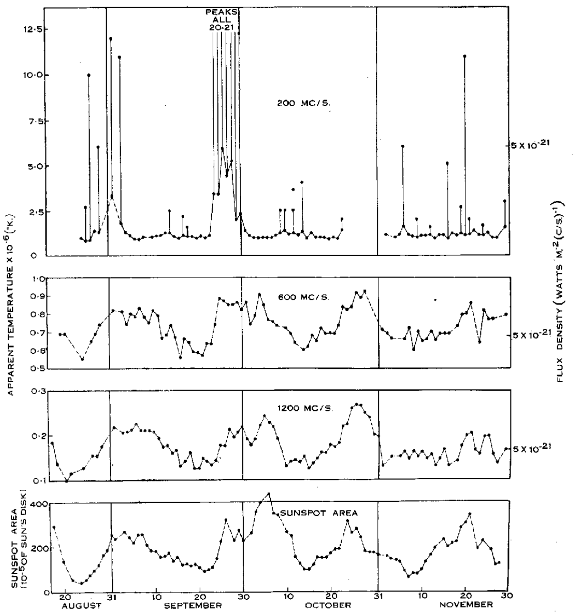

Figure 12: A diagram showing the correlation between solar radio emission at 600 and 1200 MHz (the two middle plots) and total sunspot area (the bottom plot). Burst emission at 200 MHz (the top plot), does not show this correlation (after Lehany and Yabsley, 1949: 56).

Figure 13: An aerial view of Potts Hill water reservoirs, looking south. The Potts Hill Field station was located around the Eastern Reservoir shown in full in this photograph. The ex-Georges Heights radio telescope was located in the flat land in the foreground, and can be seen as the small white square a little left of centre and directly in front of an isolated tree (courtesy: CRAIA, B3253-1).

Figure 14: The refurbished ex-Georges Heights antenna at Potts Hill (courtesy: CRAIA, B1803-5).

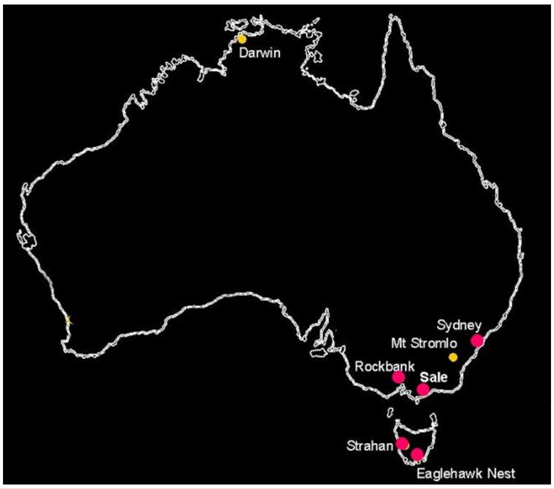

Figure 15: A map showing non-Sydney locations mentioned in the text (map: Wayne Orchiston).

Figure 16: Photographs of the eclipse were taken through the 6-in (15.2-cm) refractor that served as a guide-scope for the 18-in (45.7-cm) reflector (courtesy: CRAIA, B1899-7).

across the disk of the Sun.

The reasoning was that as the Moon's limb moved across the Sun's disk and masked different radio-emitting regions there would be obvious dips in the chart record (Hey, 1955). Covington (1947) was the first to pioneer this technique, in 1946, and the RP radio astronomers were keen to take advantage of the 1948 eclipse, which was visible from Australia.

If there was only one observing site, then any dip in the chart record would simply indicate that the source region was located *somewhere* along the arc subtended by the lunar limb *at that particular moment*, but by using several widely-spaced observing sites the intersections of the different limb profiles allowed the precise positions of the radio-active regions to be determined.

For the 1948 eclipse, the ex-Georges Heights radar antenna—complete with a new equatorial mounting (Figure 14)—was used at Potts Hill, while 10-ft AN/TPS-3 U.S. radar dishes were installed at temporary observing stations at Rockbank, near Melbourne, and Strahan, on the west coast of Tasmania (see Figure 15 for non-Sydney locations). For the States of Victoria and Tasmania, this eclipse represented their very first forays into the exciting new world of radio astronomy (e.g. see Orchiston, 2004d). All three radio telescopes operated at 600 MHz, a frequency where the radio emission was known to be associated with sunspot activity. Meanwhile, photographs taken at the Sydney Technical College's observatory (Figure 16) provided optical coverage of the event (Millett and Nester, 1948).

The observations at the three sites were coordinated by Wilbur Norman ('Chris') Christiansen (1913–2007; Figure 17; Davies, 2009; Frater and Goss, 2011; Swarup, 2008; Wendt et al., 2011a), Bernard Yarnton ('Bernie') Mills (1920–2011; Figure 18; Frater et al., 2013; Orchiston, 2014a) and Don Yabsley. This was the first solar research project conducted by Christiansen, who would go on to establish an international reputation in this field with innovative new radio telescopes (Wendt et al., 2008b) and associated research programs at Potts Hill (Wendt et al., 2008c), and later at the Fleurs Field Station (location 6 in Figure 3). Bernie Mills would build an equally-impressive international reputation by inventing the 'Mills Cross' type of radio telescope, and through his non-solar research on discrete sources, first at Fleurs Field Station and later at Hoskinstown after he left RP and accepted a Chair at the University of Sydney (see Frater et al., 2013).

Successful observations were made at all three sites, and small, but obvious, variations in the levels of solar emission were noted during the eclipse (see Figure 19). Meanwhile, photographs taken in Sydney revealed the presence of six groups of sunspots, but their total area was small, amounting to only ~0.085% of the total area of the visible disk of the Sun.

The radio observations made at Potts Hill, Rockbank and Strahan showed that radio emission from the Sun began to decrease ~10 minutes before the commencement of the optical event (consistent with the idea that 600 MHz radio emission originated in the corona). As the eclipse progressed, the troughs in the declining emission curve indicated that several different localized regions of enhanced solar emission were present, and their precise positions—projected onto the solar disk—are shown in Figure 20.

Calculations indicated that the eight localized regions of enhanced emission shown in this figure contributed ~20% of the total solar radiation received on 1 November 1948. These emitting regions were assumed to be approximately circular, and their areas varied by little more than a factor of two, with a mean of ~0.4% of the total area of the visible disk of the Sun. Their effecttive temperatures varied by more than 10:1, and if we assume a quiet Sun temperature of ~0.5 × 10^6 K at 600 MHz, then the brightest localized regions in Figure 20 (numbers 4 and 6) would have had effective temperatures of ~10^7 K.

Figure 20 shows that peak number 1 was located ~1.7 × 10^5 km beyond the solar limb, and above a magnetically-active region in the chromosphere marked by a conspicuous prominence. All other emission peaks were on the solar disk, and in the case of numbers 2, 7 and 8 coincided with sunspot groups. However, peaks 3–6 did not appear to be associated with any obvious photospheric features, although three of these were close to the positions occupied by sunspot groups exactly one solar rotation earlier. Meanwhile, two small sunspots groups and one large group (near the western limb) were not associated with measurable levels of solar radio emission.

In addition to determining the positions of radio-active regions, the RP radio astronomers also wanted to use the 1948 eclipse to determine whether limb-brightening existed at a frequency of 600 MHz (as postulated by D.R. Martyn in 1946) and see whether radio-emitting regions in the northern and southern hemispheres of the Sun exhibited opposite senses of circular polarization—as also predicted by Martyn.

Unfortunately, the limb brightening investigation produced inconclusive results:

Figure 17 (left): 'Chris' Christiansen in 1952 (adapted from CRAIA B2842-66).

Figure 18 (right): Bernie Mills in 1956 (adapted from a CRAIA image).

> … roughly half the (presumed) thermal component of the radiation originated close to, and predominantly outside, the edge of the visible disk of the sun. The details of the brightness distribution could not be derived from the records. The latter were shown to be consistent with two tentative distributions, the first a theoretical one, involving limb brightening … and the second a uniform one over a disk having 1.3 times the diameter of the optical disk of the

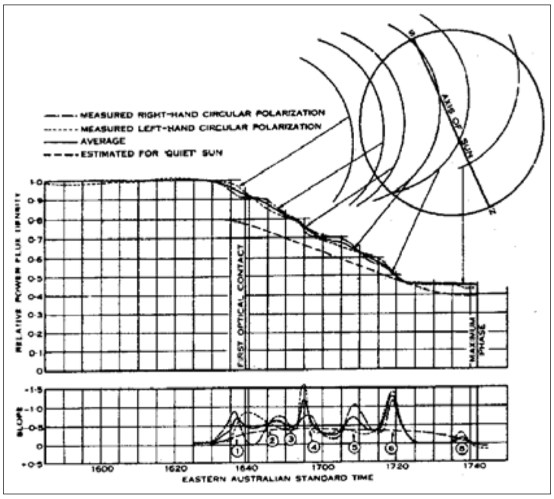

Figure 19: The solar eclipse chart record obtained at Rockbank (upper plot). In the lower plot this has been corrected for the slope and vertically-exaggerated, and the different emission peaks are numbered (after Christiansen et al., 1949a: 511).

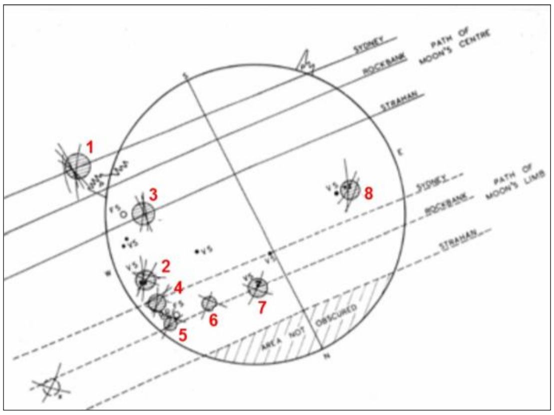

Figure 20: A map showing the distribution of 600 MHz active regions (hatched) during the 1 November 1948 eclipse. The small black dots indicate visible sunspots (VS), P indicates a prominence, and FS marks the position of a sunspot group that was prominent 27 days earlier (after Christiansen et al., 1949: 513; modifications: Wayne Orchiston).

Figure 21 (left): Jack Piddington (courtesy CRAIA).
Figure 22 (right): Jim Hindman in 1952 (courtesy: adapted from a CRAIA image).

> sun. The existence of limb brightening, therefore, was not proved. (Christiansen et al., 1949b: 570).

The polarization analysis proved interesting in that Rockbank was the only site to provide relevant data. Before the eclipse the two modes of circular polarization differed in amplitude by less than 2%, but on 1 November 1948,

> The eclipsing of the active areas produced changes that sometimes were confined to one or other circularly-polarized component, or in some cases involved both components. (Christiansen et al., 1949a: 521).

The changes were of short duration, and the two components quickly returned to equality. This is illustrated in Figure 19, where the most significant variations in the relative levels of left-hand and right-hand circular polarization are associated with active regions 1, 4 and 5. Since the difference in the two polarizations curves was <3% at the maximum phase of the eclipse, this indicated that the general magnetic field strength of the Sun at the poles was <8 gauss. We should note that this is in line with current thinking, but that in 1948 a value of ~50 gauss was assumed. Christiansen, Yabsley and Mills summarized their three-station observations in a letter to *Nature* (1949b) and provided a full account in a paper published in the *Australian Journal of Scientific Research* (1949a).

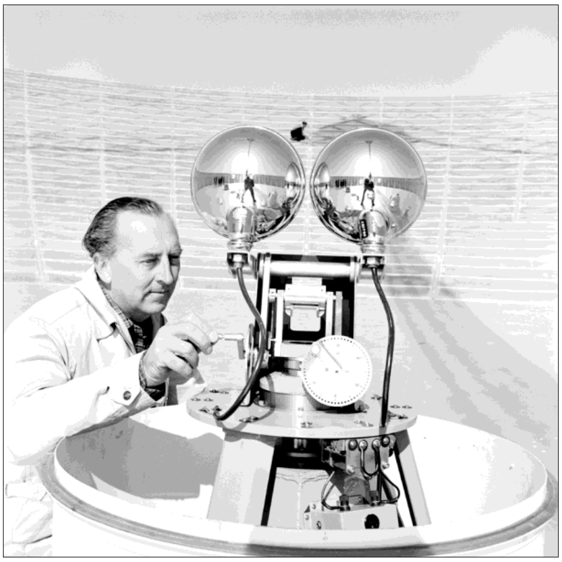

Figure 23: A photograph of Harry Minnett taken more than twenty years after his discovery of Sgr A, testing the surface accuracy of the 64-m Parkes Radio Telescope (courtesy: CRAIA, B7500-2).

Two other small teams of RP radio astronomers carried out observations of the 1 November 1948 eclipse at Potts Hill in conjunction with Christiansen's group. Jack Piddington (1910–1997; Figure 21; Melrose and Minnett, 1998; Orchiston, 2014c) and Jim Hindman (b. 1919; Figure 22) used a 1.7-m (68-in) dish to make observations at 3,000 MHz, while Harry Minnett (1917–2003; Figure 23; Orchiston, 2014b; Thomas and Robinson, 2005) and Norman Labrum (1921–2011; Orchiston, 2011) observed at 9,428 MHz with the relocated 44-inch (1.1-m) Eagle's Nest antenna.

Neither team noticed obvious chart record variations during the eclipse, apart from one dip at 3,000 MHz that Piddington and Hindman associated with active region #3 in Figure 20. However, their eclipse curve supported the existence of limb-brightening, and from their polarization observations they concluded that "… if a general magnetic field exists at all it is considerably smaller than the usually accepted value of 50 gauss at the poles." (Piddington and Hindman, 1949: 534). Minnett and Labrum's observations at 9,428 MHz produced few memorable results, although they did notice that the radio event began seven minutes before first optical contact, which "… could possibly have been caused by a localized emitting region extending from the sun's limb." (Minnett and Labrum, 1950: 69).

We will meet up again with Piddington, Hindman and Minnett later in this paper.

Overall, the 1 November 1948 eclipse observations—led by the ex-Georges Heights radio telescope—were a resounding success. The emission at 600 and 1,200 MHz originated from the corona, and mainly coincided in position with photospheric sunspots or locations where sunspots were present one solar rotation earlier. Circular polarization showed that magnetic fields were implicated, and later RP's leading solar theoretician, Stefan ('Steve') Smerd (1916–1978; Orchiston, 2014d; Wild, 1980) used the 1948 eclipse to establish "… an upper limit of 11 gauss for the surface field-strength at the solar poles at the time of observation." (Smerd, 1950: 265). This figure was significantly lower than the commonly-accepted value at that time.

5 THE OCTOBER 1949 PARTIAL SOLAR ECLIPSE

Flushed with the success of their 1948 eclipse program, the RP radio astronomers looked with

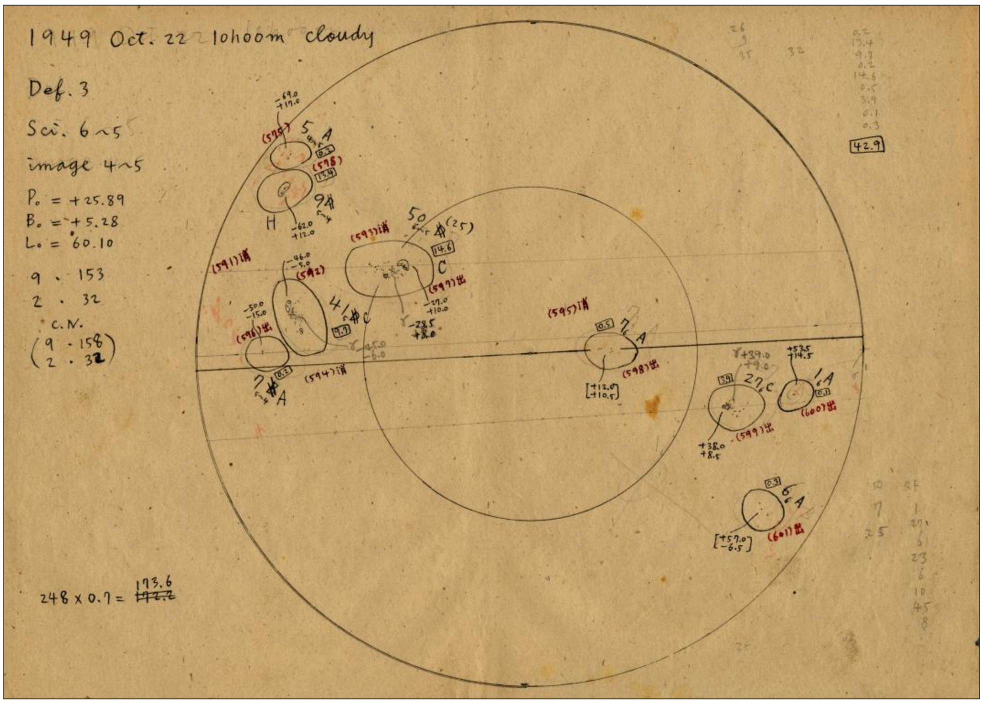

Figure 24: Sunspot observations on 22 October 1949. Note that North is at the top and East is to the right (courtesy: National Astronomical Observatory of Japan).

anticipation at another partial solar eclipse that would be visible from Australia on 22 October 1949. But unlike the 1948 sunset eclipse, this eclipse would begin soon after sunrise.

Once again a multi-site campaign was planed, centred on the ex-Georges Heights Radio Telescope at Potts Hill, while the two portable 10-ft U.S. Army radar dishes were readied for further service interstate, but at locations that offered a clear view of the eastern horizon. One dish was sited in Sale, in eastern Victoria, and the other at Eaglehawk Neck on the east coast of Tasmania, near Hobart (see Figure 15). However, all observations were to be made at 1,200 MHz instead of 600 MHz (as in 1948), and the intention also was to conduct polarisation measurements in order examine further evidence of the existence of a general magnetic field of the Sun (Bowen, 1949b).

In addition, ancillary observations at 60, 100, 200, 600, 3,000 and 4,900 MHz would be made from the Dover Heights, Hornsby Valley and Potts Hill Field Stations (sites 5, 9 and 16, respectively in Figure 3), and from the Eagles Nest (site 17 in Figure 3) on top of the Radiophysics Laboratory (Bowen, 1949c).

As the eclipse occurred early in the morning, the observations would be complicated by ground reflection effects, and in order to allow for these, observations were made in the week leading up to the eclipse and for up to three days afterwards in order to obtain a base set of measurements.

Successful observations were made at all frequencies except 3,000 MHz (Christiansen, 1949) but, strangely, no research papers were published reporting on this second eclipse program. Why was this?

Christiansen (1950) noted that small changes on the eclipse chart records were not as clearly defined as those seen during the 1948 eclipse records, while Bowen (1950) mentioned that because the Sun was rather free of sunspots at the time "… more accurate measurements of the distribution of radio "brightness" across the "quiet" sun were obtained." (ibid.). In a letter to Ryle in Cambridge, Pawsey (1950) also mentioned a "… lack of solar activity …" at the time, again suggestive that sunspots were rare or absent, but in fact nothing could be further from the truth: Carter Observatory in Wellington (New Zealand) sent Bowen (1949d) thirteen photographs of the eclipse that clearly showed the presence of sunspot groups, and a drawing made at the Tokyo Astronomical Observatory confirmed this (see Figure 24).

In our earlier analysis of the 1949 eclipse we concluded the

> Unlike the earlier suggestions, it is clear that enhanced radio emission was observed and correlated with sunspot areas in much the same way as during the 1948 eclipse. The clearest results from the 1948 eclipse had come from the 600 MHz observations, with the higher frequencies showing less definitive results. It seems that at the higher frequency of 1,200 MHz there was also a correlation in

> 1949, but it was much less well defined ... *In our opinion, the most likely outcome was that after the very successful observations of 1948, the 1949 observations provided no 'new' information of sufficient importance to warrant publication*. (Wendt et al., 2008a: 76; our italics).

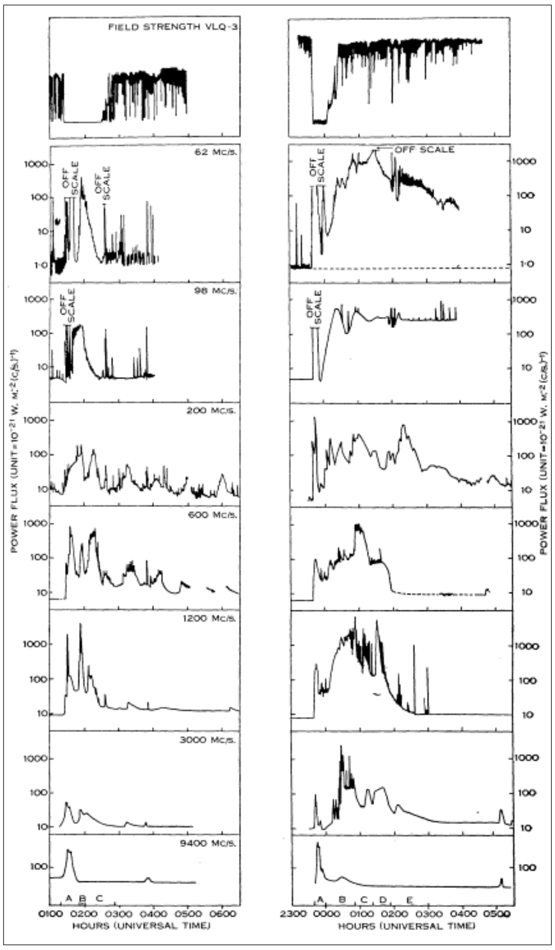

Figure 25: Multi-wavelength plots of two major outbursts, recorded on 17 February 1950 (left) and 21-22 February 1950 (right). The 600 and 1,200 MHz observations were made with the ex-Georges Heights radio telescope (after Christiansen et al., 1951: 53).

6 MULTI-WAVELENGTH SOLAR MONITORING AT POTTS HILL FIELD STATION

During 1949 and through to June 1951, the ex-Georges Heights antenna, Payne-Scott and Little's position interferometer, a 62 MHz Yagi and two small parabolas at Potts Hill were used to simultaneously record solar activity at 62, 97, 600, 1,200, 3,000 and 9,400 MHz, with support monitoring from Mount Stromlo Observatory (Figure 15) at 200 MHz.

The initial publication associated with this project reported on the observation of "… two large solar disturbances …" (Christiansen et al., 1951: 51) that occurred on 17 February and 21-22 February 1950. These are shown in Figure 25. Both events were associated with solar flares, and short-wave radio fadeouts were experienced at the Earth. The 17 February outburst also produced a magnetic crochet, and one was suspected following the 21-21 February outburst.

Later, the analysis of the 400 solar bursts recorded at all frequencies during the 18-month period from January 1950 was assigned to a young RP scientist, Rod Davies, and he also looked at their association with other solar events and with terrestrial magnetic crochets and radio fadeouts.

Davies found that these observations confirmed an earlier discovery, namely that over time intervals of many months variations in the level of solar emission at frequencies above 200 MHz mirrored changes in sunspot area. Many bursts were associated with solar flares and linked to terrestrial effects.

In his analysis, Davies (1954: 90) suggested:

> … there may be two separate components of bursts, one which shows rapid fluctuations and predominates at the lower frequencies, and one which is smooth and is characteristic of the high frequencies (although it may occur at low frequencies also).

He further suggested that these components may be due to plasma oscillations and thermal emission, respectively.

Davies' 1954 research paper was published after he had left RP and joined the Jodrell Bank radio astronomers (Davies, 2009). Like others who received their initial training in radio astronomy at RP and then went overseas, he became a major figure in international radio astronomy. Rodney Deane Davies (1930–2015) advanced from an Assistant Lecturer to become a Professor of Astronomy at Manchester University. He was Director of Jodrell Bank Observatory from 1988 to 1997, and was President of the Royal Astronomical Society in 1987–1989. He was elected a Fellow of the Royal Society in 1992, and was awarded a CBE in 1995 (Professor Rod Davies …, 2015).

7 THE DETECTION OF SAGITTARIUS A AND CYGNUS X

While the ex-Georges Height 16 × 18-ft parabola was being used during the day for the aforementioned solar monitoring project, Jack Piddington (Figure 21) and Harry Minnett (Figure 23), used it at night—in conjunction with one of the 10-ft U.S. radar dishes—to conduct an all-sky survey at 1,210 MHz (Figure 26).

They looked at known sources (e.g. Cygnus A, Centaurus A, Taurus A, and the Moon), and they searched for emission from the Galactic Centre, from M31, NGC 7293 (a large planetary nebula) and from the Andromeda Nebula. The results of their observations were published in the *Australian Journal of Scientific Research* (Pid-

Figure 26: A view of the ex-Georges Heights antenna and on the extreme right the 10-ft U.S. radar antenna used by Piddington and Minnett for their 1,210 MHz all-sky survey (courtesy: CRAIA, B2639).

dington and Minnett, 1951). This is an historically important paper because it includes the discovery at RA 17hr 44m and Dec –30° of what

> … appears to be a new, and remarkably powerful, discrete source … [which] lies very close to the centre of the Galaxy ... (Piddington and Minnett, 1951: 465, 469).

This source (Figure 27) is now known as Sagittarius A, and the discovery isophote plot is shown in Figure 28. Goss and McGee (1996) and Orchiston and Slee (2002b) have discussed the many misconceptions relating to the discovery of Sagittarius A. Although Piddington and Minnett were the first to discover this source and they published evidence of it in 1951, credit for the discovery often is incorrectly assigned (e.g. see Kerr, 1983: 297) to the Dover Heights radio astronomers, John Bolton (1922–1993; Robertson, 2017), Richard Xavier ('Dick') McGee (1921–2012), Bruce Slee and Gordon Stanley (1921–2001; Kellermann et al., 2005). In fact, McGee, Slee and Stanley only detected this source, at

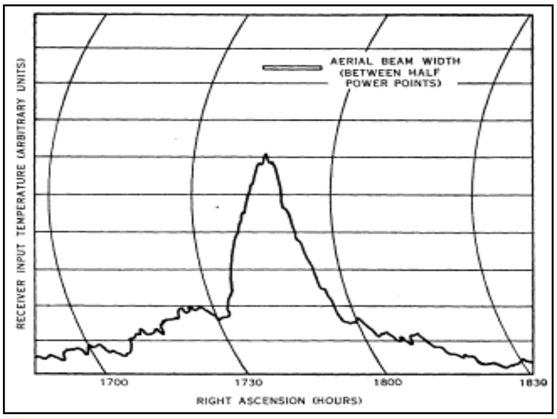

Figure 27: The chart record of Sagittarius A (after Piddington and Minnett, 1951: 463).

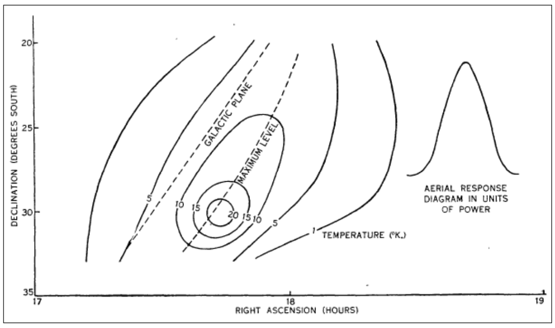

Figure 28: The contour plot showing Sagittarius A (after Piddington and Minnett, 1951: 465).

400 MHz in 1953 using the remarkable 'Hole-in-the-Ground' radio telescope (Orchiston and Slee, 2002b). The isophote plot of this source was first published by McGee and Bolton (1954) in *Nature*, so it quickly reached a wide international audience, while a more detailed account appeared later (McGee et al., 1955) in the *Australian Journal of Scientific Research* (*AJSR*). RP's usual strategy at this time was to quickly send 'letters' to *Nature* announcing important new discoveries, whilst reserving the details for later publication in the *AJSR*. For some reason, Piddington and Minnett's discovery was not publicised in *Nature* (thereby effectively denying them credit for the discovery) whereas the later Dover Heights detection was. It is strange that Dick McGee and John Bolton were the sole authors of the *Nature* paper, because by this time Bolton had already abandoned radio astronomy and was working in the cloud physics and rain-making section of RP. The authorship of the later *AJSR* paper reflects the active research team that was involved in this project. Obviously political considerations came into play in selecting the authors of the *Nature* paper …

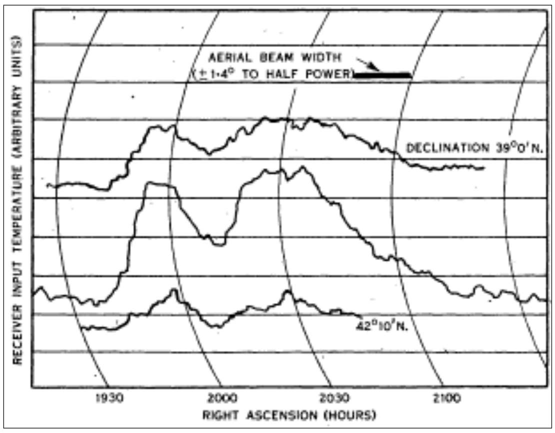

Figure 29: Chart records of Cygnus X at three different declinations (after Piddington and Minnett, 1952: 18).

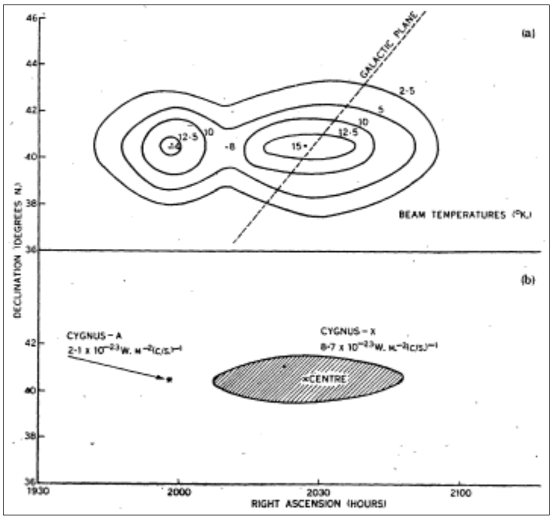

Figure 30: The upper plot shows contours of equal aerial beam temperature at 1,210 MHz. The lower chart shows the derived flux density of the sources Cygnus A and X (after Piddington and Minnett, 1952: 19).

In the course of their 1,210 MHz survey with the ex-Georges Heights antenna Piddington and Minnett (1952) detected a new diffuse discrete source near Cygnus A, which they designated Cygnus X (see Figures 29 and 30). They claimed in their published paper that this may be the first 'radio nebula' to be recognised by associating the strong Cygnus X source with the bright galactic nebulae surrounding the star γ Cygni. They determined that the radio spectrum of Cygnus X was consistent with thermal radiation from ionised gas, unlike the spectrum of Cygnus A.

Piddington and Minnett (1951) investigated three other known discrete sources. However, only Centaurus A could be detected at 1,210 MHz with a flux density of 4.1×10^{-24} W.m^{-2}.Hz^{-1} and an uncertainty of 20%. An upper limit of 1×10^{-24} W.m^{-2}.Hz^{-1} was set for Hercules A and Virgo A. Piddington and Minnett also were unsuccessful in detecting 1,210 MHz emission from the planetary nebula NGC 7293[4] and from the Andromeda Galaxy (M31). At about the same time Hanbury-Brown and Hazard (1950) detected emission from M31 at 158 MHz with an observed flux density of 4×10^{-24} W.m^{-2}.Hz^{-1}. Piddington and Minnett noted that if the spectrum of M31 was similar to our own Galaxy then the flux density at 1,210 MHz would be 2×10^{-24} W.m^{-2}.Hz^{-1}, well below the detection threshold of the ex-Georges Height radio telescope.

8 DETECTION AND OBSERVATIONS OF THE 1420 MHz HYDROGEN LINE

8.1 Introduction

Apart from the detection of Sgr A, arguably the most important research carried out with the ex-Georges Heights radio telescope was observation of the 1,420 MHz hydrogen line (H-line).

Nearly all of the early major discoveries in radio astronomy, including the original detection of cosmic radio emission by Karl Jansky (1905–1950), were serendipitous. Serendipitous discoveries in radio astronomy have been extensively discussed in the literature (see Kellermann and Sheets, 1983). Perhaps the best example of an exception to this phenomenon was the discovery of the 1,420 MHz emission line of hydrogen. As Woody Sullivan (1982: 299) has noted, the prediction of the H-line was remarkable on two counts; both for its scientific prescience and for the conditions under which it was produced. Hendrik Van de Hulst (1918–2000) was a student at the time of the Nazi occupation of Holland and his supervisor from Utrecht University had been interned. Van de Hulst spent three months visiting Leiden (van Woerden and Strom, 2006: 17, Note 2), where under the guidance of Jan Oort (1900–1992) he examined the possibility of radio line emission from neutral hydrogen. In a paper published immediately after the war ended, van de Hulst cautiously noted the possibility of detecting an emission line:

> The ground state of hydrogen is split by hyperfine structure into two levels with a separation of 0.047 cm^{-1}. The spins of the electron and proton are pointed in the same direction in one state and are opposite in the other state. A quantum of wavelength 21.2 cm is emitted due to a spontaneous flip of the spin. (van de Hulst, 1945).

Van de Hulst noted that the transition to the ground state was a forbidden transition and therefore it was necessary to assume a probability for the spontaneous transition to the preferred ground state. Provided that the lifetime of the hydrogen atom in the upper hyperfine-structure level was less than 4×10^{8} years, there was a possibility of detection. He also noted that the sensitivity of radio receivers would need to be improved by a factor of 100 over the 1940s levels of equipment for the emission to be detected.

The actual value of the emission frequency from the spin flip transition to the ground state is 1,420.47 MHz (λ = 21.1 cm) and is due to the hyperfine structure transition being 5.9×10^{-6} eV (Wild, 1952). This is an extremely small energy level when compared (for example) to the Lyman-alpha transition of 10.19 eV which produces an emission at the much shorter wavelength of 122 nm. The probability of transition to the ground state is 2.9×10^{-15} sec^{-1} (~10^{7} years), and is within van de Hulst's original limit.

Joe Pawsey was well aware of the potential that detecting radio spectral lines could provide. He also was familiar with the predicted 1,420.47 MHz hydrogen emission and also the prediction of a deuterium emission line at 237.38 MHz.

It was the American radio astronomy pioneer Grote Reber (1911–2002; Kellermann, 2005) who had alerted Pawsey to the theoretical predictions and to the possibilities of detection during a visit Pawsey made to the U.S. in early 1948. Given the important implications that the detection of a radio-frequency spectral line would bring to radio astronomy, Pawsey alerted the Chief of the Division of Radiophysics, Dr E.G. ('Taffy') Bowen (1911–1991; Bowen, 1987; Hanbury Brown et al., 1992) to this potential in a letter dated 23 January 1948. Pawsey (1948) also included a section titled, "The Search for Atomic Spectral Lines in Noise" in the report that he wrote following his visit to the United States. After a discussion of the potential in the report he concluded:

> The position is therefore quite uncertain. Lamb of Columbia, for example, did not expect we should be able to find lines owing to low probabilities of emission or absorption and "smearing", due to changes due to magnetic fields and so on. (ibid.).

During his U.S. visit Pawsey also visited Harvard and met Oort who was visiting Yerkes Observatory at the time. However, there is no mention of any discussion on the H-line potential with these parties.

Bowen responded to Pawsey's U.S. visit report in a letter dated 18 May 1948. In this he noted:

> This [atomic spectral lines] possibility is certainly an interesting one but, in view of the present state of knowledge, I doubt very much whether we should yet devote a special effort to it. A search for the atomic hydrogen and deuterium lines could be made with the Georges Heights equipment … but this would involve dislocation of other work which is scarcely justified at present. At the moment Harry Minnett is chasing up the references you supplied and we are hoping that Williamson will live up to the promise he made you to let us have a survey of the whole subject. (Bowen, 1948).

The report from Pawsey triggered some activity at RP. In early 1949, Paul Wild (1923–2008; Frater and Ekers, 2012; Stewart et al., 2011b) produced an internal report titled, "The Radio-Frequency Line-Spectrum of Atomic Hydrogen. 1. The Calculation of Frequencies of Possible Transmissions." This report was a comprehensive survey of the earlier theoretical work on the subject, and Bowen noted in a letter to F.W.G. White (Chief Executive Officer of the C.S.I.R.O. and former Chief of the Division of Radiophysics) on 21 March 1949: "There is nothing very original about it but it serves to indicate the direction in which this work might go." (Bowen, 1949a).

White replied to Bowen's letter on the 28 March 1949 and noted:

> I have looked through it [the report] and find that, even to one who is not a spectroscopist, it is relatively easy to follow. The end results are certainly very interesting, and I hope that experimental data can now be found to which

> these can be related. (White, 1949).

As Sullivan (2017) has reported, in 1949 Bernie Mills had considered taking on the H-line search as an independent line of research, but dismissed it as too speculative. John Bolton and Kevin Westfold (1921–2001) had also considered searching for the H-line (Robertson, 1992: 82). They had a copy of a Russian paper translated in an effort to obtain more details, however no search was undertaken. John Murray (pers. comm., 5 August 2007) also recalls that on a number of occasions at meetings of the Solar Noise Group Ruby Payne-Scott proposed a search for the H-line.

Despite this early insight, there was no detection attempt made by the RP Group. Westfold has attributed the lack of an immediate investigation to Pawsey's conservative nature (Robertson, 1992: 82). As late as February 1952, in a meeting of the Radio Astronomy Sub-Committee on Galactic Work, Alex Shain (1922–1960; Pawsey, 1960) raised the possibility of looking for line spectra as part of the group's research efforts. In attendance at this meeting were Pawsey, Bolton, Mills, Minnett, Piddington and Shain. The outcome was recorded in the minutes as: "It was decided, however, not to plan for this as it could be easily fitted into other projects." (Mills, 1951).

8.2 DETECTION OF THE H-LINE

On 25 March 1951, H.I. Ewen (1921–2015) from the Lyman Laboratory at Harvard University detected the 1,420 MHz hydrogen emission line (Ewen and Purcell, 1951) while working on his doctoral thesis.

By a remarkable coincidence, van de Hulst was visiting Harvard at the time and he was able to discuss the detection with Ewen and his supervisor, E.M. Purcell (1912–1997). Van de Hulst indicated that a Dutch group under Oort and C.A. Muller (b. 1924) had been attempting to detect the H-line for some time. By Ewen's own account (2003), he was unaware of the Dutch group's work and had dismissed the possibility of the Dutch actively pursuing a detection attempt because he had interpreted van de Hulst's comments in his original paper as indicating that a detection was highly unlikely. In fact, Ewen thought it likely that his thesis would indicate a negative result. Ewen believed that if anyone would undertake a detection attempt it would be a group from the Soviet Union on the basis of the independent prediction proposed in 1949 by I. Shklovsky (1916–1985) (with which Ewen was familiar).

Also visiting Harvard at this time was Frank Kerr (1918–2000; Westerhout, 2000) from RP. Kerr (1984: 137) was on a fellowship to Harvard University to undertake an M.Sc. in Astronomy and had written to Pawsey on 17 March 1951 (Kerr, 1951a) drawing his attention to the fact that Ewen and Cornell University's Leif Owren (b. 1918) had made unsuccessful attempts to detect the H-line (Kerr, 1951). Owren had used an 8-ft parabola, and a receiver similar to Ewen's but with less sensitivity.

On making the initial discovery Purcell and Ewen shared details of the discovery with the Dutch group and were keen to obtain an independent confirmation of the detection. Kerr (1951b) sent Pawsey an airmail letter dated 30 March 1951 alerting him to the discovery and asking if the RP group could assist in the confirmation, even though no prior work had been done in Sydney. The letter included a hand-drawn sketch of the H-line response on Ewen's receiver. In a letter dated 20 April 1951, Pawsey (1951b) wrote to Purcell saying that because of the "... great potentialities ..." he had assigned two separate groups to attempt the independent detection and they were optimistically hoping to get results "... in a few weeks." He also asked about Purcell's plan to publish the discovery, and suggested that the RP team would privately advise the Americans of any detection and then publish a confirmation note at the same time Ewen and Purcell published their result.

8.3 THE DIVISION OF RADIOPHYSICS CONFIRMATION OF THE DETECTION

In his letter to Purcell, Pawsey had referred to "... two independent groups ..." working on attempting a confirmation. A meeting had been held on 12 April to coordinate the RP activities in attempting a confirmation observation, and in attendance were Pawsey, Arthur Higgs (b. 1904), Piddington, Christiansen, Wild and Bolton. The minutes state:

> It was agreed that parallel investigations to check dectability of lines were desirable in order to obtain independent checks but that, in order to avoid cut-throat competition, the groups who were experimenting in the same field, e.g. Piddington, Christiansen and Wild, should consider themselves, at least on the 1420 Mc/s line, as a single group and possible publication should be joint.
>
> Wild outlined the theoretical results he had obtained (mainly in RPL. 33 and 34). The chief point of interest is the existence of fine-structure lines at 10,905, 3,231 & 1,363 Mc/s with "inherent" line widths of the order of 100 and 20 Mc/s respectively.
>
> It was agreed to recommend Wild to write up this material for publication.
>
> Christiansen and Bolton outlined schemes for attempting to detect the 1420 Mc/s line with which they were proceeding (also corresponding deuterium line). They hope to have equipment for tests to start in a week or so.

Figure 31: The ex-Georges Heights radio telescope at the time it was used for the H-line observations (courtesy: CRAIA, B2649-3).

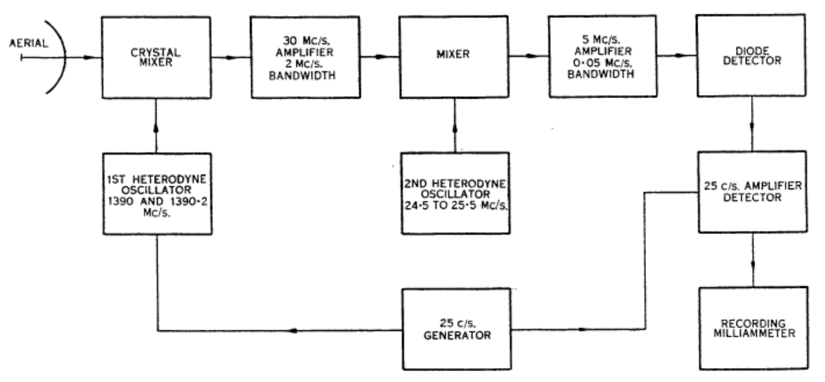

Figure 32: Block diagram of the Potts Hill H-line receiver (after Christiansen and Hindman, 1952a: 439).

> Piddington outlined a different scheme with which he was proceeding. (Pawsey, 1951a).

After a short period, Christiansen took over the leadership of the group, with support from Hindman. It is unclear when Bolton's and Piddington's detection attempts were abandoned. However, later, in 1953–1954, an unsuccessful attempt to detect the deuterium line was made by Gordon Stanley and Robert Price using the 'hole-in-the-ground' antenna at Dover Heights (see Stanley and Price, 1956; cf. Orchiston and Slee, 2002b).

Purcell replied to Pawsey in a letter dated 9 May 1951. He welcomed the efforts of the Sydney group and provided further details of the detection and the receiver equipment. He also indicated that he and Ewen intended announcing their discovery in *Nature* "… fairly soon …", but would allow time for a reply before proceeding. Pawsey replied on 18 May 1951, saying that Christiansen would be, "… attempting the first observations tonight …" and since he (Pawsey) would be away for the next fortnight Christiansen would communicate directly if the attempt was successful, although he noted it would likely take several weeks. He also suggested (Pawsey, 1951c) that Ewen might wish to publish a detailed report in the newly created *Australian Journal of Scientific Research*.

Christiansen and Hindman (1952a: 438) were able to construct a 'makeshift' receiver very quickly thanks to a great deal of improvisation. The receiver was in principle similar to those used by Ewen and by Muller and Oort. Upon coupling the receiver to the ex-Georges Heights antenna (Figure 31), they were able to confirm the detection by the beginning of June.

Figure 32 shows a block diagram of the maj-

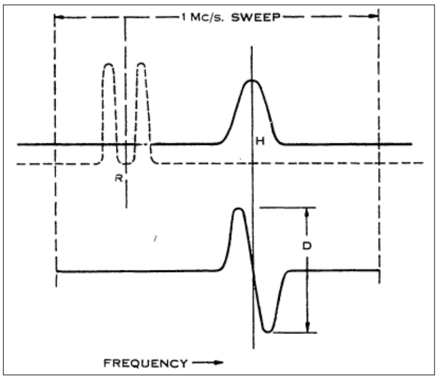

Figure 33: Illustration of H-line receiver operation and theoretical output signal. R = receiver pass-bands, H = H-line signal, D = recorder signal output (after Christiansen and Hindman, 1952a: 440).

or components of the receiver. It consisted of a super-heterodyne receiver with double-frequency change. It had two intermediate-frequency channels. The first operated at 30 MHz with a bandwidth of 2 MHz and the second at 5 MHz with a bandwidth of 0.05 MHz. A second heterodyne oscillator was used to continuously sweep the tuning of the receiver back and forth over a 1 MHz range. The signal from the hydrogen emission-line was detected as a small increase in signal when the pass-band of the receiver swept over the H-line frequency. As the signal increase was very small an additional balancing method was used to improve sensitivity. This was done by switching the first heterodyne oscillator at 25 Hz between two frequencies 0.16 MHz apart at around 1,390 MHz. This caused the centre frequency of the band-pass to alternate between the two frequencies and therefore allowed comparison between the signals. Any difference between the signals appeared as a 25 Hz component of the rectified receiver output. This component could then be recognised by using a selective amplifier and a phase-sensitive detector which was synchronised with the 25 Hz generator. As the receiver was tuned over the 1 MHz frequency band where detection of the H-line was predicted to appear, the energy produced by the H-line was first detected in one band-pass of the two switch components 0.16 MHz apart. This caused an in-phase 25 Hz signal. It was then detected in the other component as an out of phase signal. This caused a characteristic sine-wave signal on the recorder output as illustrated in Figure 33.

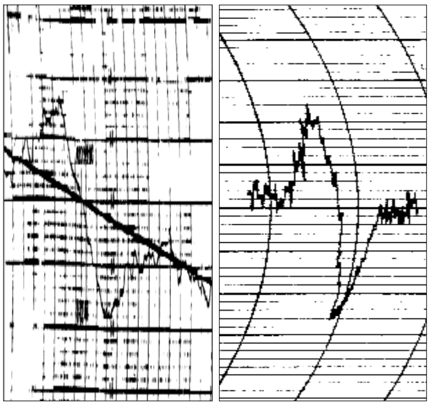

Figure 34: A rescaled example of an H-line observation made by Ewen on 9 April 1951 (left) and a later observation made by Christiansen and Hindman (right) (after Ewen, 2003; and Christiansen and Hindman, 1952a: 444, respectively).

This H-line receiver was assembled in just six short but hectic weeks, an incredibly short time period for so challenging a project, and was "… the most terrible piece of equipment I've ever seen in all my life ... It was a monster …" (Christiansen, 1976). Later, Christiansen also commented:

> Our research was done crudely but it was good fun and the results were exciting. When Purcell's research student Ewen came over and saw the gear I had, with cables lying all over the floor and ancient oscillators, he said, 'My God. I can understand why you could do it in six weeks and it took me two years.' (Chrompton, 1997).

And

> We knew when we started that our gear was so rotten it mightn't work at all. Without exaggeration it was held together with string and sealing wax; Pawsey said it kept going through sheer will power. To make matters worse sparrows kept nesting in the aerial. We were stuck out at Potts Hill reservoir and it rained like all hell all the time. After observing for 10 days, without any luck we got fed up and went home, leaving the machine switched on. The next morning we found what we were after sitting up on the chart. (Christiansen, 1954).

Figure 34 shows an example of the H-line chart record obtained by Christiansen and Hindman, and this can be compared and contrasted with Ewen's original observations, a rescaled example of which has been included in this same figure.

Ewen and Purcell's discovery was published in the 1 September 1951 issue of *Nature* in a letter dated 14 June 1951, and was followed by a confirmation paper from the Dutch group dated 26 June (Muller and Oort, 1951). After the Dutch paper was a short cabled communication dated 12 July that reported the Australian detection of the H-line. This read:

> Referring to Professor Purcell's letter of June 14 announcing the discovery of hyperfine structure of the hydrogen line in galactic radio spectrum, confirmation of this has been obtained by Christiansen and Hindman, of the Radio Physics Laboratory, Commonwealth Scientific and Industrial Research Organization, using narrow-beam aerial. Intensity and line-width are of same order as reported, and

> observations near declination 20° S. show similar extent about galactic equator. (Pawsey, 1951e).

The following day Pawsey sent Bowen a letter advising of the confirmation:

> Christiansen has worked … for the last two months trying to get this gear working and it is a very creditable performance on his part. The line is really exceedingly weak and it is necessary to make the right compromises all along the way in order to make the spectrum line evident. (Pawsey, 1951d).

8.4 THE RADIOPHYSICS SOUTHERN SKY H-LINE SURVEY

Following the initial confirmation, between June and September 1951 Christiansen and Hindman proceeded to make a preliminary survey of hydrogen emission in the southern sky. The detailed findings of this survey were published in the *Australian Journal of Scientific Research* (Christiansen and Hindman, 1952a), and a sumary paper appeared in *The Observatory* (Christiansen and Hindman, 1952b).

By taking a series of measurements in progressive steps of declination they were able to obtain a series of line profiles. Figure 35 shows an example of a series of records taken along the Galactic Equator.

From these individual records, the maximum deflections could be measured and hence a series of brightness intensities could be calculated. Figure 36 shows an example of the profile of peak brightness for the declination +10°.

By combining these profiles a contour chart of peak brightness was constructed. A peak brightness corresponding to a brightness temperature of approximately 100 K was observed. Figure 37 shows the final contour map of H-line emission. From this map it was evident there were marked variations in the peak brightness along the Galactic Equator. Christiansen and Hindman (1952a) noted that there were two likely causes of these variations: (1) line broadening caused by rotation of the Galaxy, and (2) structural features in the Galaxy (a more interesting proposition).

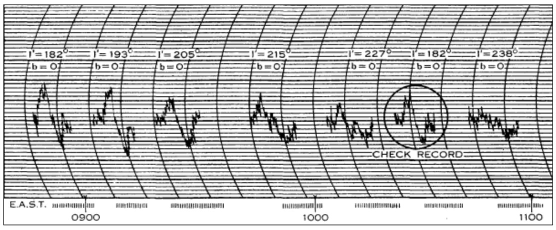

Figure 35: A series of six records taken along the Galactic Equator. A ‘check record’ was performed near the end of each observing run to check the receiver stability (after Christiansen and Hindman, 1952a: 445).

The line profiles were calculated based on the receiver response in the two swept band filters. Figure 38 shows examples of arbitrary line profiles and their corresponding receiver outputs.

The process of reconstruction of the line profiles from the receiver records was essentially the reverse of that shown in Figure 38. Figure 39 shows examples of the smoothed records and reconstructed line profiles from the Galactic Centre, the Anti-centre and Cygnus regions.

Based on the broadening of line profiles, random velocities of the order of 12 to 18 km/s were estimated to be present in the neutral hydrogen clouds. In a number of cases double line profiles were also detected as shown in Figure 40.

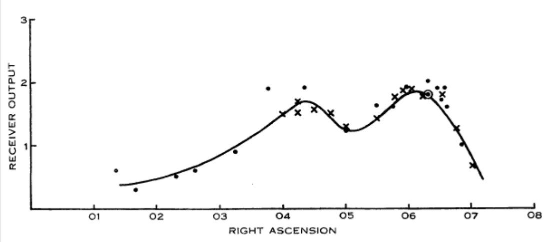

Figure 36: An example of the peak brightness profile in a strip along a declination of +10° (after Christiansen and Hindman, 1952a: 445).

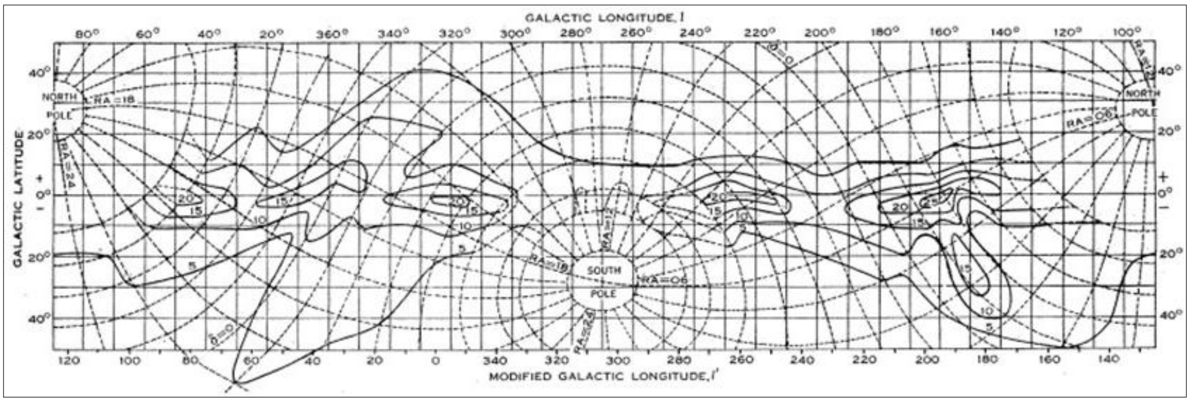

Figure 37: Southern sky contour map of H-line emission. The peak brightness of 25 units corresponds to a brightness temperature of approximately 100 K (after Christiansen and Hindman, 1952a: 446).

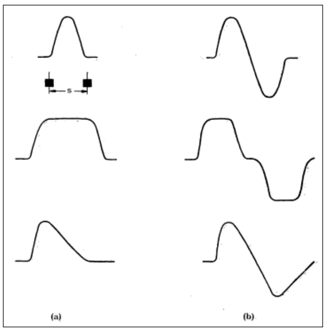

Figure 38: Example line profiles (a), and the corresponding receiver outputs (b). The sweep (s) of the two pass-bands (black boxes) is shown in the top left (after Christian-sen and Hindman, 1952a: 442).

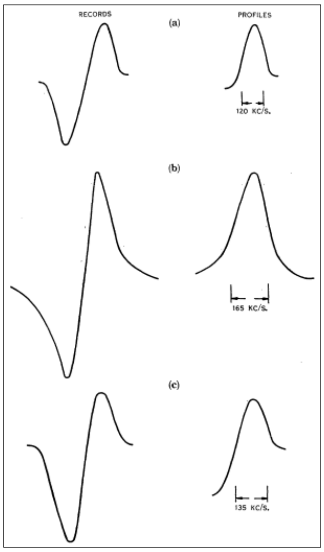

Figure 39: Examples of smoothed records and the calculated line profile in the region of the Galactic Centre (a), the Anti-centre (b) and the Cygnus region (c) (after Christiansen and Hindman, 1952a: 447)

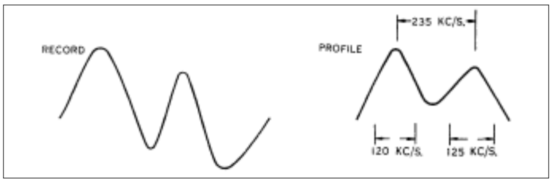

Figure 40: Examples of a smoothed record and a double line profile (after Christiansen and Hindman, 1952a: 448).

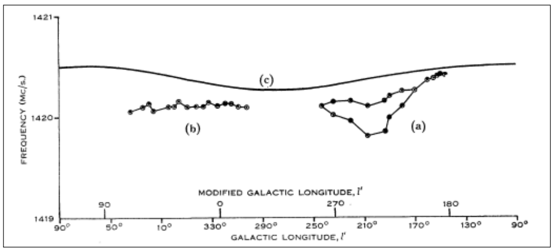

Figure 41: Plot of centre frequencies for line profiles showing double line profiles (a) and single line profile (b) regions. Line (c) is the expected frequency variation due to the Earth's relative motion (after Christiansen and Hindman, 1952a: 448).

The existence of these double line profiles indicated regions with different radial velocities. Assuming a circularly symmetrical rotating galaxy, the radial velocity (v) of different regions is given by:

$$v = r.A.\sin 2l' \qquad (1)$$

where r is the distance of the source from the Sun, A is 6×10^{-16} $\sec^{-1}$, and l' is the modified galactic longitude with respect to the galactic centre. From this equation, given a radial velocity estimate derived from the Doppler frequency shift compared to the rest frequency, a distance to the source can be estimated. The estimate for the two major regions showing double lines was 1,000 and 4,000 parsecs. Given the large size and the constant separation of the double lines as shown in Figure 41, the structure was suggestive of spiral arms in the Galaxy.

Further evidence supporting the detection of galactic structure was found by comparing the theoretical effect of galactic rotation with the actual observations. Assuming a uniform medium producing radiation, it is possible to calculate the brightness profiles for different hydrogen densities. Figure 42 shows the theoretical plots where (n) is the number of ground state hydrogen atoms per cm^3.

This plot showed reasonable agreement with a density of somewhere between 1 and 0.5 atoms per cm^3. However, there were clearly regions that had factors other than rotation causing brightness variations. Also, by comparing the overall hydrogen emission to the general radio emission, which would not be effected by rotation, it is clear that there was general agreement between structural areas as shown in Figure 43. These factors suggested the existence of spiral arms in the Galaxy, and Christiansen and Hindman concluded that a much more detailed investigation was warranted.[4]

Overall there were clear indications that the hydrogen-line emission had approximately the same distribution in the sky as the visible Milky Way. This association, and the ability to penetrate the obscuring medium to discover galactic structure, heralded the beginning of a very important branch of investigations in radio astronomy.[5] It also marked the beginning of a major international collaboration, particularly with the Dutch group working at Leiden, and was characterised by close cooperation that started with the pre-publication communications by Ewen and Purcell to both the Dutch and Australian groups.

It is coincidental that at the same time that the breakthrough discovery of a radio frequency emission line occurred, the first optical evidence for the spiral arm structure of our Galaxy was also published (Morgan et al., 1952).

Immediately following the Australian confirmation of the H-line, Wild decided to update and publish the internal report he had written prior to the detection of the line (Wild, 1952). This was a comprehensive review of the radio-frequency line spectrum of atomic hydrogen and is largely in accordance with modern theory. The report provided a very solid theoretical base for planning further observations by the Australian radio astronomers. The one exception in this analysis was the conclusion that the 1,420 MHz emission would be the only detectable line emission and that it would be unlikely the higher order recombination lines would be detectable. It would be nearly two decades before recombination lines were finally detected by Soviet Union radio astronomers (Sullivan, 1982: 300).

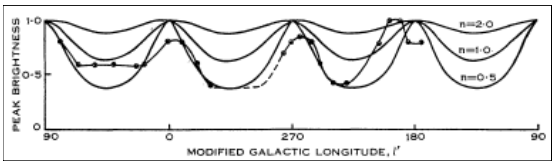

Figure 42: Calculated brightness peaks due to galactic rotation for given hydrogen densities (n). Dots indicate actual observations (after Christiansen and Hindman, 1952a: 450).

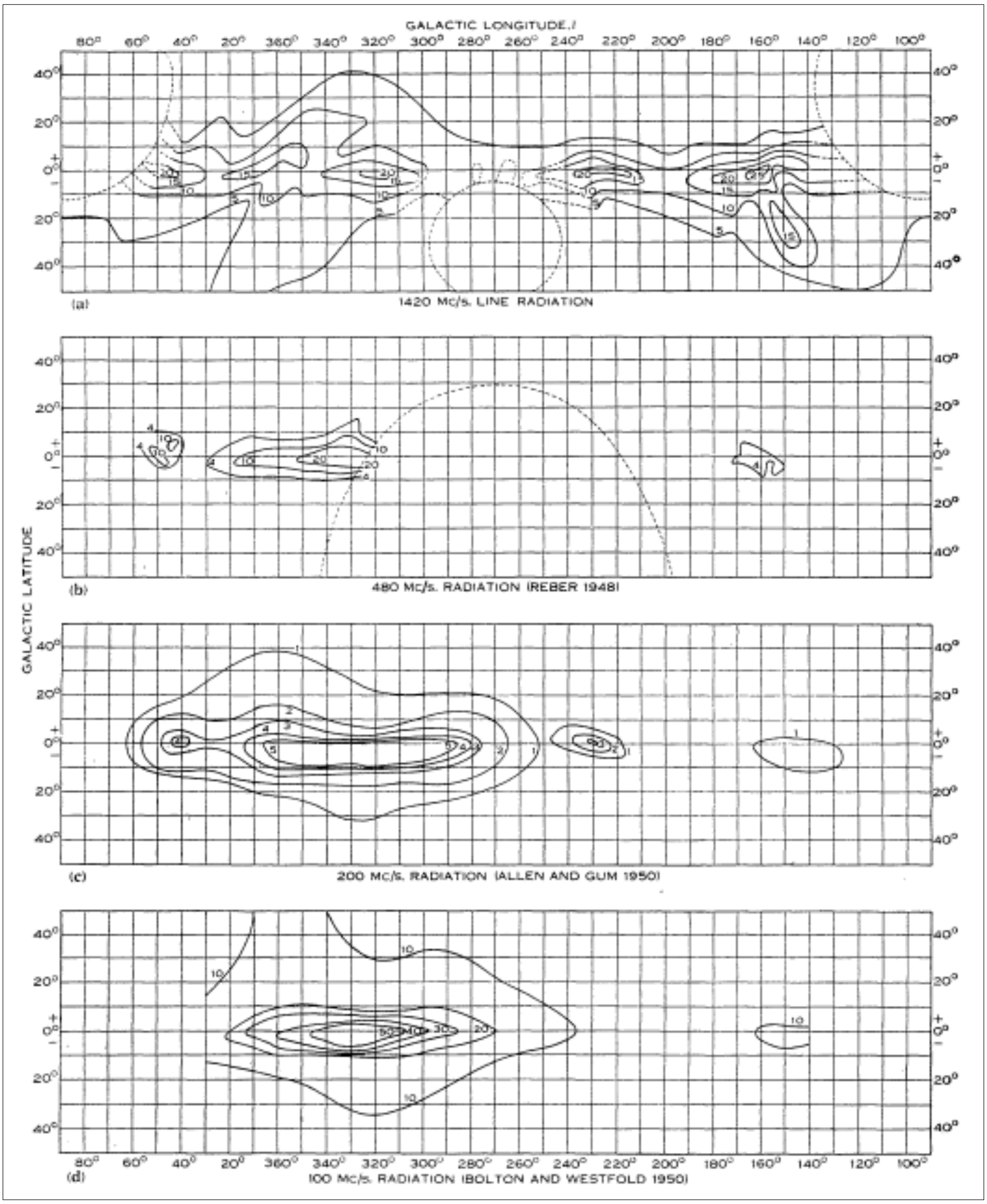

Figure 43: Comparison of H-line emission (top) and continuum emission at 480 MHz, 200 MHz and 100 MHz (bottom). Structural similarities are evident (after Christiansen and Hindman, 1952a: 451)

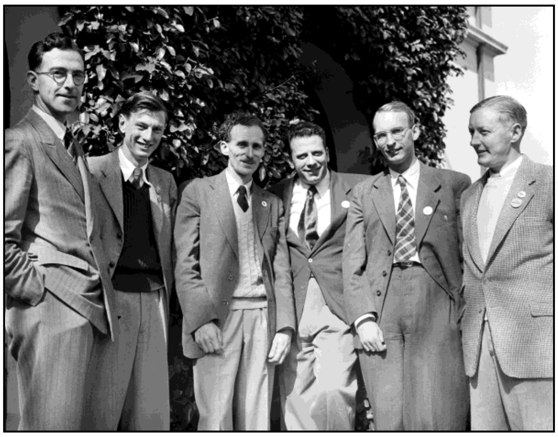

Figure 44: Gathering at the 1952 U.R.S.I. meeting in Sydney of those involved in the initial detection and confirmation of the H-line. From left to right: Kerr, Wild, Hindman, Ewen, Muller and Christiansen. Note also that all wore special U.R.S.I. 'Kangaroo' lapel buttons (courtesy: CRAIA, B2842-45).

The H-line survey carried out by Christiansen and Hindman was to be the last major research program using the old ex-Georges Heights 16-ft × 18-ft antenna. Having originally been designed as an experimental radar, it was far from ideal as a survey radio telescope. It suffered from sagging and distortion of the reflector surface and the multiple dipoles at the prime focus caused further losses in sensitivity (see Piddington and Trent, 1956b: 490n). These problems notwithstanding, it was used for one final short-lived project, as outlined below in Section 9.

8.5 THE 1952 URSI CONGRESS AND AUSTRALIAN H-LINE STUDIES

In recognition of the growing contribution of Australian researchers to the new field of radio astronomy, the Tenth General Assembly of the International Union of Radio Science (U.R.S.I) was held in Sydney between 8 and 22 August 1952 (see Robinson, 2002). Among those who attended the Congress were Ewen from Harvard and Muller from Leiden. This meant that those who had been involved in the initial detection of the H-line were able to meet face-to-face for the first time (see Figure 44).

Table 1: Initial distribution list of the H-line newsletter.

H.I. Ewen	Ewen Knight Corporation, Massachusetts, U.S.A
B.J. Bok	Harvard Observatory, U.S.A
C.R. Burrows	Cornell University, U.S.A.
H. Tatel	Carnegie Institution, U.S.A.
J. Hagen	Naval Research Laboratory, Washington, U.S.A.
F.J. Kerr	Radiophysics Laboratory, Sydney, Australia
J.L. Pawsey	Radiophysics Laboratory, Sydney, Australia
O. Storey	T.R.E., Malvern, U.K.
A.C.B. Lovell	Jodrell Bank, U.K.
M. Ryle	Cambridge University, U.K.

At the Congress those shown in Figure 44 decided to arrange a regular exchange of information by way of a newsletter that tracked the progress of the various groups undertaking H-line research. The first issue appeared in December 1952, and it was circulated to those listed in Table 1.

9 THE APRIL 1959 SOLAR ECLIPSE

The final solar research paper from Potts Hill was based on observations of the 8 April 1959 partial solar eclipse (Krishnan and Labrum, 1961). The eclipse was observed both at Potts Hill using the ex-Georges Heights parabola as a high sensitivity total power radiometer at 1,423 MHz. Meanwhile, the Chris Cross at Fleurs, the world's first cross-grating interferometer (Orchiston and Mathewson, 2009), was used to help identify areas of enhanced radiation.

No spectroheliogram observations were available in Australia at the time. However, these were provided by Dobson at the McMath Hulbert Solar Observatory in the U.S., and this allowed Krishnan and Labrum to compare the distribution of calcium K-line plages with their radio observations. They found a very close correlation between optical and radio plages, both in their intensity and their overall shape.

Krishnan and Labrum also were able to test a number of quiet Sun models against the eclipse observations. They found that the best fit was achieved by a model based on Christiansen and Warburton's (1955) work for sunspot minimum which showed limb-brightening at the equator, but absent at the poles. After allowing for an overall increase in brightness temperature by a factor of two to allow for the sunspot maximum, Krishnan and Labrum found that a stepped-up gradient of limb-brightening (the ear component) provided the best fit. It is likely that the lower resolution of the grating arrays used by Christiansen and Warburton for measurements of limb-brightening would have washed out the steeper gradient and therefore the ear would not appear as pronounced. The higher resolution of the eclipse observation allowed the steeper gradient to be more accurately measured.

The 1959 eclipse observation marked the end of the 'research career' of the ex-Georges Heights experimental radar antenna, and the end of solar research at Potts Hill. By this time, the solar focus had shifted to the Dapto (Stewart et al., 2011a) and Fleurs (Orchiston and Mathewson, 2009) Field Stations.

10 DISCUSSION

10.1 Lehany, Yabsley and Christiansen

In one way or another the Georges Heights experimental radar antenna marked the end of an era for some of those who used it.

For Fred Lehany it provided his sole research foray into radio astronomy, a field in which he admitted to having little interest (Lehany, 1978), whereas it proved the perfect radio astronomy training ground for a youthful Don Yabsley. However, Yablsey spent 1951–1961 working in the air navigation group at RP, and only returned to radio astronomy once the Parkes Radio Telescope was commissioned. He was involved in a number of collaborative research projects and in the up-grading of the dish, and his unexpected death late in 2003 robbed Australian radio astronomy of one of its pioneers.

Following the initial H-line survey with the ex-Georges Heights antenna, Chris Christiansen returned to solar radio astronomy, and constructed the world's first solar grating arrays, which were used for the observation of 1,420 MHz radio plages and to establish the distribution of quiet Sun radio emission across the solar disk (see Stewart et al., 2011c; Wendt et al., 2008b).

But RP certainly was not going to abandon H-line research after so auspicious a start (even if a belated one—see Section 10.2, below). By this time Frank Kerr had returned from Harvard University, and he and Hindman focused on the construction a new multi-channel H-line receiver and on the construction of a new 36-ft (11-m) purpose-built dedicated H-line transit parabola (Figure 45). These would replace the aging ex-Georges Heights radio telescope, and would be used for a dedicated H-line survey of the southern sky. Kerr and Hindman were joined by a recent graduate student, Brian Robinson, who would go on to lead the CSIRO's Radio Astronomy Group within RP during the 1970s (Whiteoak and Sim, 2006: 265).

10.2 AUSTRALIA AND THE H-LINE: A MISSED OPPORTUINITY?

In retrospect, the H-line confirmation was a missed opportunity for Radiophysics (Sullivan, 2005: 14). Had a serious effort been made to detect the 1,420 MHz emission line when the possibility was first raised it appears very likely that the Group would have been successful.

The Group's early success in both solar and cosmic research and the wealth of discoveries made in the late 1940s and early 1950s meant that they were reluctant to pursue the more speculative search for the emission line even though they were aware of the significance that such a discovery would bring to radio astronomy. Joe Pawsey was a dynamic, inspirational, research leader but in this instance his decision not to pursue the H-line (that is, until after its discovery by Ewen) led perhaps to RP's greatest 'missed opportunity'.

11 CONCLUDING REMARKS

In its first year of operation as a radio telescope, the 16 × 18-ft Georges Heights experimental radar antenna played a significant role in the early development of solar radio astronomy in Australia. Research carried out at the short-lived Georges Heights Field Station by Lehany and Yabsley aided our understanding of the association of 200 MHz bursts and solar flares, and of the correlation between sunspots and radio emission at 600 and 1200 MHz. However, consolidation of research at the Dover Heights and Potts Hill Field Stations saw the close down of radio astronomy at Georges Heights towards the end of 1948, and the transfer of the experimental radar antenna to Potts Hill. Once there, it received a new lease of life, and a brand new (equatorial) mounting.

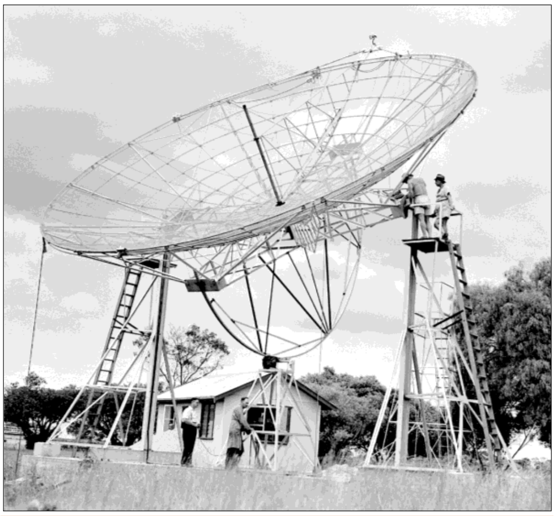

Figure 45: The 36-ft H-line dish at Potts Hill, soon after its completion. This was built to replace the aging ex-Georges Heights experimental radar antenna. The receiver hut shown in this photograph is the only radio astronomy structure still at Potts Hill. As Orchiston and Slee relate (2017: Figure 19.95), in 2015 it was renovated, and it now serves as a fitting reminder to the pioneering radio astronomy that once occurred on this site (courtesy: CRAIA, B2975-21).

The 1948 eclipse program was one of the research highlights of the Potts Hill Field Station, as for the first time it provided precise 2-dimensional positions for the radio-emitting regions that were in the solar corona at that time. The ex-Georges Heights radar antenna played a key role in this innovative project.

By way of marked contrast, the 1949 solar eclipse program is an enigma. Once again the ex-Georges Height radar antenna played a key role. Although successful observations were made at all sites, nothing was published to justify the enormous outlay in time, effort and expenditure associated with what at first sight would seem to have been a successful project. There certainly were adequate sunspots in attendance to aid searching for the locations of radio-emitting

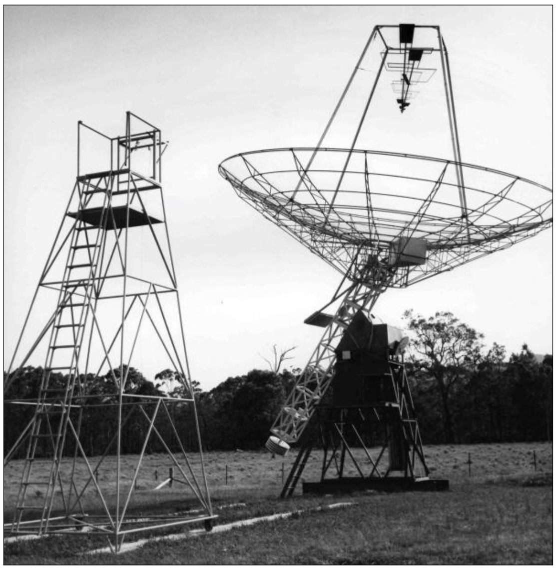

Figure 46: The new 10-m dish with the old ex-Potts radar antenna mounting that was installed at Dapto Field Station in 1963 (courtesy: CRAIA, 004032).

regions, but perhaps the choice of 1,200 MHz, instead of 600 MHz (as in 1948), was a critical error in judgement. Whether this decision was made by Pawsey, Christiansen, or the entire research team, is not known.

As an aside, this conspicuous non-event was the trigger that inspired Chris Christiansen (1984: 117)

> … to devise some method of viewing the Sun [at high resolution] more frequently than was possible with eclipse observations. This of course meant devising some antenna system of very great directivity.

We now come to undoubtedly the most important research carried out with the Georges Heights radio telescope: the initial confirmation of the 1,420 MHz hydrogen emission line, and subsequent observations of the distribution of H-line emission in our Galaxy.

Figure 47: A recent view at Potts Hill of the concrete pad that supported the ex-Georges Height experimental radar antenna (photograph: Harry Wendt).

The achievement of Chris Christiansen and Jim Hindman in constructing an H-line receiver from scratch in just six weeks is nothing short of remarkable. They then went on to conduct the world's first detailed H-line survey, and in the process produced the first radio evidence for the spiral arm structure of our Galaxy.

The 1959 partial solar eclipse was a fitting finale to the 'career' of the aging ex-Georges Heights radio telescope as a major research instrument. In just over a decade it made important contributions to solar and cosmic radio astronomy, and played a vital role in pinpointing the positions of radio-emitting regions in the solar corona, and revealing the distribution of neutral hydrogen along the plane of our Galaxy.

After this eclipse the experimental radar antenna became 'surplus to requirements' and was probably categorised as scrap metal. However, the cannibalisation of radio telescope (and receiver) components was an important feature of the RP field station era, and in this fine tradition part of Potts Hill antenna's distinctive equatorial mounting was recycled in 1963, and was attached to a new 10-m (33-ft) parabolic dish (Figure 46) with a log-periodic feed that was installed at the Dapto Field Station (site 4 in Figure 3). This dish was used to extend the upper frequency limit of the field station's solar spectrographic coverage from 210 MHz to 2,000 MHz (see Suzuki et al., 1965). Stewart et al., (2011a) have published an excellent review of developments at Dapto Field Station.

Now all that remains at the Potts Hill site as a reminder of the historic ex-radar antenna that once played so important a role there is the concrete base that originally supported the radio telescope (see Figure 47).

12 NOTES

1. This later became the Commonwealth Scientific and Industrial Research Organisation (CSIRO).
2. The first author of this paper worked at the Fleurs Field Station from December 1961 until this Field station was handed over to the University of Sydney in 1965. At first he assisted Dr Bruce Slee (Orchiston, 2004) with research involving the Mills and Shain cross-type radio telescopes, and then he was responsible for operating the Chris Cross (see Orchiston and Mathewson, 2009) and producing the daily maps of 1420 MHz solar radio emission.
3. These were AN/TPS-3 radar aerials that had been developed during WWII by the U.S. Army Signal Corps as a light weight portable 600 MHz early warning radar (Orr, 1964). These aerials also were known as the 'British Type-63 Radar' (Wendt et al., 2008a: 74).

Each aerial was made up of eight 45º aluminium frame sections covered with wire-mesh that could be packed in a very compact bundle and quickly reassembled through a series of speed-clips. In 2007, one of the RP radio astronomers informed the second author of this paper that two people could assemble an aerial in about five minutes (John Murray, pers. comm., 2007).

4. This planetary nebula was first successfully observed from Australia in 1963 when Orchiston detected it at 11cm with the 64-m radio telescope at Parkes (see Orchiston, 1965). This detection led to the subsequent multi-wavelength survey of southern planetary nebulae by Slee and Orchiston (1965).
5. James Lequeux (pers. comm., December 2017) stresses the remarkable quality of the Christiansen and Hindman (1952a) paper, which paved the way for a new field of galactic radio astronomy six years before the appearance of the famous paper by Oort, Kerr and Westerhout (1958). However, Christiansen and Hindman's paper appeared in the relatively little-known *Australian Journal of Scientific Research*, and Oort et al. do not even mention it in their *Monthly Notices* paper.

13 ACKNOWLEDGEMENTS

We are grateful to Kathryn Brennan from the National Archives of Australia in Sydney for help in accessing archival material, and John Murray for providing useful information. We also wish to thank Dr James Lequeux (Paris Observatory) and Dr Peter Robertson (University of Melbourne) for reading and commenting on the manuscript. Finally we are grateful to the National Astronomical Observatory of Japan, the late Dr Bruce Slee, and CSIRO Astronomy and Space Sciences for kindly supplying many of the figures published in this paper.

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PERIPHERIES OF EPICYCLES IN THE *GRAHALĀGHAVA*

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Abstract: For finding the true positions of the Sun, the Moon and the five planets the Indian classical astronomical texts use the concept of the *manda* epicycle which accounts for the equation of the centre. In addition, in the case of the five planets (Mercury, Venus, Mars, Jupiter and Saturn) another equation called *śīghraphala* and the corresponding *śīghra* epicycle are adopted. This correction corresponds to the transformation of the true heliocentric longitude to the true geocentric longitude in modern astronomy. In some of the popularly used handbooks (*karaṇa*) instead of giving the mathematical expressions for the above said equations, their discrete numerical values, at intervals of 15°, are given.

In the present paper using the data of discrete numerical values we build up continuous functions of periodic terms for the *manda* and *śīghra* equations. Further, we obtain the critical points and the maximum values for these two equations.

Keywords: Equation of the centre, epicycle, periphery, apogee, perigee, equation of the conjunction, *śīghraphala, mandaphala, paridhi, Grahalāghava,* Gaṇeśa Daivajña

1 INTRODUCTION

The *Grahalāghava* (*GL*) is one of the most popular *karaṇa* texts of Indian astronomy, and was written by the famous sixteenth-century author Gaṇeśa Daivajña. After Bhāskara-II of the twelfth century there was a decline for a brief period in the development of mathematics and astronomy in India. But we see tremendous work was done in the south i.e., in Kerala and Maharashtra, giving rise to some of the great and eminent luminaries like Nilakaṇṭa Somayājī and Gaṇeśa Daivajña.

Gaṇeśa Daivajña is unique because he dispensed with trigonometric terms in his computations and replaced them with suitable algebraic approximations. This method helped many almanac (*pañcāṅga*) makers to do calculations in a simple way. So even today, the *GL* is one of the popular texts among almanac-makers.

The text of the *GL* consists of 187 verses (*ślokas*) distributed in 14 chapters. In chapters 2 and 3 the true positions of the Sun, the Moon and the five planets are discussed. For the Sun and the Moon there is only one correction, namely the *mandaphala*, which corresponds to the equation of the centre, taking into account the eccentricity of the body's orbit. But for the five planets, apart from the *mandaphala* one more equation called *śīghraphala* is applied. *Śīghraphala* converts heliocentric position to geocentric position of the planets. In order to determine the two equations *manda* and *śīghra,* Gaṇeśa Daivajña gives discrete values, called *mandāṅkas* and *śīghrāṅkas.* These are obtained by multiplying the actual *manda* and *śīghra* corrections by 10. Further, these values are in arc minutes (*kalās*), and given in integers for every 15°. Gaṇeśa Daivajña does not provide either the peripheries (*paridhis*) of the epicycles nor does he mentions explicitly the expressions for the two equations. However, in the case of the Sun and the Moon he gives explicit approximate algebraic expressions for the equation of the centre. In this paper we estimate the ranges of peripheries of the equations for each of the bodies.

2 THE METHOD OF THE *GRAHALĀGHAVA* FOR THE EQUATION OF THE CENTRE

In obtaining the mean positions of the Sun and the Moon it was earlier assumed that these bodies moved in circular orbits around the Earth with uniform angular velocities. However, observations revealed that the motions were non-uniform. The true positions were related to the epicyclic theory that is explained in the following section.

2.1 Epicyclic Theory and the Equation of the Centre

The theory is that while the mean Sun or the Moon move along a big circular orbit (see Figure 1), the actual Sun and Moon move along a smaller circle called an epicycle, whose centre is on the larger circle.

The larger circle *ABP* with the Earth *E* as its centre is called the deferent circle (*kakṣāvṛtta*). Let *A* be the position of the mean Sun when the true Sun is farthest from the Earth. The line *AEP* is called the apse line and *AE* is the radius (*trijyā*) of this orbit. The epicycle, with *A* as centre and a prescribed radius (smaller than *AE*) is called the *nīcoccavṛtta.* Let the apse line *PEA* cut the epicycle at *U* and *N.* The two points *U* and *N* are respectively called the apogee (*mandocca*) and the perigee (*mandanīca*) of the Sun. Note that as the Sun moves (as seen from Earth) along the epicycle, the Sun is farthest from the Earth at *U* and nearest at *N*.

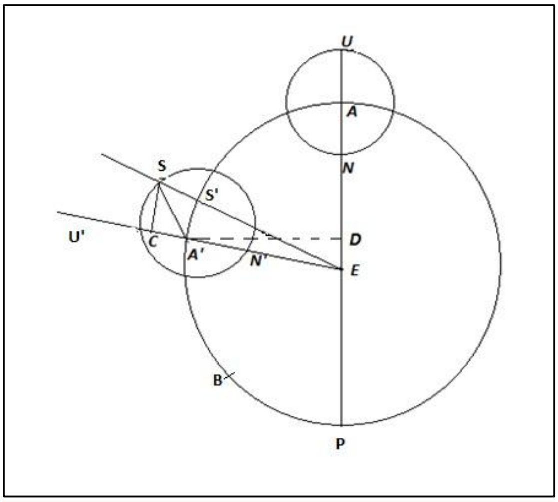

Figure 1: Epicyclic theory.

The epicyclic theory assumes that as the centre of the epicycle (i.e. mean Sun) moves along the circle *ABP* in the direction of the signs of the zodiac (from west to east) with the velocity of the mean Sun, the true Sun itself moves along the epicycle with the same velocity but in the opposite direction (from east to west). Further, the time taken by the Sun to complete one revolution along the epicycle is the same as that taken by the mean Sun to complete a revolution around the orbit.

Now in Figure 1, suppose the mean Sun moves from *A* to *A'*. Let *A' and E* be joined, cutting the epicycle at *U'* and *N'*, which are the current positions of the apogee (*mandocca*) and the perigee (*mandanīca*). While the mean Sun is at *A'*, suppose the true Sun is at *S* on the epicycle so that $U'\hat{A}'S = U'\hat{E}A$. Join *ES*, cutting the orbit (i.e., circle *ABP*) at *S'*. Then *A'* is the mean Sun (*madhya Ravi*) and *S'* is the true Sun (*spaṣṭa* or *sphuṭa Ravi*). The difference between the two positions viz., $A'\hat{E}S'$ (or arc *A'S'*) is called the equation of the centre (*mandaphala*).

In order to obtain the true position of the Sun, it is necessary to get an expression for the equation of the centre which will have to be applied to the mean position.

In Figure 1 *SC* and *A'D* are drawn perpendicular to *U'N'E* and *UNE* respectively. The arc *AA'* (or $A\hat{E}A'$), the angle between the mean Sun and the apogee, is called the mean anomaly (*mandakendra*, henceforth *MK*) of the Sun.

We have, in the right-angled triangle *A'DE,*

$\sin A\hat{E}A' = \sin D\hat{E}A' = A'D/A'E$

so that, $A'D = R\sin AA' = R\sin MK$ is called *R* sine of anomaly (*mandakendrajyā*), where $R = A'E$ and $MK = \text{arc } AA'$.

From the similar right-angled triangles *SCA'* and *A'DE*, we have

$SC/SA' = A'D/AE'$

and

$SC = (SA' \times A'D)/A'E$

Since *SA'* and *A'E* are respectively the radii of the epicycle and the orbit, these are proportional to the circumferences of the two circles; that is

SA'/A'E = circumference of the epicycle/ circumference of the orbit

∴ *SC* = (circumference of the epicycle/ circumference of the orbit) × *A'D*

Taking the circumference of the orbit as 360°, we have

SC = (circumference of the epicycle × *mandakendrajyā*)/360°

Now, taking *SC* approximately the same as *A'S'*, the equation of the centre (*mandaphala,* henceforth *MPH*) is given by

$R\sin(MPH)$ = circumference of the epicycle × *mandakendrajyā*)/360°

$= (p/R) \times R\sin MK$

i.e. $\sin(MPH) = (p/R) \times \sin MK$

where $R\sin MK$ is the 'Indian sine' (*jyā*)[1] of the anomaly *MK* of the Sun. The maximum value of the equation of the centre, i.e., $\sin(MPH)$ is p/R (in radians) or $p/2\pi$ (in degrees).

In his *Grahalāghava*, Gaṇeśa Daivajña gives the following verse to obtain the anomaly from the apogee (*mandakendra*) of the planet:

> If the *bhuja* (of the *manda* anomaly) is less than three *rāśis* (signs) then take that itself, if the anomaly is greater than three *rāśis* and less than six *rāśis* then consider the difference of six *rāśis* (180°) and the anomaly as the *bhuja*, if the anomaly is greater than six *rāśis*

> and less than nine *rāśis* then subtract six *rāśis* (180°) from the anomaly to get the *bhuja* and if the anomaly is greater than nine *rāśis* and less than twelve *rāśis* then the remainder of subtracting it from twelve *rāśis* (360°) is the *bhuja.* (*Grahalāghava*, Ch-II, *śloka* -1; our English translation).

This means the anomaly from the apogee (*mandakendra*, *MK*) = apogee (*mandocca*) of the planet – Mean planet. *MK* is expressed as an acute angle; to get this, we use the following procedure:

(1) If $0° \leq MK < 90°$ then *MK* itself is the argument (*bhuja*) i.e., $bhuja = MK$.
(2) If $90° \leq MK < 180°$ then $bhuja = 180° - MK$
(3) If $180° \leq MK < 270°$ then $bhuja = MK - 180°$
(4) If $270° \leq MK < 360°$ then $bhuja = 360° - MK$

According to the *Grahalāghava*, the apogees of the heavenly bodies are as shown in Table 1.

It is assumed that the apogee of the Moon varies, whereas those of the other bodies are fixed.

The method of finding the equation of the centre of the Sun is explained in the following verse*:*

> The difference between the *mandocca* (apogee) and the mean planet is called (*manda*) *kendra* (anomaly). If the *kendra* is within six *rāśis* from *Meṣa* or within six *rāśis* from *Tulā*, (correspondingly) the *mandaphala* (the equation of the centre) is positive or negative.
>
> In the case of *Ravi* (Sun), divide the *bhuja* (of the *mandakendra*) by 9, subtract it from 20 and multiply the result by itself; (this is the numerator). Divide the numerator by the difference between 57 and one-ninth of the numerator. (*Grahalāghava*, Ch-II, *śloka* -2; our English translation).

This means, find the anomaly from the apogee (*MK*) of the Sun and express *MK* in terms of *bhuja* of *MK* as explained earlier. Denote *bhuja* of *MK* by *BMK*.

(1) Subtract ($BMK/9$) from 20 and multiply this by ($BMK/9$).
(2) Divide the result of (1) by 9.
(3) Subtract the result of step (2) from 57.
(4) Express the results of step (3) and step (1) in seconds of arc (*vikalās*) and divide the result of step (1) by that of step (3).

Then the result is the equation of the centre of the Sun.

i.e., The equation of the centre of the Sun =

$$[20 - (BMK/9)] \times (BMK/9) / [57 - \{(20 - (BMK/9)) \times (BMK/9) / 9\}]$$

Note:

(1) In devising the above equation the author dispenses with the trigonometric ratio sine.
(2) If the anomaly from the apogee is within 6 signs from Aries (*Meṣa)* (i.e., $0° < MK < 180°$) then the equation of the centre is additive.
(3) If the anomaly from the apogee is within 6 signs from Libra (*Tulā*) (i.e., $180° < MK < 360°$) then the equation of the centre is subtractive.
(4) If the anomaly is 0° or 180° then the equation of the centre is zero.

2.2 Rationale for the Equation of the Centre of the Sun

Śrīpati Bhaṭṭa's (ca. tenth century) expression for the *R* sine (*jyā*) of the anomaly is as follows:

> Subtract the *manda* anomaly from 180 and multiply by itself; (this is the numerator). Divide the numerator by the difference between 10125 and one-fourth of the numerator. (Finally) thus obtained result is multiplied by 120 to get the *jyā* (*R*sine) of the *manda* anomaly of the Sun. (*Siddhānta-śekhara*, Ch-III, *śloka*-17; our English translation).

This implies the anomaly from the apogee (*MK*) in degrees is subtracted from 180° and the remainder is multiplied by the same quantity (MK). Then the result is divided by its one-fourth, subtracted from 10125. This result is multiplied by twice sixty (i.e., by 120).

Table 1: Apogee of the heavenly bodies.

Body	Apogee
Sun	78°
Mars	120°
Mercury	210°
Jupiter	180°
Venus	90°
Saturn	240°

i.e. In symbols, R sine of anomaly $= [(180 - MK)MK \times 120] / \{10125 - [(180 - MK)/4] \times MK\}$

where *MK* stands for the *bhuja* of the anomaly

i.e., $R \text{ sine } (MK) = [(180 - MK)MK \times 480] / [40500 - (180 - MK)MK]$

$$= \{[(180 - MK) / 9]\ [(MK/9) \times 480]\} / \{[405000/(9 \times 9)] - [(180 -- MK)/9](MK/9)\}$$

(dividing by 9 × 9)

$$= \{[20 - (MK/9)[MK/9] \times 480]\} / \{500 - [20 - (MK/9)](MK/9)\} \tag{1}$$

The above derivation is based on the significant and unique formula of Bhāskara I (c. 629 CE);

i.e., $\sin\theta = [4\ (180° - \theta)\ \theta] / [40500 - (180° - \theta)\ \theta]$

Now, according to the *Grahalāghava* the maximum equation of the centre (*parama mandaphala*) of the Sun

$= (125°/57) \approx 2°\ 11'\ 34''$.

Table 2: The Sun's equation of the centre, *MPH* and *manda* periphery, *p*

MK	*MPH*	*Manda periphery (p)*
15°	0.570	13°.834
30°	1.093	13°.735
45°	1.541	13°.69
60°	1.886	13°.68
75°	2.104	13°.689
90°	2.179	13°.692

∴ The equation of the centre of the Sun = (125°/57) × (*mandakendrajyā*)/120)

$= [125 / (57 \times 120)] \times \{[(20 - (MK/9)(MK/9) \times 480] / 500 - [20 - (MK/9)(MK/9)]\}$ Using (1)

$= \{(125 / (57)[(20 - (MK/9)(MK/9) \times 4]\} / \{500 - [20 - (MK/9)](MK/9)\}$

$= \{(500 / (57)[(20 - (MK/9)(MK/9)]\} / \{500 - [20 - (MK/9)](MK/9)\}$

$= \{[(20 - (MK/9)](MK/9)\} / \{[500/(500/57)] - [20 - (MK/9)](MK/9) / (500/57)\}$

$= \{[(20 - (MK/9)](MK/9)\} / \{57 - [20 - (MK/9)](MK/9) / 8.771928\}$

i.e., Equation of the centre of the Sun

$\approx \{[(20 - (MK/9)](MK/9)\} / \{57 - [20 - (MK/9)](MK/9) / 9]\}$

The exact formula for the equation of the centre of the Sun is $\sin^{-1}[(p/R)\sin MK)$ where R = 360°, p is the periphery of the *manda* epicycle (in degrees) and *MK* is the Sun's anomaly (from the *apogee*, *mandocca*).

Using this formula with the range of *MK* from 15° to 90° the Sun's equation of the centre, *MPH*, and the periphery (*paridhi*) of the *manda* epicycle, *p*, are estimated and listed in Table 2.

In order to estimate the *manda* periphery of the Sun from 0° to 90°, we adopt the formula $p = A + B \sin(MK)$. The related procedure is explained in later sections. The periphery of the Sun for *MK* = 0° is 14°.001 and for *MK* = 90° is 13°.692.

Similarly, the equation of the centre of the Moon is given in the following verse

> In the case of *Vidhu* (Moon), one-sixth of the *manda* anomaly is subtracted from 30 and the remainder is multiplied by the same; (this is the numerator). This numerator is divided by the difference between 56 and one-twentieth of the numerator. This is Moon's equation of the centre. (*Grahalāghava,* Ch-II, *śloka* -3; our English translation).

Table 3: The Moon's equation of the centre, *MPH* and *manda* periphery, *p*

MK	*MPH*	*Manda periphery (p)*
15°	1.307	31°.752
30°	2.512	31°.573
45°	3.547	31°.526
60°	4.347	31°.544
75°	4.854	31°.576
90°	5.027	31°.591

This can be expressed as the following formula:

Equation of the centre of the Moon = $\{[30 - (MK/6)](MK/6)\} / \{56 - [30 - (MK/6)(MK/6) / 20]\}$

2.3 Rationale for the Equation of the Centre of the Moon

We have *R* sine of anomaly = $[(180 - MK)MK \times 480)] / [40500 - (180 - MK)MK]$

According to Śrīpati Bhaṭṭa, dividing the numerator and the denominator by 6 × 6,

$R\sin(MK) = \{[(180 - MK)/6)]MK \times (480/6)\} / \{(40500/ 6 \times 6) - [(180 - MK/6)](MK/6)\}$

$= \{(30 - MK/6)(MK/6) \times 480\} / \{120 \times [1125 - [30 - (MK/6)](MK/6)\}$ (2)

According to the *Grahalāghava* the maximum equation of the centre of the Moon = 5°.

∴ Equation of the centre of the Moon = (5 × *R* sine of anomaly) / 120

$= \{5 \times [30 - (MK/6)](MK/6) \times 480\} / \{120 \times [1125 - [30 - (MK/6)](MK/6)]\}$ using (2)

$= \{(2400/120) [30 - (MK/6)](MK/6) \} / \{[1125 - [30 - (MK/6)](MK/6)]\}$

$= \{20[30 - (MK/6)](MK/6)\} / \{[1125 - [30 - (MK/6)](MK/6)]\}$

$= \{[30 - (MK/6)](MK/6)\} / \{(1125/20)[30 - (MK/6)](MK/6) / 20\}$

$= \{[30 - (MK/6)](MK/6)\} / \{56.25 - [(30 - MK/6)](MK/6) / 20\}$

i.e., Equation of the centre of the Moon $\approx \{[30 - (MK/6)](MK/6)\} / \{56 - [(30 - MK/6)(MK/6)]/ 20\}$

In the similar way as in the case of the Sun's periphery, the Moon's periphery is estimated and listed in Table 3.

The periphery of the Moon for *MK* = 0° is 32°.075 and for *MK* = 90°, it is 31°.591.

3 EQUATION OF THE CENTRE OF THE PLANETS

In the case of the five planets in the *GL*, instead of providing direct expressions, Gaṇeśa Daivajña gives discrete numerical values for the equation of the centre (*mandaphala*) in degrees at intervals of 15° of the *manda* anomaly. He has multiplied the equation of the centre by 10 (to avoid fractions) and calls them as *mandāṅkas,* as given in Table 4.

In order to estimate the underlying *manda* per-

Table 4: Discrete values of the equation of the centre (*mandāṅkas*) of the planets.

Planets	15°	30°	45°	60°	75°	90°
Mars	29	57	85	109	124	130
Mercury	12	21	28	33	35	36
Jupiter	14	27	39	48	55	57
Venus	06	11	13	14	15	15
Saturn	19	40	60	77	89	93

ipheries of the different planets, we adopt the following two procedures:

(1) As a first approximation, the

Equation of the centre $(MPH) = (p/R)\sin(MK)$ in radians (3)

$\therefore\ p = (MPH \times R) / \sin(MK)$ in degrees. (4)

(2) As the second approximation, or the correct expression

$\sin(MPH) = (p/R)\sin(MK)$ in radians (5)

where p is periphery of the epicycle, MK is the *manda* anomaly and R is 2π radians or 360°.

As an example, based on equation (4) the *manda* periphery (p) of Mars is given in Table 5.

We find from Table 5 that the *manda* periphery increases from 70°.40145 to 81°.68142 as the *manda* anomaly (MK) increases from 15° to 90°.

Note: The *manda* periphery for $MK = 0$ cannot be obtained from equation (4) since the denominator vanishes.

Now since p varies from 70°.40145 to 81°.68142, we express the periphery p for any given MK in the form

$p = A + B\sin(MK)$ (6)

for which we have to determine the constant coefficients A and B. Tentatively, for $MK = 30°$ and 90°, we get the respective linear equations as

$p = A + (B/2)$ and $p = A + B$ (7a)

Solving these equations, we obtain A = 61°.5752 and B = 20°.10622. (It is to be noted that we do not get the same values of A and B as above if we consider the other pairs of the linear equations.)

This means that for the above values of A and B, periphery p varies from 66°.77908 to 81°.68142 as MK varies from 15° to 90° in the case of Mars. Similarly, estimating the *manda* peripheries for the other four planets namely, Mercury, Venus, Jupiter and Saturn, we get the values as shown in Table 6.

When MK = 0°, formula (6) becomes $p = A$ hence the above table of *manda* peripheries can be now listed for MK = 0° to 90° by solving equations (7) by finding the A and B values.

Now, considering the actual expression for the equation of the centre given by equation (5) we have

$\sin(MPH) = (p/R)\sin(MK) \Rightarrow$
$p = [R \times \sin(MPH)] / \sin(MK)$ (7b)

Following the same procedure as for Mars in the case of the remaining four planets we get the *manda* peripheries as shown in Table 7.

From Table 8, we find that the *manda* periphery 'p' increases as anomaly MK increases from 0° to 90° in the case of superior planets viz. Mars, Jupiter and Saturn. On the other hand, in the case of the two interior planets Mercury and Venus 'p' decreases as MK increases from 0° to 90°.

Table 5: *Manda* periphery of Mars in degrees.

MK	*MPH*	*Manda periphery (p)*
15°	2.9	70°.40145
30°	5.7	71°.62831
45°	8.5	75°.52901
60°	10.9	79°.08165
75°	12.4	80°.65991
90°	13	81°.68142

Table 6: The range of *manda* peripheries of other planets.

Planet	*Manda periphery (p)*	
	MK (15°)	*MK* (90°)
Mercury	28°.20784	22°.61947
Jupiter	33°.01997	35°.81416
Venus	15°.944	09°.42478
Saturn	46°.25	58°.43363

Table 7: The range of *manda* peripheries of all the planets for MK = 0° and 90° (using equation 7a).

Planet	*Manda periphery (p)*	
	MK (0°)	*MK* (90°)
Mars	61°.5752	81°.68142
Mercury	30°.15929	22°.61947
Venus	18°.22124	09°.42478
Jupiter	32°.04424	35°.81416
Saturn	42°.09733	58°.43363

Table 8: The range of *manda* peripheries of all the planets (using equation 7b).

Planet	*Manda periphery (p)*	
	MK (0°)	*MK* (90°)
Mars	62°.03774	80°.9824
Mercury	30°.16235	22°.60459
Jupiter	32°.07817	35°.75511
Venus	18°.220618	09°.42370
Saturn	42°.09733	58°.43363

Manda peripheries according to some Indian classical astronomical texts are listed in Table 9, together with our computations for comparison.

From Table 9, it is interesting to note that the same behaviour is seen in the *Āryabhaṭīya* also. In fact, even the ranges of variation of the *manda* periphery as estimated based on the *GL* are close to those of the *Āryabhaṭīya*. However, in

Table 9: Comparison of *manda* peripheries from different texts.

Bodies	Computed Values based on *GL*	The *Āryabhaṭīya*	The *Sūryasiddhānta*
Sun	13°.69 – 14°	13°.5	13°.66 –14°
Moon	31°.59 – 32°.07	31°.5	31°.66 – 32°
Mars	62°.03 – 80°.98	63° – 81°	72° – 75°
Mercury	30°.16 – 22°.60	31°.5 – 22°.5	28° – 30°
Jupiter	32°.07 – 35°.75	31°.5 – 36°.5	32° – 33°
Venus	18°.22 – 09°.42	18° – 9°	11° – 12°
Saturn	42°.09 – 58°.43	40°.5 –58°.5	48° – 49°

Table 10: Discrete values of the equation of the conjunction (*śīghrāṅkas*) of the planets.

Planets	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
Mars	58	117	174	228	279	325	365	393	400	368	249	0
Mercury	41	81	117	150	178	199	212	212	195	155	89	0
Jupiter	25	47	68	85	98	106	108	102	89	66	36	0
Venus	63	126	186	246	302	354	402	440	461	443	326	0
Saturn	15	28	39	48	54	57	57	53	45	33	18	0

the case of the Sun and the Moon the peripheries vary as in the *Sūryasiddhānta*.

4 EQUATION OF THE CONJUNCTION OF THE PLANETS

Gaṇeśa Daivajña has provided *śīghrāṅkas* similarly as in the case of the equation of the centre (*mandaphala*) for the convenience of computation. Actual equations of the conjunction (*śīghrāphalas*) are obtained from these *śīghrāṅkas* dividing by 10. The discrete numerical values of *śīghrāṅkas* for the intervals of 15° degrees are listed in Table 10.

In order to determine the *śīghra* peripheries of different planets we adopt the following procedure:

$$\text{\textit{Śīghraphala}}\ (SPH) = \sin^{-1}\{[(p/360)\sin(SK)] / \sqrt{[(p/360)^2 \pm 2(p/360)\cos(SK) + 1]}\} \qquad (8)$$

where p in the *śīghra* periphery, SPH is the *śīghraphala* and SK is the anomaly of the conjunction (*śīghrakendra*).

Here SK is the anomaly of the conjunction (with the Sun) i.e., SK is the Mean Sun – Mean planet for the superior planets. In the case of Mercury and Venus, SK is the Mean planet – Mean Sun.

Let $(p/360) = r$ (9)

$$SPH = \sin^{-1}\{[r\sin(SK)] / \sqrt{[(r)^2 \pm 2(r)\cos(SK) + 1]}\} \quad \text{or}$$

$$\sin(SPH) = \{[r\sin(SK)] / \sqrt{[(r)^2 \pm 2(r)\cos(SK) + 1]}\} \qquad (10)$$

On squaring both the sides and simplifying equation (10) we get a following equation:

$$r^2\sin^2(SPH) + 2r\ \cos(SK)\sin^2(SPH) + \sin^2(SPH) - r^2\sin^2(SK) = 0$$

$$[\sin^2(SPH) - \sin^2(SK)]\,r^2 + 2\cos(SK)\sin^2(SPH)\,r + \sin^2(SPH) = 0$$

This equation is of the form $Ar^2 + Br + C = 0$, which is a quadratic equation, where $A = [\sin^2(SPH) - \sin^2(SK)]$, $B = 2\cos(SK)\sin^2(SPH)$ and $C = \sin^2(SPH)$.

The roots of a quadratic equation $Ar^2 + Br + C = 0$ are:

$$r = \{-B \pm \sqrt{[B^2 - 4AC]}\} / 2A$$

$$r = \{-B + \sqrt{[B^2 - 4AC]}\} / 2A \quad \text{or}$$

$$r = \{-B - \sqrt{[B^2 - 4AC]}\} / 2A$$

Between these two roots, the valid solution is provided by the equation

$$r = \{-B - \sqrt{[B^2 - 4AC]}\} / 2A$$

From equation (9) we have $p = 360° \times r$.

Thus the *śīghra* periphery

$$p = 360° \times \{-B + \sqrt{[B^2 - 4AC]}\} / 2A \qquad (11)$$

Using the above equations we computed the *śīghra* peripheries of Mars and listed the values in Table 11.

Table 11*: Śīghra* periphery of Mars.

SK	*SPH*	*Śīghra* periphery (*p*)
15°	5.8	227°.545
30°	11.7	232°.500
45°	17.4	232°.366
60°	22.8	230°.740
75°	27.9	229°.958
90°	32.5	299°.345
105°	36.5	230°.150
120°	39.3	231°.054
135°	40.0	232°.287
150°	36.8	234°.621
165°	24.9	236°.297
180°	0	0°

From Table 11 as SK varies from 15° to 165° the *śīghra* periphery '*p*' varies from 227°.545 to 236°.297. We express the *śīghra* periphery '*p*' for any given SK in the form

$$p = A + B\sin(SK) \qquad (12)$$

To determine A and B we choose, for example SK = 30° and 165°. By solving the linear equations, we obtained A = 240°.372 and B = –15°.7429.

When SK = 0° or 180° equation (12) becomes $p = A$. Hence we can determine the *śīghra* peri-

Table 12: The range of *śīghra* peripheries of all the planets for *MK*= 0° and 90°.

Planet	*Śīghra* periphery (*p*)	
	SK (0°)	*SK* (180°)
Mars	230°.8441	236°.2975
Mercury	133°.0147	137°.4724
Jupiter	68°.1567	72°.55133
Venus	259°.0559	262°.653
Saturn	37°.13942	40°.36791

Table 13 : Comparison of *śīghra* periphery values from different texts.

Planet	Computed Values Based on the *GL*	The *Āryabhaṭīya*	The *SūryaSiddhānta*
Mars	230°.8441 – 236°.2975	229°.5 – 238°.5	232° – 235°
Mercury	133°.0147 – 137°.4724	130°.5 – 139°.5	132° – 133°
Jupiter	68°.1567 – 72°.55133	67°.5 – 72°	72° – 70°
Venus	259°.055 – 262°.653	256°.5 – 265°.5	260° – 262°
Saturn	40°.36791 – 37°.13942	40°.4 – 36°	40° – 39°

pheries of planets from the range of *SK* = 0° to 180° which are listed in Table 12.

The above values of *śīghra* peripheries are compared with other texts to draw a conclusion on our method of computation (see Table 13).

5 CONCLUDING REMARKS

In the above sections we have analyzed the discrete *mandāṅkas* and *śighrāṅkas* given in the *Grahalāghava* of Gaṇeśa Daivajña. We have obtained the ranges of the corresponding *manda peripheries for all bodies* and *śīghra* peripheries for the five planets and compared them with those of the *Āryabhaṭīya* and in the *Sūryasiddhānta*. We find that the ranges of peripheries of planets are closer to those of the *Āryabhaṭīya*, while ranges of *manda* peripheries of the Sun and the Moon vary as in the *Sūryasiddhānta*. However the results obtained are approximate ones; the reasons for this are:

(1) The equation of the centre and the conjuncttion (*manda* and *śīghraphalas*) given in the *GL* are over wide intervals of 15°; and
(2) The given numerical values are in integers, avoiding fractions in the case of the five planets.

The constants *A* and *B* in equations (7) and (8) obtained are slightly different for different choices of related linear equations. This discrepancy is due to the approximations mentioned above.

6 NOTES

1. Āryabhaṭa I (born 476 C.E) gives, just in one *śloka* (verse), the rule to obtain the *jyā* (*R* sine) of any angle between 0° to 90° at an interval of 3° 45′. He gives the differences between successive values in arc-minutes (*kalās*). Āryabhaṭa's value for the constant co-efficient *R* is 3438′, which is the nearest integer value to a radian.

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DID ABORIGINAL AUSTRALIANS RECORD A SIMULTANEOUS ECLIPSE AND AURORA IN THEIR ORAL TRADITIONS?

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Abstract: We investigate an Australian Aboriginal cultural story that seems to describe an extraordinary series of astronomical events occurring at the same time. We hypothesise that this was a witnessed natural event and explore natural phenomena that could account for the description. We select a thunderstorm, total solar eclipse, and strong *Aurora Australis* as the most likely candidates, then conclude a plausible date of 764 CE. We evaluate the different factors that would determine whether all these events could have been visible, include meteorological data, alternative total solar eclipse dates, solar activity cycles, aurorae appearances, and sky brightness during total solar eclipses. We conduct this study as a test-case for rigorously and systematically examining descriptions of rare natural phenomena in oral traditions, highlighting the difficulties and challenges with interpreting this type of hypothesis.

Keywords: Aboriginal Australians; oral traditions; cultural astronomy; geomythology; solar eclipse; *Aurora Australis*

Warning to Aboriginal Readers: This paper contains references to cultural subjects that may not be appropriate for the reader.

1 INTRODUCTION

The oral traditions of Aboriginal Australians are multi-layered and multi-faceted. Within these traditions are descriptions of natural events, both mundane (e.g. lunar phases) and rare (e.g. eclipses). These descriptions often are incurporated into a narrative, or storyline, which can include mythological elements. This serves as a mnemonic for remembering the information encoded in the story.

In this paper, we examine an oral tradition recorded by Peck (1933) from an Aboriginal person that appears to describe simultaneous rare natural events. There are several explanations for this oral tradition. The description could be based on a witnessed event. It could be purely 'mythological' in nature, serving a symbolic and/ or mnemonic purpose. It is also possible that elements of the story could have utilised a degree of 'poetic license' by Peck. It is difficult to know the reasons, but some of them can be tested.

We hypothesise that the story reflects a living memory of simultaneous natural events that were witnessed and recorded in oral tradition. We test our hypothesis by exploring various natural phenomena that the tradition could be describing, then utilise historical records and scientific studies to test each one rigorously to identify the phenomena that best fit the narrative in the storyline.

This study serves as a test case for showing how the methods and frameworks of cultural astronomy and geomythology can be used rigorously to examine Aboriginal oral traditions for records of natural events. Our analysis is not conclusive, but rather highlights the various challenges and uncertainties researchers face when conducting this type of research.

Cultural astronomy is the study of the effect of astronomical knowledge or theories on ideologies or human behaviour (Campion, 2004), sometimes called the 'anthropology of astronomy' (Platt, 1991). It incorporates the sub-disciplines of archaeoastronomy (the study of past cultures, relying heavily on the archaeological record), ethnoastronomy (the study of contemporary cultures, relying heavily on the ethnographic record) and historical astronomy (the study of written records about astronomical objects and phenomena). A related field, geomythology, examines geological events described in oral and material traditions (Vitaliano, 1968). These disciplines are highly interdisciplinary, drawing from the social sciences, humanities, and natural sciences.

2 THE STORY

Aboriginal stories generally were collected and recorded by non-Aboriginal people. These individuals were often missionaries and 'explorers' in the early days of European colonisation, followed later by linguists, ethnographers and government-agents. In the early 1900s, a number of people published collections of Aboriginal stories as popular books. As part of a project exploring the Aboriginal astronomical traditions of the Sydney region, we identified an unusual story in one of these books that seems to describe simultaneous rare sky phenomena.

In 1925 Charles W. Peck published a book about Aboriginal stories titled *Australian Legends: Tales Handed Down from the Remotest Times by the Autochthonous Inhabitants of our Land*, which "… is by far the richest source of Illawarra Dreaming stories …" (Organ, 2014: 54), from the areas west and southwest of Sydney. Charles Peck (1875–1945) was born on the south coast of New South Wales, and was a schoolteacher from the age of 16, only breaking his career for two years to serve in the First World War. He travelled to areas around Sydney after 1920, including the Blue Mountains and the Burragorang Valley, to collect stories from Aboriginal people (Organ, 2014). At the time of the publication of the first edition of *Australian Legends* … in 1925 he was one of only a handful of writers who treated Aboriginal cultural stories with the respect they deserved as often accurate depictions of natural events. His sources are not definitely known, but Michael Organ, who has written on Peck and *Aboriginal Legends* (ibid.), has confirmed that Peck's stories are faithful, and not embellished linguistically (Organ, pers. comm.). Although not an academic, Peck clearly understood the importance of the stories that he collected, and that they would be a valuable resource for future researchers.

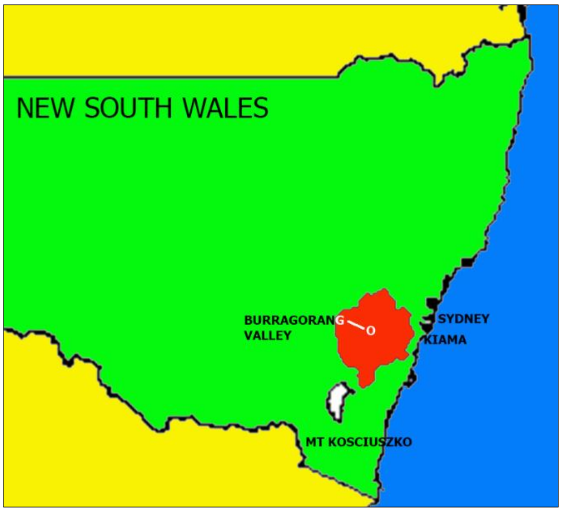


Figure 1: The location of Peck's story (Commonwealth of Australia, NNTT).[1]

This story is centred on the Burragorang Valley (Figure 1), however, Peck does not identify a specific Aboriginal community where he obtained the story, and it could have come from several different communities in that area.

The story, entitled "The First Kangaroo" (Peck, 1933: 85–86), tells how the first kangaroo was borne to Australia upon the "… greatest wind that ever blew." It was blowing across Australia from Perth (on the far western coast of the Australian continent) to the area of the story, where it was able to touch down. At the same time, an Aboriginal leader was searching for new country, and saw the following in the sky:

> The strangest mass of cloud he had ever seen was there. It was sepia coloured with black edges. It seethed and curled and split. It billowed and curled and broke – and frayed out. Long spirals of lighter colour worked wonderful patterns against the brown, but drawing out and contracting, waving like giant battle-plane streamers, now straight as spears, now bent over like millions of boomerangs, now detaching, then adhering; the awe-striking masses of vapour came on from the west. Big rocks were tumbling there. Hugh walls built up and tottered over and tumbled and crashed. Giant forests were born and waved in a giant storm and were felled. And with all that turmoil of vapour up aloft, the earth below was calm and serene. It faced an inevitable, and inevitable was a catastrophe.
>
> Suddenly it grew dark.
>
> A night in the daytime descended in a second, blotting out everything. But in the heavens a wondrous light appeared. Long streams of liquid fire started from the south, and shot sheer across the heavens from pole to pole. They waved from west to east. Red and yellow, purple and brown, pink and grey, golden and black, white and pale green. All these colours in long straight fingers stretched from pole to pole, waved and crossed, and passed away towards the east. The unfortunate black man had never seen such a sight.
>
> But he had heard of it.
>
> It seemed to him that perhaps once in a lifetime a man was privileged to see such a thing. He cowered before it. Then came the tornado. With the wind the lights waved out and the clouds passed, and the night (for it was really night then) showed starlight and clear.

The story goes on to describe the arrival of the first kangaroo, and the leader's further investigation of the new country. The story says Aboriginal people from a large area witnessed this event, ranging from Mt. Kosciusko in the south, the Nepean River in the north, Kiama to the east and Goulburn to the west, also including Mittagong, Currockbilly Mountain, Burragorang, and the Monaro District (Figure 2).

This remarkable description of multiple phenomena in the sky easily could be mistaken for a mythological story, which may be the case. But is it more than this? Could this story describe an actual event or events, as fantastic as it appears to be? We study this possibility.

3 METHODS

We examine a range of possible phenomena that could explain the three natural events:

Figure 2: Map of south-eastern New South Wales, the Australian Capital Territory, and north-eastern Victoria, featuring places mentioned in the oral tradition from where the event was visible. The story is centred on the Burragorang Valley (generated using Google Maps).

1. A large thunderstorm cell;
2. Something causing the day to turn to darkness very quickly; and
3. The appearance of multi-coloured streams of light stretching across the sky.

The approaching mass of cloud seems to be a clear description of a large thunderstorm cell, which are common in the Blue Mountains.

The sudden darkening of the sky could be attributed to cloud cover, but this seems an unlikely explanation given the description. Rather, an eclipse of the Sun seems to better fit the description in the story. The sky will only turn noticeably dark during a total solar eclipse. A partial eclipse can pass relatively undetected. A total solar eclipse would explain how the light display in the sky could be seen, which would not occur if the sky were over-cast. Partial eclipses largely are ignored, as Hughes (2000: 205) calculated that it is possible for a person to miss the change in sky brightness that would signal an eclipse when the Moon covers less than 93.7% of the Sun's disc.

As for the light display, we consider several atmospheric phenomena, including nacreous clouds, Sun pillars, parhelia, lightning sprites and the *Aurora Australis*. Nacreous clouds (Figure 3(A)) are very high-altitude clouds illuminated by the Sun that can exhibit a wide range of colours, including many of those mentioned in the story. These clouds can also exhibit long streams, but there are a number of behaviors in the story that nacreous clouds do not exhibit, including "… waving from west to east …" (they do move, but very slowly), and their location is normally from about 50º to 60º latitude (although they can be seen further from the poles).[2] Sun pillars (Figure 3(B)) are caused by low angle sunlight reflecting from horizontal ice crystals.[3] There is no reported evidence of Sun pillars moving rapidly in the sky. Parhelia, also known as sundogs (Figure 3(C)), are a similar phenomenon formed when sunlight reflects off ice crystals, creating a halo effect around the Sun.[4] Under certain conditions, smaller phantom Suns can be visible on either side of the Sun. Generally, they are seen when the Sun is near the horizon, and under the right conditions can produce a range of colours. Sundogs and parhelia are not associated with the movement of the lights described in the story. A solar eclipse would rule out Sun pillars, parhelia and possibly the nacreous clouds (except in areas near the edge of the path of totality). Given a description of an approaching storm cell, lightning sprites (Figure 3(D)) are another possibility. These transient luminous events are high altitude plasma discharges that can appear as large reddish flashes in the sky, similar to lightning (Füllekrug

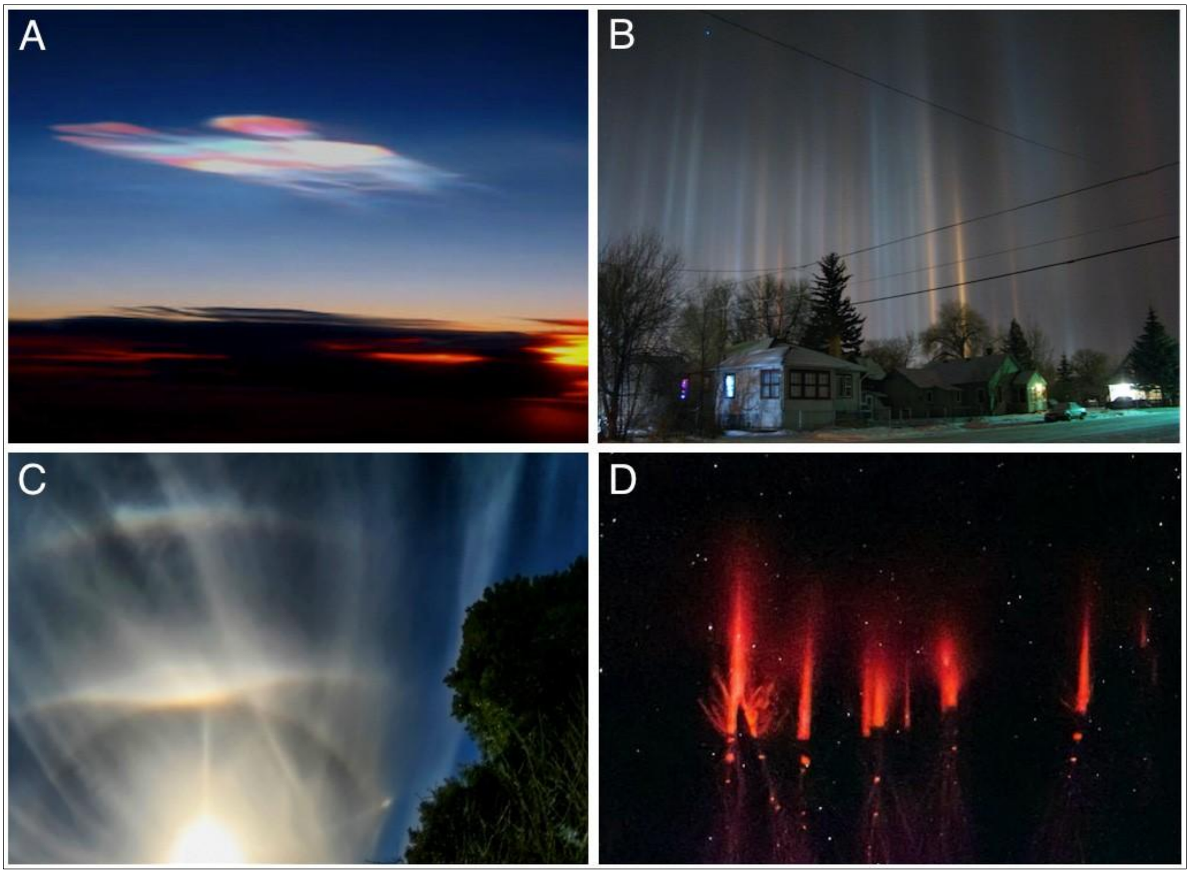


Figure 3: (A) Nacreous cloud (Wikipedia Commons: Foobaz); (B) Light pillars (Wikipedia Commons: Christoph Geisler); (C) Parhelia/solar halo phenomenon (Wikipedia Commons: Brocken Inaglory); (D) Lightning sprites (University of Alaska: Jason Arhens, Creative Commons).

et al., 2006). They occur on very short timescales (fraction of a second), but could certainly have been visible during the event in question given the approaching thunderstorm. However, sprites would not be able to produce the full display described in the story (Heavner, 2016).

Our final consideration is that the story describes an unusually bright display of the *Aurora Australis*. The *Aurora Australis* is recorded in Aboriginal traditions across the southern half of Australia (Hamacher, 2013) and as far north as southwestern Queensland and the Central Desert. Technically, aurorae can occur on any day of the year and in any year. They also can be seen far closer to the Equator, depending on the intensity of the event. For example, Willis et al. (1996) report on an aurora that was seen on 16 September 1770 by Cook and others on the *Endeavour* when it was at latitude 10º South and to the north of Australia. This aurora also was reported by Chinese and Japanese observers. Aurorae also were seen in Cuba and Hawaii during the Carrington Event in 1859 (Windridge, 2016). However, events seen at latitudes near the equator are rare and the frequency and intensity of aurorae are generally dependent on cyclic solar activity and the latitude of observers. Aurorae are more frequent within the auroral zones—a ring-shaped band stretching around the Earth's poles where auroral displays are the strongest and most frequent. While dynamic and changing, the northern edge of the southern auroral zone can extend to the far southern extremities of Australia, such as southern Victoria, South Australia, Western Australia, and all of Tasmania.

While uncommon, aurorae are visible from the Sydney region. Powerful geomagnetic storms resulting from a large solar coronal mass ejection (CME) can expand the range of visibility on the Earth and increase the intensity of the display. On the night of 1–2 September 1859, a CME led to a powerful auroral display that was visible from tropical latitudes such as Queensland, Australia, Cuba, Sub-Saharan Africa, Colombia, and Hawaii (Cárdenas et al., 2016; Green, 2005).

But do significant auroral displays exhibit the characteristics described in the story, and can they be seen during a total solar eclipse? The story describes "… long streams of liquid fire …" in "… red and yellow, purple and brown, pink and grey, golden and black, white and pale green." Several references (e.g. Douma, 2008, Tate, 2016, Trondsen, 1998: 86–88) describe the possible colours of aurorae to include all of those mentioned in the story, assuming brown could be

Figure 4: Strong displays of the *Aurora Borealis* over Norway. Displays like this could potentially be visible over the Sydney region during a powerful geomagnetic solar storm, such as the 1–2 September 1859 Carrington Event (Telegraph.co.uk: Tommy Eliassen).

a dark red, and purple could be a dark blue. Grey is an absence of colour due to low light intensity, and is seen in aurorae (Windridge, pers. comm., 13 October 2016). The description of streams of liquid fire waving from west to east is typical of aurorae bands following the Earth's geomagnetic lines and the colours "… in long straight fingers …" (Peck, 1933) are seen in curtain-like bands in aurorae (Windridge, 2016); Figure 4 (left image).

Critical to our hypothesis is whether an auroral display of this magnitude could be seen in the brief darkness of a total solar eclipse? Silverman and McMullen (1975) investigated the sky brightness during total solar eclipses in 1963, 1966 and 1970, and reported that it was not uncommon for observers to see 3rd magnitude stars during totality. They estimated that the sky brightness at totality was equivalent to approximately –5° to –7° of solar elevation during twilight, or the equivalent of 10^{-3} the brightness of the daytime sky. Können and Hinz (2008) also reported that +3.5 magnitude stars were visible during totality. More recently, Zainuddin et al. (2013) measured the sky brightness during a 2009 total eclipse at Hangzhou, China, using a Sky Quality Meter. At totality, they measured the sky brightness as 16.13 mag/arcsec^2 at the zenith. This enables us to compare the brightness of aurorae. The brightness measure for aurorae is based on the International Brightness Coefficient, Classes I, II, III and IV, which are expressed in kilo-Rayleighs. A Rayleigh is a unit of photon flux (see Hunten et al., 1956).

To compare auroral brightness to the sky brightness at totality requires finding equivalent (visual) mag/arcsec^2 values for the IBC Classes, which are not part of the IBC data. The brightness of the Milky Way, which is the equivalent of IBC Class I, is magnitude 21.4 (Crumley, 2014). The brightness of the full Moon (IBC Class IV) is magnitude –12.6 (Strobel, 2010). The sky brightness equivalents for Classes II and III are 21.1 and 18.0, respectively. We calculate these values by fitting the data to a linear (log) plot (Figure 5). The Class III value of 18.0 mag/ arcsec² is within the range of the *B*, *V*, and *R* bands (16.6 to 18.5) reported by Dempsey et al. (2005). This provides a first order approximation.

Using Zainuddin et al.'s (2013) measured sky brightness of 16 mag/arcsec² during the 2009 eclipse, we calculate that an auroral flux of approximately 185 kilo-Rayleighs is necessary for an aurora to equal this sky brightness, and a flux exceeding this value if it were to be visible during a total eclipse. Therefore, for an aurora to be visible during a total solar eclipse, it would need to have a brightness between Class III and IV (see Table 1).

We consider a significant display of the *Aurora Australis* to be the best description of the light display in the story, although lightning sprites could also have been visible given the approaching thunderstorm. Therefore, the best fit to the description in the story is an approaching large thunderstorm, a total eclipse of the Sun, and a simultaneous strong auroral display. Two of these (eclipse and aurora) are extremely rare events. The probability of them occurring simultaneously is very low, but we will demonstrate that this is possible under the right conditions.

If this is the case, can we use scientific studies and historical records to pinpoint when this event may have taken place?

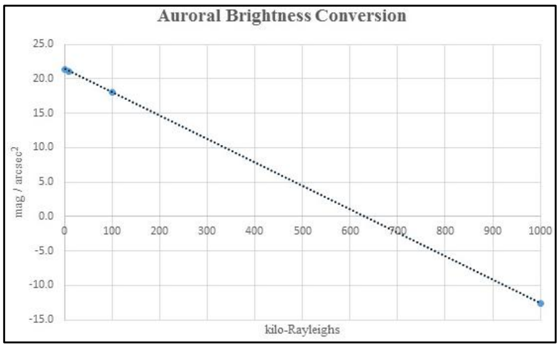
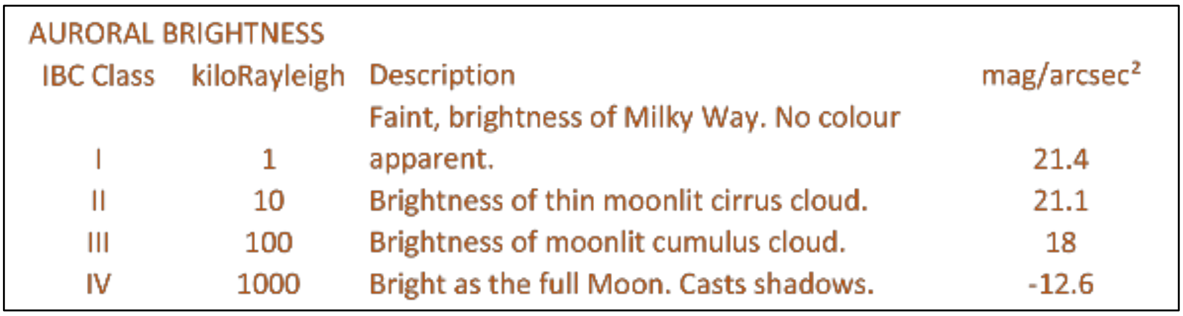


Figure 5: A linear plot fitting data of sky brightness (mag/arcsec^2) versus auroral photon flux (kilo-Rayleighs) using data from Crumley (2014) and Strobel (2010).

Table 1: International Brightness Coefficient (after Thomson, 2016).



AURORAL BRIGHTNESS

IBC Class	kiloRayleigh	Description	mag/arcsec²
I	1	Faint, brightness of Milky Way. No colour apparent.	21.4
II	10	Brightness of thin moonlit cirrus cloud.	21.1
III	100	Brightness of moonlit cumulus cloud.	18
IV	1000	Bright as the full Moon. Casts shadows.	-12.6

Table 2: Data for the five total eclipses visible from the Burragorang valley between 1500 BCE and CE 1900. Data include the year, time of maximum totality, the duration of totality and the altitude of the Sun at totality. We also show the maximum eclipse coverage (as a percentage of the Sun's disc) visible from Mt. Kosciusko, Kiama, Mt Currockbilly, Goulburn and the Nepean River. Values in red are those that fall below the 93.7% visibility threshold.

Year	Date	T $_{\text{max tot.}}$	D	Alt	Mt K.	Kiama	C'billy	G'burn	N. River
189 CE	27 October	15:04:53	1m 41s	40º	96.3	100	99.9	100	99.5
196 CE	14 June	08:31:04	2m 41s	15º	99.0	99.8	99.2	100	100
764 CE	28 November	13:43:14	2m 52s	63º	96.6	100	99.2	100	100
1033 CE	04 January	12:43:19	2m 04s	76º	93.3	98.9	96.6	99.2	100
1857 CE	25 March	10:47:15	1m 24s	8º	92.6	98.7	96.1	98.8	100

4 ANALYSIS

To identify the date of the event, we establish the following ranking criteria:

1. The solar eclipse should be total in the Burragorang Valley area, centring on the Valley, and should be visible as a total or high percentage-coverage partial eclipse (>93.7% of solar disc coverage) from all locations described in the story. We reject annular eclipses.
2. There should be a high probability of an *Aurora Australis* being visible in Southeast Australia during the year of the nominated solar eclipse or historical records of aurora in that year.
3. There should be a high likelihood of a thunderstorm occurring in the area of the event at the time of year and time of day the eclipse took place.

With respect to criterion #1, we used the Alcyone Eclipse Calculator[5] and the NASA Javascript Solar Eclipse Explorer[6] to search for total solar eclipses with the path of totality passing over the Burragorang Valley (33º 56′ S, 150º 24′ W). Our search was limited to the period between 1500 BCE and CE 1900 for this study so as to work within the limitations of eclipse calculating software. We acknowledge that the event may have occurred at an earlier date. We ignored the period CE 1900 to 1925, as this is the period that Peck may have been told the story, and there were no relevant eclipses in this period.

We identified five total solar eclipses visible from the Burragorang Valley in this time frame and calculated the visibility of this eclipse from the locations described in the story (Table 2). Any eclipses that fell below the 93.7% threshold were rejected. Of the five eclipses identified, two (CE 1033 and 1857) were rejected as they fell below the visibility threshold as seen from Mt Kosciusko. This left three candidate eclipses, which occurred in CE 189, 196 and 764 (Figure 6).

To address criterion #2, we searched for evidence of a major auroral event that would have occurred during the time of the CE 189, 196 and 764 eclipses. Attolini et al. (1988: 12,733) established an 11.4-year periodicity in the period CE 1180–1450 through the record of ^{10}Be deposits in polar ice (^{10}Berylium is a by-product of solar particle interaction with the upper atmosphere). Through historic reports of aurorae for the period 687 BCE to CE 1720, they also were able to establish a variable periodicity of aurorae in the range of 9.5 to 11.5 years.

Usoskin et al. (2013) reported a CE 774–776 SEP (solar energetic proton) event calculated at >30 MeV (the Carrington Event of 1859 was similarly assessed as >30 MeV). This CE 775 event was determined by ^{10}Be deposits in polar ice samples and ^{14}C measurement in trees. The CE 774 event is the strongest spike in the last 11,000 years of cosmogenic isotope records (Usoskin and Kovaltsov, 2014). Strong aurorae were recorded in a number of historical records in CE 770 and 776 (Yau et al., 1995).

Assuming that the CE 775 event took place at the maximum part of the Sun's periodic activity, then subtracting an average 11.4-year periodicity would mean that in CE 764 the Sun would only just be past its maximum peak. Švesta (1995) and Bai (2006) both suggest that the declining phase of a solar cycle often has energetic solar events, such as CMEs. The variable periodicity of aurorae for this time suggests that CE 764 could be consistent with the declining phase of a peak in solar activity, with ths possibility of a CME resulting in a aurorae.

We investigated whether the location of the South Magnetic Pole (SMP) (the Dip pole, where the lines of electromagnetic force are vertical) might have a bearing on the strength of the aurora at the Burragorang Valley. Historical records of the SMP exist from 1590 CE, and the National Oceanic and Atmospheric Administration (NOAA) publishes a historical declination map (Historical Magnetic Declination Viewer)[7] from that date. During that period, the SMP has been located along the coast of Antarctica, moving west from approximately 170º W longitude to 130º E at present, which is directly South of the Great Australian Bight. Extrapolating the movement back to CE 764, assuming that the movement has been west along the Antarctic coast, would put the SMP somewhere under South America, which is opposite Australia. If anything, this means that aurorae would have been centered further south of the Australian continent in CE 764, but any movement before CE 1590 is only conjecture.

Further evidence of a possible peak period coinciding in CE 764 was inconclusive. McCracken et al. (2001) examined the Gleissberg periodicity of sunspot activity (an 80-year cycle which has a peak in solar particle events in the middle of the cycle) between the years CE 1561 and 1994. Working backwards from the peak year CE 1620 of the CE 1580–1660 Gleissberg cycle (ibid.) in 80-year increments, the closest peak to CE 764 is CE 740, which means that CE 764 is on the 'shoulder' of the peak in that cycle. Steinhilber et al. (2009) used ^{10}Be records from polar ice to establish a Total Solar Irradiance (TSI) record for the Holocene over the last 9,300 years. This 40-year cycle (ibid.) does not show any peaks near CE 764. Rather, it shows a possible minimum around CE 700.

Using CE 775 as a peak in the various estimated solar cycles (11, 11.4, and 11.8-year cycles), we extrapolate backwards to CE 189 (586 years). None of the results shows the CE 189 eclipse as occurring near a peak in solar activity. Using the first solar maximum year reported (CE 1620), the CE 189 eclipse would have occurred on the shoulder period extrapolating back using the 80-year Gleissberg periodicity. From historical records, Chinese aurora accounts show activity on CE 24 November 195 (Yau et al., 1995: 2). This is pushing the data to its limits and is only a rough first-order estimate: there is little evidence for auroral activity in CE 189 or that this was a peak of any solar cycle maxima estimates.

As for criterion #3, Rasuly (1996) found that Katoomba, in the Blue Mountains 40 km from the centre of the Burragorang Valley, has the highest number of thunderstorm days, and the highest thunderstorm rainfall annually, in the entire Sydney Basin (which extends from Newcastle to Wollongong). Rasuly (1996: 199) also found that thunderstorm frequency is highest in the Spring and Summer (October to February) in the Sydney Basin, with a peak in November. Therefore, we reduce the ranking of eclipses occurring outside of this time frame. Thunderstorms are also more likely to occur in the afternoon and evening, as they tend to form at the warmest and most humid times of the day. Therefore, highest ranking will be given to eclipses that are visible at totality in the late afternoons or early evenings from October to February.

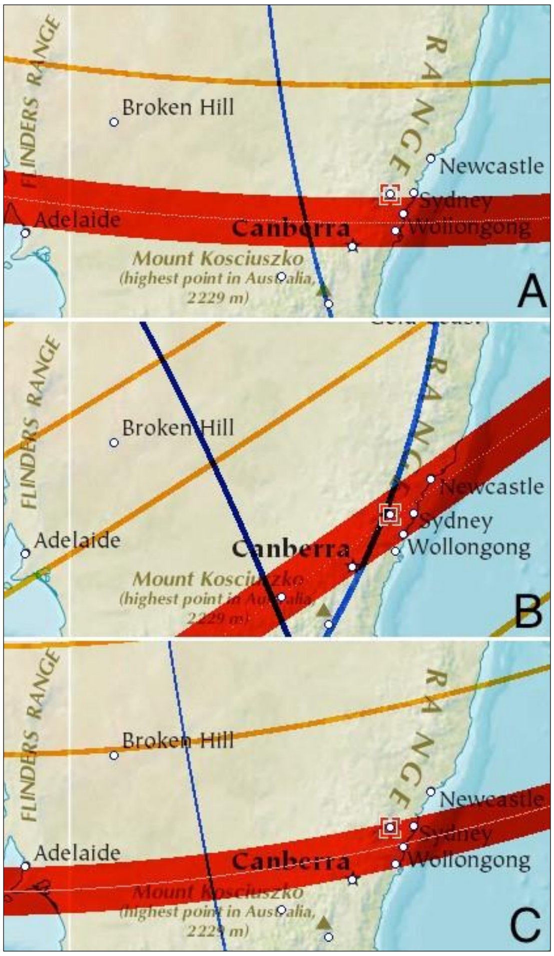


Figure 6: The paths of the three eclipses that meet the first criterion: (A) CE 189, (B) CE 196 and (C) CE 764. The box west of Sydney denotes the Burragorang Valley. The triangle in the bottom-centre denotes Mt Kosciusko (created with the Alcyone Eclipse Calculator).

Another line of evidence for the time of year the story may have taken place is in reference to the Aboriginal leader following a native bee (*Tetragonula carbonaria*) to its hive. Honey was a food source for Aboriginal people, and bees are most active from November to March (Dollin et al., 2000). This indicates the story may have occurred at a time between late spring and early autumn.

We developed a ranking system to estimate how well each candidate fitted these criteria (rejecting any that did not meet criterion #1). The points system was intended to reflect the probability of each category supporting the data. For example, auroral activity is difficult to determine, so a combination of historical accounts and the year being within the solar maxima attains a high rank, while those candidates not meeting these criteria were given a very low rank. The next two categories reflect the probability thunderstorms will occur at a particular time of the year and day. Since thunderstorms can occur at any time of the year or day, the point system is not as far removed between top and bottom ranking and therefore is worth less overall.

Auroral Activity:

- The eclipse coincided with a peak in the solar cycle in that year, and records of aurorae visible in that year could be identified. 5 points.
- The eclipse coincided with a peak in the solar cycle in that year, but it was not mentioned in the historical record. 3 points.
- The eclipse did not coincide with a peak in solar cycle in that year, or in the historical record. 1 point.

Time of Year:

- The eclipse occurred in November, coinciding with a peak in thunderstorm activity in the region. 4 points.
- The eclipse occurred in the period between October and February, but not November, coinciding with the period of more frequent thunderstorms (and bee activity). 3 points.
- The eclipse occurred in the period between March and September. 2 points.

Time of Day

- The eclipse occurred in the afternoon or early evening. 2 points.
- The eclipse occurred in the morning. 1 point.

Each candidate was ranked using the following guidelines:

- 10–11 points: Highly supported by the data
- 7–9 points: Moderately supported by the data
- 4–6 points: Poorly supported by the data

For each eclipse event, the combined scores are ranked as follows: CE 764 (9), 189 (6) and 196 (4). Note that none of the candidates received a top ranking of 'highly supported'. Of the three candidates, the CE 764 eclipse best fits the description in the story, but it is only moderately supported by the data.

5 DISCUSSION

We conclude that it is plausible that a thunderstorm, solar eclipse and auroral display could have occurred at the same time in the Burragorang Valley. Our best fit date to the description, assuming this event occurred within the 3,400-year time frame of this analysis, is on the afternoon of CE 26 October 189 or CE 28 November 764 (the latter achieving a higher ranking). We acknowledge that this is inconclusive and an aurora and eclipse happening simultaneously is highly improbable, but not impossible.

It is also possible that the Burragorang story is an amalgamation of two or even three events witnessed in the sky at different times. Certainly, a total solar eclipse and a strong aurora (at night) on different dates would be memorable (for example, the CE 764 eclipse and the CE 774–775 auroral event), and incorporating them into a single story featuring the more frequent appearance of a thunderstorm could add a dramatic element to serve a mnemonic function.

It is equally plausible that this is a description of a witnessed natural event that occurred much earlier than the time period of our study. With an Aboriginal presence in the Burragorang Valley stretching back at least 15,000 years (Attenbrow, 2010), the story could be much older. Aboriginal oral traditions are flowing and dynamic, not static in time. Oral traditions often incorporate new information and new events. The story reported by Peck may or may not be an example of this.

A key question often asked about Aboriginal oral traditions is how long they could be transmitted from generation to generation without loss of fidelity? Hamacher and Norris (2009), and Hamacher and Goldsmith (2013) have demonstrated that records of volcanic and meteoritic impact events in Aboriginal oral traditions extend back from 4,000 to >10,000 years ago. Meanwhile, Nunn and Reid (2015) reported Aboriginal oral traditions of sea level change around Australia's coastline dating back more than 7,000 years. Research by Kelly (2016: 29) may explain the mechanism whereby Aboriginal communities can use "… knowledge … passed down accurately within oral tradition for a thousand years." Kelly's research focused on the concept of a memory code created by using fixed objects such as landscape or night sky to encode memory over long periods of time. Thus, the idea that the memory of a rare natural event in CE 764 recorded in oral tradition surviving to 1925 is entirely plausible.

Upon reviewing the events mentioned in Peck's book and witnessed by the Aboriginal leader, the sequence at the very end initially was of concern *vis-a-vis* our hypothesis:

> Then came the tornado. With the wind the lights waved out and the clouds passed, and the night (for it was really night then) showed starlight and clear.

The time of totality of the CE 764 eclipse was in the early afternoon. Astronomical twilight (when the Sun is 18° below the horizon and the sky is

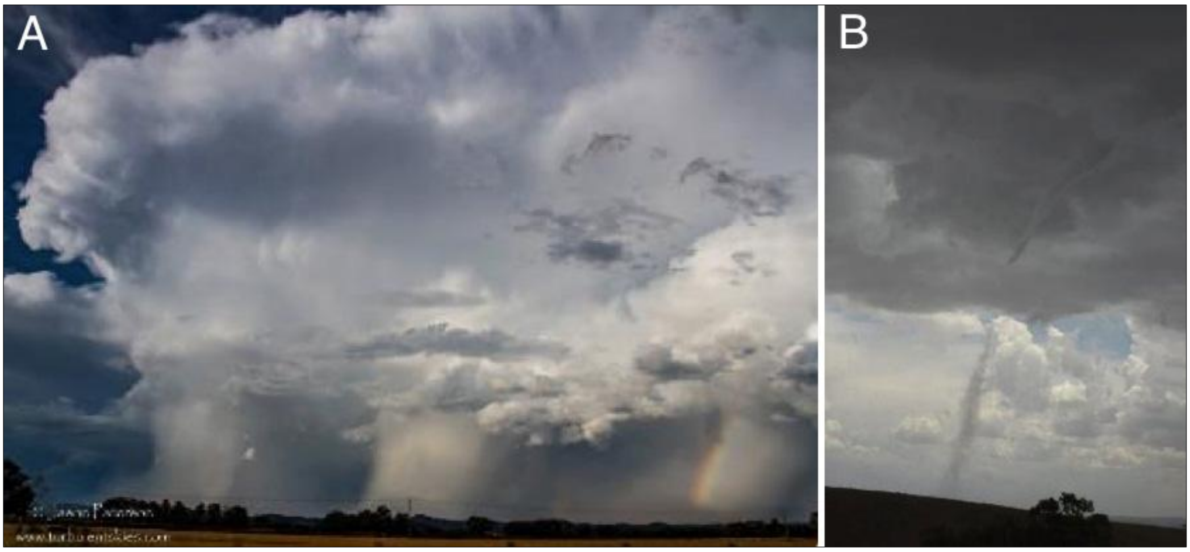


Figure 7: (A) Supercell thunderstorm. Lismore, NSW (Jason Paterson), (B) Tornado at Bathurst, NSW on 16 December 2015 (Ray Pickard).

effectively dark) was not until 19:54 on the evening of 28 November. What happened in the intervening time between totality and the sky becoming dark? We suggest one possibility is that the ‘tornado’ was the arrival of the thunderstorm (Figure 7A), which had been coming from the west but had not reached the Aboriginal person mentioned in the story. Thus, the person was able to see the sky during totality to observe the *Aurora Australis*. Before totality was over, the thunderstorm passed overhead, blocking off the view of the sky, and reducing the light level significantly. Thunderstorms in the Blue Mountains can be very large (Rasuly, 1996: 47) and take some time to clear to the East. Rasuly (1996: 49, their Figure 2.10) also shows that they start over higher terrain to the west of the Blue Mountains in the time 13:00 to 16:00, and move eastwards in the time 16:00 to 19:00 (while still being active in the Burragorang area). So, it is possible that it was nearly dark by the time the sky had cleared, and that the story, while not being detailed in terms of time, may have reflected the sequence of events. Night would have fallen six hours after the eclipse.

Another possibility is that the ‘tornado’ in question was actually a meteorological tornado (Figure 7B). On 20 November 1994, an estimated F0/F1 tornado struck Yellow Rock in the Blue Mountains, so tornadoes have occurred there.[8] As most tornadoes are concurrent with thunderstorm activity, both could have occurred on the day in question.

6 CONCLUSIONS

We determine that the Burragorang story recorded by Peck (1933) is a *plausible* description of the simultaneous occurrence of a thunderstorm, a total solar eclipse and an *aurora* observed by Aboriginal people in the Burragorang Valley and incorporated into their oral traditions. We determine that this could have occurred on CE 28 November 764, given the best fit to our analysis. However, there is no recorded documentation or scientific data that demonstrate an aurora was visible during that solar eclipse.

While there are many assumptions and variables in our analysis, it was a useful exercise in rigorously and systematically evaluating an Aboriginal oral tradition that includes a description of natural events. The analytical methods used in investigating this story show promise for future research into plausible descriptions of natural events in other Aboriginal oral traditions.

7 NOTES

1. After Commonwealth of Australia, National Native Title Tribunal, Creative Commons Attribution 3.0 Australia License.
2. Atmospheric Optics, *Nacreous Clouds (Type II Polar Stratospheric Clouds)* viewed 31 August 2016, http://www.atoptics.co.uk/highsky/nacr1.htm
3. Atmospheric Optics, *Sundogs*, *Parhelia, Mock Suns* viewed 31 August 2016, http://www.atoptics.co.uk/halo/parhelia.htm
4. Atmospheric Optics, *Pillar* viewed 31 August 2016, http://www.atoptics.co.uk/halo/pillar.htm
5. The Alcyone Eclipse Calculator uses data based on the Five Millennium Canon of Solar Eclipses –1999 to +3000, with eclipse predictions by Fred Espenak.
6. The NASA Javascript Solar Eclipse Explorer calculates eclipses from the time range 1500 BCE to 3000 CE. http://eclipse.gsfc.nasa.gov/JSEX/JSEX-AU.html
7. *NOAA Historical Magnetic Declination* (no

date), National Centers for Environmental Education, viewed 3 July 2016, https://maps.ngdc.noaa.gov/viewers/historical_declination

8. List of Southern Hemisphere tornadoes and tornado outbreaks, viewed 17 August 2016
9. https://en.wikipedia.org/wiki/List_of_Southern_Hemisphere_tornadoes_and_tornado_outbreaks>

8 ACKNOWLEDGEMENTS

We acknowledge and pay our respects to the traditional owners and Elders, both past and present, of the Aboriginal peoples of the Burragorang Valley. We thank Dr Melanie Windridge for her help and guidance on aurora phenomena, Trevor Leaman for the IBC Class/mag/arcsec² plot, Tim Heard for advice on native bees, and Cliff Cunningham, Dimitri Douchin, Carla Guedes, Wayne Orchiston, Jay Pasachoff and David Willis for reading and commenting on the manuscript.

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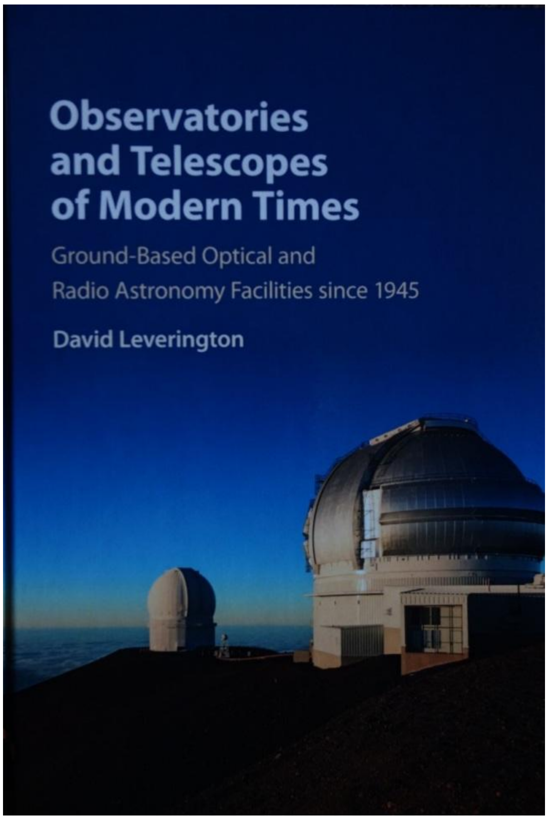
Journal of Astronomical History and Heritage, 20(3): 360–365 (2017).

BOOK REVIEWS

***Observatories and Telescopes of Modern Times: Ground-Based Optical and Radio Astronomy Facilities since 1945*, by David Leverington. (Cambridge University Press, Cambridge, 2017). Pp. xii + 490. ISBN 978-0-521-89993-2 (hardback), 180 × 250 mm, US$175.**

Anyone even passingly familiar with astronomy during the past few decades knows the number of telescopes—especially large telescopes—has mushroomed. While other books have focused on a survey of telescopes and observatories in various eras of astronomy, this is the first to comprehensively tackle the complex task of the post-1945 era.



Dr David Leverington wisely looks in this book only at optical and solar observatories (in 260 pages) and radio telescopes (in 210 pages). Observatories dedicated to other portions of the electromagnetic spectrum are excluded, and are now sufficiently numerous to merit their own volume.

For each observatory, beginning with the 200-in Palomar Telescope, the author carefully explains the scientific and political considerations that led to their construction. It would have been easy to give the human dimension short shrift, but by examining often contentious conversations and negotiations, Leverington offers us a superb capsule history of each observatory.

Just to cite one example of many, he spends six pages on the divisive tale of the Very Large Telescope of the European Southern Observatory. It is a tale of bankruptcy, resignations and lawsuits. Another ESO project, the New Technology Telescope of 1989, had a jaw-dropping mistake: Zeiss realised the mirror had a curvature error, "… but they made a mistake in quoting the sign of the error, and so in trying to correct it had doubled the error." (page 88). The creation of these modern behemoths maintains an element of 'art' in addition to pure science and engineering. Leverington lovingly exposes every mis-step, which makes for a delightful read, as this extract about the Sloan Digital Sky Survey attests:

> Unfortunately early operation of the telescope indicated that it had been installed with a slight tilt, which caused problems with the scanning software. That problem was easily solved but a much more threatening one was the discovery in October 1999 that there was a crack near the centre of the secondary mirror. In this case the Mirror Lab cut out the centre and capped the hole. (page 226).

It seems that an expertise in surgery is now a prerequisite to build telescopes!

Just two minor quibbles: the travails of the telescopes he studies are so numerous that Leverington tends to rely a bit too much on the word "unfortunately", and while he is excellent on the technical details these are not always explained. One wonders, for example, what a Gascoigne astigmatic corrector is on page 223.

The book is profusely illustrated (all in black and white) so that each telescope or observatory has at least one photo or artist conception. The work of Professor Orchiston is well represented in the section on radio telescopes in Australia, with several of his papers in this journal cited in the references. The role of Dr Lequeux, one of our *JAHH* Associate Editors, is also included in a discussion of the IRAM radio telescope project of the 1970s.

I found a few typos: on page 102 Herzburg should read Herzberg (it is correct in the Index); on page 166 "There where" should be "there were"; on page 204 "That the had" should read "That he had"; and on page 304 "immediately the war" should be "immediately after the war". As a great assist to those using this as a reference work, considerable care was taken with the Index: there are separates ones for names, Optical/Infrared Observatories, Radio Observatories, and a general index. The text includes developments up until 2015 when the manuscript was completed, so the fact that Arizona State University joined the Giant Magellan Telescope project in 2017 is not included. The text suggests the GMT will be ready with three of its primary mirrors in 2021, but the project website now pushes that back to 2023.

David Leverington has written the definitive account of modern observatories that is not only readable but a valuable sourcebook for the telescopic era of the past 70 years.

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***Radio Astronomer: John Bolton and a New Window on the Universe*, by Peter Robertson. (NewSouth Publishing, Sydney, 2017). Pp. viii + 421. ISBN 978-1-742-23545-5 (hardback), 158 × 242 mm, AU$59.99.**

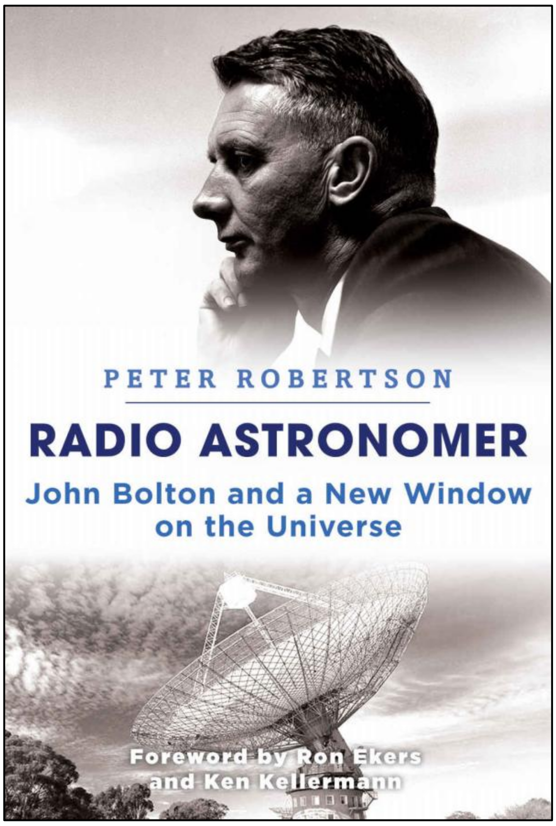
Although he died in 1993, John Bolton's name is well known today as the inaugural Director of the Parkes Radio Telescope, and the founder of radio astronomy at the California Institute of Technology in the USA. For those of us who knew John personally and worked with him, he was a hard task-master, as I found when using the 64-m Parkes Radio Telescope in the 1960s.

It was only much later, in the early 1990s (not long before his premature death) that I encountered the 'other' John Bolton, always happy to help me with my research on early Australian radio astronomy. And he had ideal credentials to do so: although born in England in 1922, he settled in Sydney when WWII ended and joined the Council for Scientific and Industrial Research's Division of Radiophysics (RP), leading the team at Dover Heights field station that identified optical correlates for the first discrete radio sources, thereby launching the new field of extragalactic radio astronomy. At the same time he forged close links with leading optical astronomers. These were the halcyon days of radio astronomy, with a seemingly never-ending supply of new discoveries, but elsewhere we have suggested that even though the Dover Heights team of John Bolton, Gordon Stanley and Bruce Slee would go on to build international reputations, none of them "… would produce another paper to rival the importance of their 1949 *Nature* letter." (Robertson et al., 2014: 302) that effectively launched extragalactic radio astronomy.

But Dover Heights was only the beginning of John Bolton's long and remarkable career in radio astronomy. In 1955 he launched radio astronomy at Caltech, culminating in the construction of the twin 90-ft antennas at the Owens Valley Radio Observatory. John was not your typical ivory-tower academic scientist. He believed the best way to effectively utilise scientific equipment was to build it, or help build it, yourself, and this included the Owens Valley interferometer. He also expected his graduate students to follow his example, so as two of them, Ron Ekers and Ken Kellermann, recount in their Foreward to Peter Robertson's book,

> … Barry Clark, who was the brains behind the Very Large Array, started at Owens Valley by learning how to use an oxyacetylene torch; Bob Wilson, who went on to win a Nobel Prize, did the circuit design for the Owens Valley instrumentation; and one of us (KK) wired the cables for the interferometer. The other of us (RE) started his PhD by using a tractor to grade the north-south track for the Parkes interferometer … (page vii).

Thus, when I worked at RP in the 1960s, 'Ph.D.' meant 'Post-hole Digger'!



In *Radio Astronomer: John Bolton and a New Window on the Universe*, Peter Robertson skilfully weaves the story of Bolton's life in and out of radio astronomy, starting with his childhood in England, and progressing to his role as the 'Dishmaster' at Parkes. Along the way we learn how the construction of the Parkes Radio Telescope led to the destruction of the RP field stations and the disintegration in the early 1960s of RP as arguably the world's foremost radio astronomy research group. We also learn about quasars, and the role that John Bolton played in the initial discovery and numerous later discoveries. And scattered throughout the book are accounts of John and Letty Bolton's numerous overseas trips, to attend conferences and meetings, to visit old friends whose names are now famous in the astronomical world, or to conduct optical follow-up observations of sources detected at Parkes. I found some of these accounts particularly appealing and informative. Also well worth reading was the discussion on whether or not Bolton should have been a co-recipient of the Nobel Prize awarded for the discovery of quasars.

These comments aside, *Radio Astronomer* … is not just about scientific research and its just rewards—like John Bolton's long-awaited election as a Fellow of the Royal Society, his involvement at a very senior level in the IAU, his role in the development of the 3.9-m (150-in) Anglo-Australian Telescope; and his television appearances. We also learn about the problems created by the popularity of the Parkes Dish as a tourist destination and how the (eventual) construction of a visitor centre effectively solved this; and about the Dish's involvement in the American Space Program, including the first manned landing on the Moon.

Nor is this book solely about radio astronomy,-notwithstanding the title, for Peter Robertson also traces John Bolton's short sojourn in RP's cloud physics and rain-making group prior to his move to Caltech.

In 1992 Peter Robertson produced what for more than two decades has remained the standard reference on the Parkes Radio Telescope, and he has now written another well-researched and very readable tome about one of Australia's and the world's foremost radio astronomers. This very affordable work belongs on the bookshelves of all those with an interest in radio astronomy, and like its 1992 predecessor is bound to become a classic.

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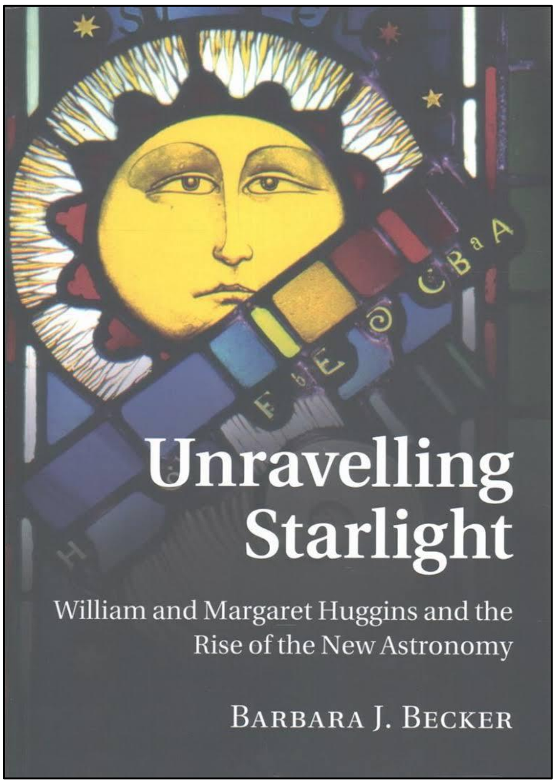
***Unravelling Starlight: William and Margaret Huggins and the Rise of the New Astronomy*, by Barbara J. Becker. (Cambridge University Press, Cambridge, 2016). Pp. xx + 380. ISBN 978-1-316-64417-1 (paperback), 170 × 244 mm, £36.99.**

Six years after the publication of the original hard-copy version of *Unravelling Starlight* … Cambridge University Press has produced a paperback edition, thereby bringing this important volume within the price-range of all astronomers. And by "all astronomers" I include amateurs, for William Huggins was surely one of the world's foremost nineteenth century amateur astronomers.



William Huggins was—by his own admission —one of the 'founding fathers' of astrophysics, the 'new astronomy' of the nineteenth century. As Barbara Becker reminds us in *Unravelling Starlight* …,

> Astrophysics is built on a range of questions and methods that were unimaginable to individuals in the first half of the nineteenth century [and in 1824, when Huggins was born]. At that time, positive knowledge of physical and chemical structure of celestial bodies was presumed to be unattainable by proper scientific methods, and hence relegated to the no-mans-land of mere speculation. (page 2).

William Huggins, with substantial help from his wife Margaret, was one scientist who completely changed this.

But as Barbara Becker recounts, Huggins came from a business background, and some of his pioneering research was opportunistic and aimed not only at progressing science but also increasing his own international standing as a scientist. Huggins was a master astronomical entrepreneur, something that is not apparent from reading earlier accounts of him written by others. As pointed out on page 156, after conducting spectroscopic observations of prominences outside of an eclipse, Huggins

> … became more aware of the need to establish and preserve his priority whenever he engaged in some research project he believed to be original.

One of the advantages Huggins had as an amateur astronomer was that he was not swayed by the dictates of observatory or university policy, and could follow his own interests and inclinations. Thus, he attacked a wide range of spectroscopic research programs, involving the Sun (sunspots, prominences, the corona, a total solar eclipse), stars (including variable stars, and a nova), nebulae and meteors. Arguably the most important of these related to unravelling the true nature of (gaseous) nebulae and revealing that by marrying the spectroscope and the Doppler effect astronomers could determine the line-of-sight motions of individual stars. Nor were all Huggins' observations spectroscopic, for he also carried out visual observations of the anomalous lunar crater Linné over a 6-yr interval.

One of the strengths of this book is the space assigned to Huggins' involvement in astropolitics (e.g. the Devonshire Commission and British Government funding of astronomy and observatories). Barbara Becker also skilfully presents the deteriorating relationships between Huggins and Norman Lockyer and Huggins and Dr Henry Draper, and the growing friendship between Huggins and George Ellery Hale. She also reveals the critical part played by Margaret Huggins (née Murray) in her husband's research, and in continuing to actively promote his public persona after his death in 1910 (see Chapters 10, 12 and 15). Margaret was 24 years younger than William Huggins, but in her "… he found both a lifelong and devoted companion as well as an interested and capable collaborator." (page 170). Largely through Margaret, astronomical photography became an important part of the research strategy at Huggins' Tulse Hill Observatory.

It was only when he was in his 70s that Huggins

> … began reaping the recognition of colleagues and the nation for the fruits of his life's work. Knighthood [in 1897] and other honours were capped by election as President of the Royal Society. Although he had no interest in retiring yet as an active investigator, he nevertheless became increasingly nostalgic and wary of encroachment upon his past accomplishments. In this important phase of his career, he – with the invaluable assistance of his wife Margaret – began the challenging task of carefully laying out the groundwork for what would become the foundations of his historical image. (page 267).

That "historical image" appeared in a 23-page paper by William Huggins titled "The new astronomy: a personal retrospect", which was published in 1897 in *Nineteenth Century: A Monthly Review*. It is this 'sanitised' autobiography that later scholars used to recount Huggins' life, but through access to original letters, observational notebooks and other archival sources, Barbara Becker has been able to create a more realistic account of the life of Sir William and Lady Huggins.

Barbara has an appealing style of writing, and consequently *Unravelling Starlight* … is an entertaining and easy read. For those wishing to go further, most chapters are accompanied by numerous endnotes, and a 28-page Bibliography (including a listing of all of the Huggins' published papers) and a 6-page Index round out this fascinating book. My only regret is that the paperback review copy I received was very poorly bound, so that the book literally fell apart as soon as I opened it.

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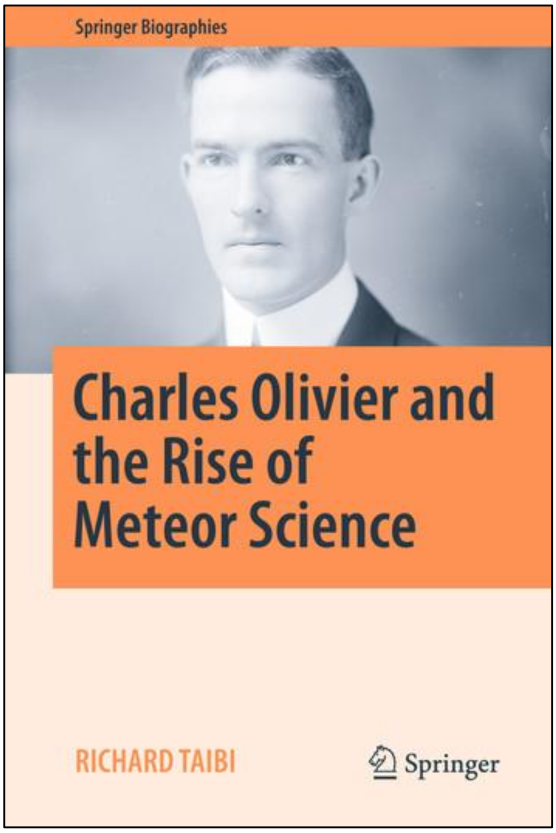
Charles Olivier and the Rise of Meteor Science, by Richard Taibi. (Springer International Publishers, 2017). Pp. xxxii + 497. ISBN 978-3-319-44518-2 (hardback), 165 × 240 mm, €99.99.

When I began visual meteor observing in 1960 I wrote to Professor Charles P. Olivier from the American Meteor Society seeking advice on observing programs and techniques. He was quick to reply with encouragement that led eventually to the publication of my first two, albeit very short, research papers (Orchiston, 1963, 1964). Although I was a rank unknown from the Antipodes, even as a busy academic Professor Olivier found time to assist me, and I was suitably impressed. Now, upon reading Richard Taibi's book I realise that I was not alone: over the decades Professor Olivier helped wean thousands of amateur astronomers—many, like me, still in their teens—into meteor astronomy.

So who is this remarkable man? Charles Pollard Olivier was born in Charlottesville, Virginia, in 1884. The family lived quite close to the University of Viriginia's Leander McCormick Observatory and from an early age Charles Olivier showed an interest in astronomy, which was encouraged by Professor Ormond Stone. In 1898 14-yr old Olivier observed the Leonid meteor shower, which launched what would become a lifelong commitment to meteor research. After graduating with B.A. and M.A. degrees in Astronomy from the University of Virginia Olivier went to Lick Observatory, where he completed a

Ph.D. on meteor astronomy in 1911. But while engaged in his Master and Doctoral studies he also conducted micrometric observations of double stars with the 26-in (66-cm) and 36-in (91.4-cm) refractors at the Leander McCormick and Lick Observatories, and he also carried out variable star observations and photometry of standard stars at the former facility, so not all of his research efforts (and publications) were in meteor astronomy.

After teaching undergraduate Astronomy at Agnes Scott College in Georgia from 1911 to 1914 Olivier joined the staff of his *alma mater*, and stayed there until 1928 when he accepted a Chair in Astronomy at the University of Pennsylvania and Directorship of the Flower Observatory (which housed an 18-in (45-cm) Brashear refractor). Charles Olivier remained at the University of Pennsylvania until his retirement, and his long and productive life came to an end in 1975.



Richard Taibi tells us that by 1911, Olivier

> … had a very ambitious goal: no less than gathering scientific data on *every meteor which fell over North America and its adjacent waters*. He hoped that volunteer citizen scientists would accomplish a great deal, but to improve chances of achieving that goal, he asked members of all organisations with scientific interests related to astronomy to relay meteor observations their members happened to make in the course of official or academic duties. (page 41, my italics).

Olivier also responded by founding the American Meteor Society (AMS), and much of *Charles Olivier and the Rise of Meteor Science* between pages 41 and 270 recounts the vicissitudes of that Society through to 1936, including its observational programs, Olivier's publications, and the general response of other professional astronomers to meteor astronomy.

Meanwhile, in 1925 Olivier's book, *Meteors*, was published, and this would remain a standard reference for many years. In 1930 his second book, *Comets*, was published. Unfortunately, both books are mentioned almost in passing in Taibi's book, and it would have been nice to learn more, especially about Olivier's first book.

To round out his detailed review of Olivier's involvement with the AMS, between pages 270 and 286 Taibi summarises non-USA amateur meteor astronomy up to 1936. Apart from a 'lengthy' (4-page) discussion of Germany, all of the other national accounts are short. The Canadian account, for example, mentions P.M. Millman, but does not include Jarrell (2009) or Tors and Orchiston (2009) in the references. It is to be hoped that Taibi and others (e.g. Martin Beech) will publish further details in the future.

The author of *Charles Olivier and the Rise of Meteor Science*, Richard Taibi, is a retired clinical and forensic psychologist with a lifetime interest in astronomy, and an avid meteor observer. Taibi tells us that his project started off as a history of the American Meteor Society, but instead evolved into a biography of its founder, Charles Olivier, from 1899 to 1936, along with scores of amateur astronomers "… who volunteered to produce the data he analysed and published." (page viii). Taibi refers to these as "The Stalwarts", and they number more than 80 and occupy pages 291–481 of this 529-page book. Putting biographical flesh onto this skeletal list of names was valuable, but if this book should go to a second edition it is important that Taibi expands some of these biographies by networking effectively with colleagues who have relevant information. For example, in reviewing only the Australian and New Zealand 'Stalwarts', there is further published and unpublished information available on Murray Geddes, Ronald McIntosh (e.g. see Orchiston, 2017), J. Fraser Patterson (he was an Australian and never lived in Auckland, New Zealand) and Ivan Thomsen. Meanwhile, it is to be hoped that Taibi will now publish papers (in refereed journals) on some of the more distinguished individuals in his book who have been thoroughly researched.

Charles Oliver and the Rise of Meteor Science is a book long overdue. C.P. Olivier is a famous name in the annals of meteor astronomy, and it is a pleasure to learn more about him, while the history of the American Meteor Society was crying out to be told. Each chapter is complete with extensive footnotes (some of which even extend for more than half a page), and at the end a list of references. So we have much to thank Richard Taibi for in producing this timely book, which belongs on the bookshelves of all avid visual meteor observers with an interest in history.

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