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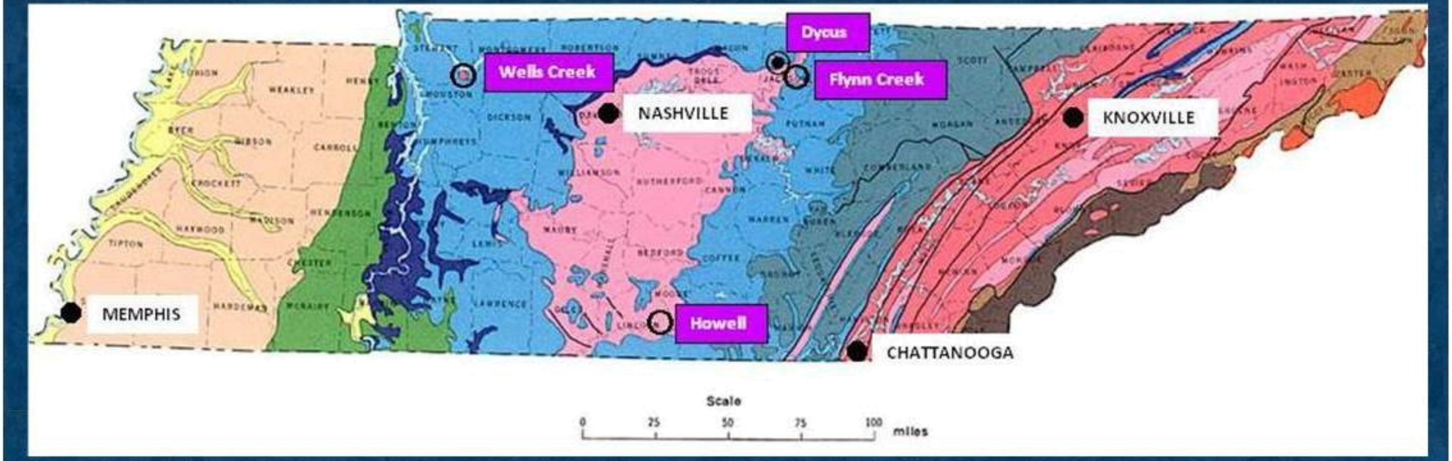

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COVER IMAGE

Map showing two confirmed (Wells Creek and Flynn Creek) and two suspected (Dycus and Howell Structures) impact crater scars in Tennessee, USA. Two unusual features of the Dycus Structure – its elongated shape and interior uplift at one end – are reminiscent of the Moon's Schiller crater (lower image; credit: NASA). They suggest that the Dycus Structure may have been caused by an oblique meteoritic impact. See the paper by Jana Ruth Ford et al. on pages 352–364 of this issue.

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THE STEBBINS GALAXY: THE ORIGINS OF INTERSTELLAR MEDIUM STUDIES IN THE SHRINKING SUPER-GALAXY

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Abstract: The development of photoelectric photometry as an observational technique by Joel Stebbins and his colleagues at the University of Wisconsin's Washburn Observatory made possible, in the early 1930s, a new approach to the effects, extent, and nature of interstellar matter. In a series of papers published between 1933 and 1936, Stebbins showed that the Shapley galaxy was too large by at least a factor of two and that the size of the Andromeda Galaxy had been significantly underestimated, thus considerably reducing the apparent discrepancy between the two neighboring galaxies. The outcome was not simply a recalibration of the Shapley model, but rather the replacement of the incongruously large and transparent super-galaxy by the modern concept of the Milky Way: a galaxy of size comparable to other spiral galaxies and, like them, containing significant quantities of interstellar dust and gas. This paper explores the role of Stebbins and his colleagues and their applications of photoelectric photometry in formulating the modern concept of our Milky Way galaxy.

Keywords: Stebbins, Shapley, interstellar matter, photometry, galaxies.

1 PRELUDE

Quotation from Elizabeth Huffer (wife of C. Morse Huffer): *There was one time I can remember Stebbins coming in saying "We shrunk the universe!" He had found out these obscuring clouds and that people thought the stars were so much further away and it was because they were going through this obscuring material and they were much closer than they thought they were. And he was absolutely jubilant to think that he had made a discovery.*

C. Morse Huffer (long time colleague of Stebbins): *Yes, he and Shapley were quite rivals. Shapley had got the length of the galaxy as 200,000 light years and Stebbins got it at 100,000.*

Elizabeth Huffer: *And, of course, Stebbins was right … he was absolutely jubilant. You would go into that observatory and there was just a feeling of exhilaration. He had made a milestone and he knew it.* (Huffer, 1977).

2 INTRODUCTION

The discovery that the Sun is nowhere near the center of our Milky Way galaxy constitutes one of the most significant insights of 20th-century astronomy. It is one among several fundamental facts that define what we now mean by the very word "galaxy," a term whose modern meaning only began to emerge in the 1920s. Harlow Shapley (1885–1972), referred to in the quotation above, opened this new direction in the study of our Galaxy with his survey of globular clusters and construction of their relative distribution in three dimensions. But the Shapley Galaxy, as formulated by him, was a factor of two or three times too large, was transparent (effectively free of gas and dust), and was asserted by him to be fundamentally different from such neighboring objects as the Andromeda Nebula, as it was then called. The structure, composition, and dynamics of a unique 'super-galaxy' as set out by Shapley would be very different from the throng of negligible wisps —the spiral nebulae and globular clusters— swarming about it. General accounts mention, often vaguely and in passive voice, that Shapley's dimensions needed correction. The nature of the 'corrections' to the Shapley Galaxy are rarely spelled out. In particular, who made these corrections, and how? As we see above, Elizabeth Huffer thought that Joel Stebbins (Figure 1) did it. Stebbins's triumphant "We shrunk the universe!" (as reported by Elizabeth Huffer) hints at the cosmological implications of the work, which not only corrected Shapley's conclusions, but opened the way to a view of a Universe filled with countless galaxies comparable to our own. Getting the dimensions of the Galaxy correct involved the first explorations of the interstellar medium with the new technology of photoelectric photometry. To understand the significance of the work of Stebbins and the other Wisconsin astronomers, we need first to see the stage that Shapley had set.

3 CONSTRUCTING THE SHAPLEY GALAXY

As early as 1917, Harlow Shapley, then working at Mt. Wilson Observatory, recognized the significance of the apparent asymmetry of the distribution of globular clusters for determining the location of our Solar System relative to the rest of the Galaxy. The distinct asymmetry of the distribution of globular clusters as seen in the sky had been established by others, such as Karl P.T. Bohlin (1860–1939), P.J. Melotte (1880–1961), and Arthur R. Hinks (1873–1945) (Jeans, 1929: 25; Smith, 2006: 320–321), but Shapley was the first to obtain distances to the globular clusters. The result of those measurements provided a three-dimensional distribution of the globular clusters from which he drew bold conclusions about the size and structure of our Galaxy. Assuming that the globular clusters form a symmetric halo around the center of the Galaxy, their apparent distribution in our sky and, critically, their distances tell us that the Sun is far from that center, which must lie roughly in the direction of the constellation Sagittarius. This was a most important result and a transformative insight, which challenged the then current statistical models constructed, for example, by Jacobus C. Kapteyn (1851–1922) and Hugo von Seeliger (1849–1924), who had concluded that the Sun was more or less centrally located within the stars of the Milky Way. By 1918, using distances he had worked out for a large sample of the globular clusters, Shapley concluded that the Sun was some 20,000 parsecs from the center of the distribution of the globular clusters, and that this distribution coincided with the general extent of our Galaxy, making the latter as large as 100,000 parsecs in diameter, although he reduced this to a value of about 60,000 parsecs in later publications (Shapley, 1918: 3–5).

3.1 Shapley's Methods

Shapley based his conclusions for the size of our Galaxy and the Sun's location within it on three fundamental arguments for the distances to globular clusters:

1) He found a way to recalibrate the period-luminosity (*p-l*) relationship discovered by Henrietta Leavitt (1868–1921) (for the Cepheid variable stars in the Magellanic Clouds) so that absolute magnitudes could be determined from observation of the periods. Using globular cluster Omega Centauri he extended the *p-l* relationship to the cluster variables. Applying the *p-l* relationship to a globular cluster in which periods could be determined for one or more variable stars, he could find the absolute magnitude of a variable star from its period and then use the difference between the absolute and apparent magnitudes to calculate the distance (Smith, 1982: 73–75).

2) For distances to globular clusters in which periodic variables could not be found, Shapley applied a statistical measure assuming the constancy of the mean absolute magnitude of the 25 brightest stars in the cluster, omitting the brightest five stars. Calibrating this measure by the globulars that succumbed to argument 1) allowed him to establish distances to dimmer, more distant clusters.

3) To extend the distance scale to clusters too dim for the use of argument 2), he took the absolute diameter of globulars to be roughly constant and inferred the distances from their apparent diameters, calibrated from the cluster distances known from the previous arguments.

In this way Shapley established a 'distance ladder', which gave absolute distances to the globular clusters. Combining the distances with the known positions in the sky allowed him to construct the three-dimensional distribution of the system of globular clusters and gauge the distance of the Sun from its center; assuming that our Galaxy was roughly co-extensive with the system of globulars allowed him to establish the rough size of the Galaxy (Shapley, 1918: 2–3).

3.2 Shapley's Conclusions

As with any such scheme, the distances of the more distant objects will depend on the accuracy of the distances measured to the closer objects as well as the validity of the methods used in reaching the higher rungs of the ladder. Shapley explicitly assumed that interstellar extinction was insignificant in applying his sequence of distance measures and that no systematic correction for it was necessary. He acknowledged, as was obvious, that there were dark, probably opaque clouds visible among the stars, but he considered their effects to be limited to small parts of the sky and thus avoidable. This would mean trouble if interstellar extinction turned out to be widely distributed and significant, because then distance would not be the only factor in determining the apparent brightness of distant objects such as the stars of globular clusters.

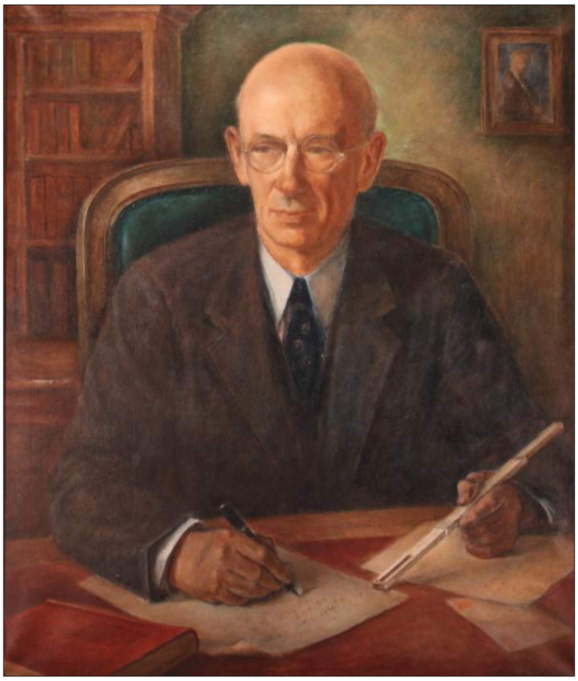


Figure 1: Joel Stebbins (1878–1966) in an undated portrait by Roland Stebbins (courtesy: University of Wisconsin-Madison Department of Astronomy).

From that foundation he began drawing conclusions, which evolved over a series of publications into a model commonly called the "Shapley Galaxy." His central conclusions, which he defended in print until 1930, can be summarized as follows:

1) The distribution of globular clusters, presumed to be centered around the center of mass of the Galaxy, shows the Sun to be far from that center.

2) The measured distances to globular clusters show the Galaxy to be about 70,000 parsecs (200,000 light-years or so) in diameter (Shapley, 1930a: 221). This is about twice the modern figure for the luminous Galaxy. In his earlier publications, as mentioned above, estimates as large as 100,000 parsecs diameter can be found (Shapley, 1918: 5).

3) Compared to other objects near our Galaxy (for example the Andromeda Nebula, whose distance and size were thought to be roughly known), our 'galactic system' is larger by perhaps an order of magnitude, hence probably fundamentally different in nature from the spiral nebulae (Shapley, 1930a: 179, 210).[1]

3.3 Shapley's Cosmology

Shapley drew cosmological implications from his conclusions, that is, he formulated ideas about the general structure, dynamics, and evolution of the Universe from his scheme of the super-galaxy, which he suspected was practically the entirety of the Universe in itself. One example is the question of the multitudinous spiral nebulae (for which there were few clues to actual distances), which many astronomers thought were galaxies comparable to our own. If they were comparable super-galaxies, then their apparent diameters implied that they were vastly more distant—hundreds of millions of light years—than Shapley thought reasonable (Shapley, 1919: 266). Therefore, Shapley concluded, those spiral nebulae must instead be relatively small, nearby objects, not like the super-galaxy of which the Sun is a member. This view was supported by the then credible observations of rotations, or perhaps internal proper motions, found in spiral nebulae by Adriaan van Maanen (1884–1946), which were consistent with the small size and distance of these objects relative to the super-galaxy. The questions one might ask about the dynamics and evolution of such a Universe, and the relevance of observations of the spiral nebulae, are very different from the approaches one would take if the spiral nebulae are actually comparable to our Galaxy.

Shapley was not shy about floating even more speculative hypotheses, albeit clearly labeled as such, connected to his super-galaxy. He posited evolutionary paths connecting spiral nebulae, globular clusters, and open clusters, and mysterious gravitational and even 'electrical' forces in the equatorial disk of the super-galaxy to explain why spirals and globulars are not seen near the plane of the Milky Way (Shapley, 1918: 14). Thus the Shapley super-galaxy, as Shapley presented it, was far-reaching: a visible Universe dominated by a discoidal super-galaxy of stars or star clouds (in which we find ourselves closer to the edge than to the center) with a vast halo of indefinite extent populated by the diminutive spiral nebulae and globular clusters and shaped by vast forces hitherto unsuspected. Such extravagant theorizing attracted international attention, both positive and negative, from European astronomers such as Antonie Pannekoek (1919), Willem J. A. Schouten (see Smith, 2006: 321), Cornelius Easton (1921), and August Kopff (1921).

3.4 Shapley's Galaxy under Siege

But already by the mid-1920s, the Shapley super-galaxy was in trouble in the view of many astronomers. First, there was the nature of the spiral nebulae. In 1923, Edwin Hubble (1889–1953) identified Cepheid variables in the Andromeda Nebula (Hubble, 1925). The apparent magnitude of those stars seemed to show that this 'nebula' was likely much farther away and hence larger than seemed consistent with the Shapley model. At about the same time there were growing doubts over the value of Van Maanen's results, thus undermining their implication of the relatively small sizes and distances of spiral nebulae (Berendzen and Hart, 1973; Hetherington, 1974). Taken together these results helped reinforce the inclination of many astronomers to understand the spiral nebulae as vast stellar structures ('island universes' as they said) and perhaps even galaxies comparable to our own.

Moreover, between about 1928 and 1930, the work of Bertil Lindblad (1895–1965), Jan Oort (1900–1992), and John Plaskett (1865–1941) made a convincing case that they had detected and measured rotational motion of our Galaxy. While it was generally agreed that the evidence of the rotation placed the Sun far from the center of the Galaxy, Oort's calculation of the distance based on the rotation was only about one-third of Shapley's distance (Smith, 2006: 326). If the discovery of galactic rotation could be seen as confirmation for Shapley's views, it was only in respect of the issue of the relative position of the Sun within it.

So Shapley was forced to back away from the view of spiral nebulae supported by Van Maanen's work, which had "… gone down under the weight of novae and variable stars." (Shapley, 1930a: 195–196), and admit that at least some were stellar in composition and not minor gaseous satellites of the super-galaxy. Nevertheless he was still making a case for the super-galaxy. He continued to assert as late as 1930:

1) The center of the Galaxy lies about 16,000 parsecs (pc), or about 50,000 light years (ly), from the Sun (Shapley, 1930a: 221).[2]

2) The diameter of the Galaxy spans about 70,000 pc, or about 230,000 ly. (ibid.).[3]

3) Our own Galaxy is at least five times larger in diameter than the Andromeda Nebula, which is itself probably much larger than more typical spirals (Shapley, 1930a: 179). Indeed,

> The lack of comparability between galactic system and spiral nebula appears now more certain than before; ours is a Continent Universe if the average spirals are considered Island Universes. (Shapley, 1930a: 195).

Shapley was well aware that his cosmic conclusions were only valid if his distances to globular clusters were trustworthy, and his methods assumed that any interstellar absorption of starlight was negligible. For that reason he included a chapter on "The Transparency of Space" in *Star Clusters* summarizing and expanding upon the defense of this assertion he had been making since 1918. He noted that such extinction could be both 'differential' (i.e. wavelength dependent, like Rayleigh scattering) and 'undiscriminating' (if produced by relatively large particles). The differential extinction would reveal itself in the colors of faint and distant stars, he pointed out, and indeed, globular clusters themselves, because of their visibility across great distances, should be good probes of differential absorption (Shapley, 1930a: 116). He compared the mean color indices (a measure of an object's color then made photographically) of samples of stars from three globular clusters: M3, M13, and NGC7006. NGC7006 lies about four times farther away from us than M3, and seven times farther than M13, but the stars of the most distant cluster are not, he concluded, significantly redder than the stars of the nearer clusters.

He also cited the lack of reddening of some extra-galactic nebulae, which are many times farther from us than the globulars, and concluded,

> Apparently, we need not disturb ourselves further about the general dimming of light in space, even when dealing with external systems, unless it happens that the diminution differs from molecular scattering and has no effect on colors. (Shapley, 1930a: 121).

The lack of reddening in globular clusters and his conclusion that apparent diameters of globular clusters seem to decrease in proportion to their apparent brightness indicate "… the essential transparency of space up to a distance of 100,000 light years." (Shapley, 1930a: 120–121). This line of reasoning is entirely consistent with his publication, with Helen Sawyer, (Shapley and Sawyer, 1929) in which, more than a decade after his first results, they published a new list of globular cluster distances based on recent studies on cluster stellar magnitudes, diameters, and variable stars. But there the possible issue of interstellar absorption in finding globular cluster distances is not even mentioned. In fact, although they revised Shapley's earlier cluster distances downward by 11%, they actually held out the possibility that recalibrations of the period-luminosity relationships for variable stars might even increase the distances again.

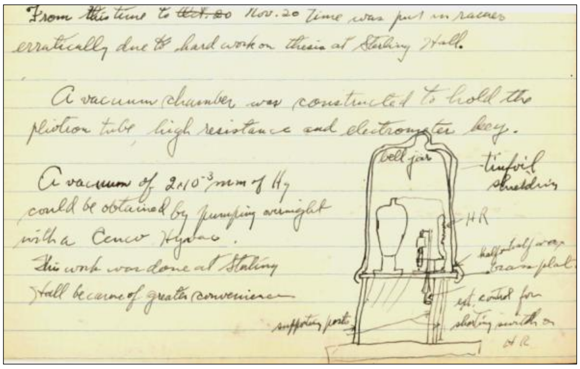
But in fact, interstellar matter and the reddening and extinction of starlight it causes are, as we will see, very significant. Why did Shapley conclude that extinction is negligible? His argument considered only three globular clusters: M3 and M13 are high in galactic latitude, +79° and +41° respectively, and NGC7006 is at –20°, which is well out of the Galactic Plane, where, as we shall see, the greatest reddening is found. Moreover, NGC7006 is near 64° galactic longitude (on the other side of the sky from the Galactic Center in Sagittarius) where the Milky Way is relatively narrow. Over there, 20° of latitude puts an object pretty well clear of the obscuring parts of the Milky Way. Shapley chose to look for a distance dependence on the assumption that selective scattering would be independent of location on the sky; he also chose a very small and rather idiosyncratic sample of clusters to examine; and his measure of reddening depended on the photographically determined mean colors of the brightest stars in a cluster, which were not necessarily typical.

In the same year that Shapley published *Star Clusters*, 1930, Robert Trumpler (1886–1956) demonstrated that interstellar extinction in the Milky Way was not, as Shapley had asserted, negligible (Trumpler, 1930a). Trumpler, working at Lick Observatory, photographically surveyed open clusters and showed that interstellar extinction resulted in overestimation of their actual distances. Moreover, he showed that this effect of interstellar matter amounted to about 0.7 magnitudes per 1000 parsecs (see, for example, Verschuur, 1989: 106ff). Trumpler's finding, while unambiguous about the extinction caused by interstellar matter, could not be applied directly to its effects on individual globular clusters. But there could be no question that Shapley's distances to globular clusters, the bedrock of his super-galaxy and the Universe it implied, had to be re-examined. So how far away are those globulars, and how large is our Galaxy?

4 THE WASHBURN OBSERVATORY RESEARCH PROGRAM

The excitement and triumph so clearly expressed in Elizabeth Huffer's account of Stebbins' (unfortunately undated) exclamation about the shrinking galaxy was surely a reaction to his success in showing that measurement of interstellar extinction could produce a better idea of what our Galaxy is really like than what Shapley had concluded. What exactly were the results that produced such exhilaration at Washburn Observatory? How did they come about, and how did other astronomers learn of these results?

The pioneering work by Stebbins in the field of astronomical photoelectric photometry has been recounted in several places (e.g. Hearnshaw, 2005; Leibl and Fluke, 2004; Susalla and Lattis, 2010). And it is for that work that he is best known. Stebbins and his colleagues at the University of Illinois, most notably physicist Jakob Kunz (1874–1938), had developed photoelectric detectors suitable for astronomical work starting about 1913 and began applying them to photometric research, particularly measuring light curves of eclipsing variable stars (Beaman and Svec, 2012). Stebbins moved to the University of Wisconsin's Washburn Observatory in 1922. There he continued improving instrumental techniques, such as more sensitive electrometers to measure the minuscule photocurrents of Kunz's detectors, and applying the techniques to new problems, most notably, for the current topic, filter photometry to measure color indices of stars.


From this time to ~~Oct. 20~~ Nov. 20 time was put in rather erratically due to hard work on thesis at Sterling Hall.

A vacuum chamber was constructed to hold the photon tube high resistance and electrometer key.

A vacuum of 2×10^{-3} mm of Hg could be obtained by pumping overnight with a Cenco Hyvac.
This work was done at Sterling Hall because of greater convenience

Figure 2: Albert Whitford's sketch of his prototype amplified photoelectric detector (courtesy: University of Wisconsin Archives).

A major step in increasing the sensitivity of the Washburn photometric instruments came in 1932 when Stebbins' young colleague Albert Whitford (1905–2002) succeeded in integrating within a vacuum chamber the photo-detector with a DC amplifier for the weak photocurrents (Figure 2). This had the effect of improving the sensitivity, on a given telescope, by about two stellar magnitudes compared to the older type instrument using only an electrometer.

The research program that Stebbins and colleagues Huffer and Whitford pursued starting in about 1930 was motivated, according to Stebbins, by his discussions of interstellar extinction with Trumpler, then at Lick Observatory, where Stebbins had long-standing connections. Trumpler and Stebbins were certainly not the only astronomers concerned about the effects of interstellar extinction. In fact, it had been raised as a potential weakness of Shapley's globular cluster distances not only by Shapley himself but also by A.C. Crommelin (1922), and by P.J. van Rhijn (1928: 123), who noted:

> The subject seems of special importance because neither the distances of globular clusters and spiral nebulae nor the density of the stars per unit of volume in the galactic system can be found without an accurate knowledge of the quantity of light absorbed per unit of length.

Trumpler's definitive result established the subtle effects of interstellar absorption to nearly everyone's satisfaction. Stebbins decided to apply his unique abilities in photoelectric photometry to measurements of the reddening of starlight from individual globular clusters as a measure of the interstellar absorption.

Reddening would be one possible result of the passage of starlight through interstellar matter, depending, in the first approximation, on the sizes of the particles in interstellar space. Gas molecules or very small particles should, presumably, scatter shorter (bluer) wavelengths of light more effectively than redder light—just as Earth's atmosphere reddens the Sun at rising and setting by preferentially scattering the bluer light away from the line of sight. The proportion of light lost to wavelength-dependent scattering (or 'selective absorption') relative to the total absorption should be determined by the composition of the interstellar matter, including factors such as the proportion of gas to solid particles and the size distribution of the solid particles. Particles of relatively large size compared to the wavelengths of light would be responsible only for non-selective absorption. The amount of reddening, then, of a star's light should correlate somehow with the amount of matter, its physical characteristics, and its composition along the line of sight to the star and therefore to the total extinction, that is, the reduction in the apparent brightness of the star. Since interstellar absorption, as Trumpler had shown, was significant, it was clear that distance was not the only factor determining an object's apparent brightness. The total extinction is hard to measure, but reddening, they hoped, which could be measured, should act as an indicator of the total extinction. Indeed, Trumpler had already suggested in print that selective absorption should be seen strongly in dim (i.e. distant) stars at low galactic latitudes (Trumpler, 1930a: 223). Stebbins would substitute globular clusters for the dim stars.

Stebbins seems to have decided right away on a two-pronged approach. He would measure the reddening of globular clusters, but he would also investigate the reddening of B-type stars, which are highly luminous and therefore visible across great distances, much brighter in our sky than typical globular clusters, and much more common than globular clusters. Measuring the reddening of B-type stars as a function of galactic longitude and latitude would roughly map the absorbing interstellar matter in the vicinity of the Sun. Measuring the reddening of light from globular clusters would probe greater distances and reveal whether Shapley's distances, and hence his conclusions about the location of the Sun and the size of the Galaxy, were correct. Comparing the reddening patterns of the two sets of objects would provide a check on the general approach.

Stebbins used a technique for measuring colors worked out by his predecessors in photoelectric photometry, Berlin astronomers Paul Guthnick (1879–1947) and Kurt Felix Bottlinger (1888–1934) (Whitford, 1978: 302). The general method, for both B-type stars and globular clusters, and regardless of which combination of instruments and telescopes the Washburn astronomers used, was to obtain a photometric magnitude measurement for a given object in two color bands defined by a 'blue' and a 'yellow' filter. The arithmetic difference between the two measurements provides a 'color index' that quantitatively characterizes the color of the object.[4] Stebbins' filter choices were constrained by the limited color sensitivity of the Kunz photoelectric cells. The filter bands had to remain close enough to the detector's peak sensitivity to detect dim objects, yet be separated enough to make meaningful color distinctions.

In general the B-type star and globular cluster observing programs ran in parallel between about 1930 and 1936. C. Morse Huffer (1894–1981) led the B-type star observing in Madison using the 15.6-in refractor at the Washburn Observatory and an electrometer-equipped photometer. Stebbins, later joined by Whitford, did most of the globular cluster observing, mainly with the 100-in Mt. Wilson telescope. As a research associate of the Carnegie Institution since 1931, Stebbins had access to the Mt. Wilson telescopes. Moreover, Mt. Wilson astronomers Walter Baade (1893–1960) and Edwin Hubble saw great potential in the techniques of photoelectric photometry and urged Stebbins to bring his work there (Sandage, 1961: 118). Early on, Stebbins used an electrometer-type photometer for the globular clusters, but he switched to the more sensitive amplifier 'outfit' (as Whitford liked to call it) for the later measurements. And in a departure from the reddening theme, Stebbins and Whitford carried out one more observation program to take on a key claim by Shapley—namely that the Andromeda Nebula, as it was known then—was considerably smaller than our own Galaxy. They used Whitford's amplifier outfit to make brightness profiles that could reveal subtle details invisible to conventional photography.

5 THE CAMPAIGN

The principal results of the Washburn Observatory program to investigate interstellar absorption emerged in a series of publications between 1933 and 1936. They first took on those problematic globular clusters that lie at the heart of Shapley's argument and measured the effects of interstellar absorption on their light showing that they are not only reddened but that the degree of reddening is dependent on galactic latitude. The second and third papers, on 'space reddening' in B-type stars, demonstrated an absorption pattern consistent with that found in the globular clusters, showed its general but irregular extent, and provided a broader mapping of the absorption effects across the sky. The fourth paper applied photoelectric photometry to measuring the extent of the Andromeda Nebula. The final paper in this group returned to the globular cluster question with new observations, presented an improved model of the distribution of interstellar matter in the Milky Way, and concluded by deriving some properties of the interstellar medium based on the spectrophotometric observations.[5]

5.1 Reddening of Globular Clusters

The very first paper in this series (Stebbins, 1933) proceeded quickly to the task of correcting the Shapley distances to globular clusters. The paper is by Stebbins alone and it presented results on the reddening of globular clusters acquired by him mostly in June and July of 1932, but with some as early as September the previous year. He used the older style electrometer instrument (the same well-understood device he had been using for years at Madison) on the Mt. Wilson 100-in telescope. His instrument, as in all the subsequent papers considered here, had a Kunz-made argon-filled photoelectric cell with a potassium hydride cathode at its heart. Such a cell had a peak sensitivity at about 4500 Å. In this work he used two filters, centered at 4300 Å and 4800 Å, to derive color indices for the globular clusters. On the scale he established for this work, a blue star with spectral type B5 has a color index of –0.36, while a red star with spectral type K5 has a color index of +0.25.[6] Stebbins acknowledged that more widely-spaced spaced filter bands would be more sensitive to measuring color indices, but explained the choice as a result of the Kunz tube's sensitivity peaking relatively narrowly in the blue:

> This amount [of wavelength difference between the filter bands] is not a large leverage for the determination of color indices, but it maintains the possibility of reaching faint objects. (Stebbins, 1933: 222)

It was entirely typical of Stebbins to accept the narrow constraints of a novel technique (as with his early photometry of eclipsing binary stars) and nevertheless produce good science by assiduous observing, careful methods, and minute attention to experimental error.

With this method he was able to determine color indices for 47 globular clusters, some as dim as magnitude 13.0, with a probable error in the color index that he estimated at ±0.055 mag. Although, as he noted, it would have been better to measure the reddening with respect to the individual spectral types of the clusters, no spectra were available for such dim, diffuse objects as globular clusters. In effect, he was measuring the redness of the clusters with respect to each other and looking for a correlation of the reddening with location on the sky. Based on the uncorrected color indices and the assumption of a thin, homogeneous absorbing layer near the Galactic Plane producing a differential reddening effect, Stebbins fit the data to a model describing a mean coefficient of absorption as a function of the cosecant of galactic latitude (Figure 3), and thus demonstrated that selective absorption shows a functional dependence on galactic latitude. The reddening of the globular clusters nearer the plane of the Milky Way is consistent with a layer of interstellar matter in the plane of the Galaxy, some component of which scatters preferentially at shorter wavelengths.

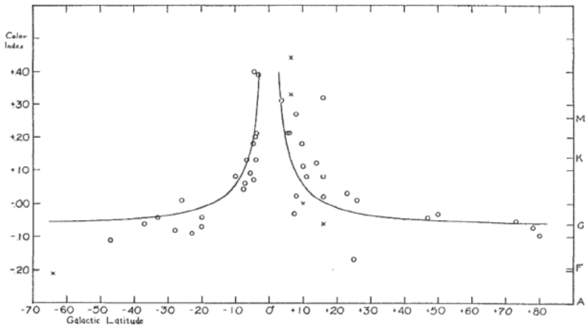


Figure 3: Globular clusters become strongly redder toward the plane of the Milky Way. The solid curves are independent fits, for northern and southern galactic hemispheres, of a cosecant function of galactic latitude. (after Stebbins, 1933: 225)

From his model for the absorbing region, idealized as a uniform layer extending some distance above and below the plane of the Milky Way, Stebbins derived its equivalent thickness to be 540 ± 60 pc. This, he noted, is about twice what Trumpler arrived at on the basis of his open cluster studies and about three times that derived by van de Kamp. Peter van de Kamp (1901–1995), like Stebbins, had done his Ph.D. work at Lick Observatory and knew Trumpler well. Van de Kamp also had a doctorate from Groningen University completed under van Rhijn, who had earlier published on the problem of interstellar absorption. Like Stebbins, van Rhijn and others, van de Kamp (1930: 159) had concluded that

> … our knowledge about the structure of the universe in low galactic latitudes depends essentially on our knowledge about the distribution and density of the galactic absorbing medium. A thorough study of the latter seems very desirable.

Like Stebbins, van de Kamp specifically mentioned Shapley's results as the target of the study. Van de Kamp in 1930, as Stebbins did in 1933, modeled interstellar absorption (although using photography to gauge the total, not selective, absorption) as a function of the cosecant of galactic latitude and had published, in 1932 and 1933, revisions to Shapley's globular cluster distances that yielded a distance from the Sun to the Galactic Center of about 5,500 pc. Stebbins was clearly far from alone in attempting to rein in Shapley's super-galaxy, but he was unique in applying the new technology of photoelectric photometry, which then produced results that conventional photographic techniques had not succeeded in doing.

Compared to Trumpler and van de Kamp, his own much larger result for the extent of the reddening layer, Stebbins suggested, came from the fact that the globular clusters are probably distant enough to show effectively all the absorption in the galactic system. But then to the heart of the matter:

> We now proceed to apply these results to a correction of Shapley's distances of globular clusters, which were derived on the assumption of transparent space. (Stebbins, 1933: 225).

Applying a magnitude correction based on his cosecant model for space absorption, Stebbins calculated new distances to the globular clusters by adjusting Shapley's distances. The overall effect was that distances to globulars closer to the plane of the Milky Way were much less than Shapley had calculated and much more than van de Kamp had concluded using his measures of total absorption. Thus, "The center of the system, which Shapley placed at 16,000 pc, is now found at 10,000 pc from the sun." (Stebbins, 1933: 226). This finding, Stebbins (ibid.) noted, had cosmological implications:

> The relatively large size of our own galaxy [according to Shapley's model] has long been an obstacle in considering it as a system quite similar to the extra-galactic nebulae, but this

> difficulty is to a great extent diminished when the inferred dimensions of the galaxy are corrected for absorption.

In his conclusion, Stebbins summarized the significance of these first results of his measurements of interstellar reddening and its effects: 1. Distances from some globular clusters are only one-fourth the distances that "… have sometimes been supposed." 2. "The diameter of the galactic system of stars is reduced from 80,000 to possibly 30,000 pc." 3. "The great difference in size between our own galaxy and other such systems largely disappears." (Stebbins, 1933: 227).

Stebbins was careful to point out that his method measured only selective absorption. But the absorption that produces the reddening is likely to be only one component of the total absorption. The total absorption (i.e. absorption-measured-by-reddening plus absorption-without-reddening) is what reduces the apparent magnitude of the globular clusters:

> It may be noted that any obstruction in space in addition to that accompanied by scattering as shown by the reddening of clusters will require a further reduction of all distances based upon photometric considerations. (Stebbins, 1933: 227)

Not only was he preparing the reader for further shrinking of the Galaxy, but this brief reference to the composition of the interstellar absorbing material, along with the demonstration of its latitude dependence, presaged a more nuanced view that would emerge in the later papers. It also set a new direction in research, on the nature of the interstellar medium, that became a major theme of Washburn Observatory research (see Liebl, and Fluke, 2004).

5.2 Reddening of B-Type Stars

As with the question of globular cluster reddening, Stebbins cited his discussions with Trumpler in autumn 1930—just when Trumpler's definitive papers on interstellar absorption were appearing—as the stimulus for measuring color indices of blue (i.e. B-type) stars. Indeed, Stebbins noted that Trumpler had already given some thought (apparently unpursued) to measuring the reddening of B-type stars and had provided Stebbins with a short list of candidate stars. This was the beginning of the work that Stebbins and Huffer would publish in a series of papers documenting successively larger sets of B-type star color measurements. All of the thousands of observations were made with the Washburn Observatory 15.6-in refractor using the electrometer-equipped photometer. Stebbins noted that while the amplifier photometer (which Whitford was perfecting at Washburn just as the B-type star work was in progress) was more sensitive, its speed was no greater for moderately bright stars, so the electrometer method was fine for this kind of measurement. The method was basically the same as for the earlier globular cluster work, although he chose filters centered at 4200 Å and 4700 Å for measuring the color index. Again, the spectral leverage was not optimal, but, "What the cell loses in leverage by having the spectral regions close together it gains in the greater precision of the measures." (Stebbins and Huffer, 1934: 219). Unlike the globular clusters, Stebbins could establish a 'normal' color index for a B-type star, which he did by adopting the mean of a group of B-type stars brighter than visual magnitude 6 and located more than 15° from the Galactic Equator.

The majority of the extremely laborious observing, which would eventually produce color indices for more than 1300 B-type stars, was carried out by Huffer, Stebbins' long-term colleague at Washburn Observatory. Huffer and his student observing assistants, with occasional participation by Stebbins, logged thousands of hours of photometric measurements between November 1930 and March 1932 to produce the results that appeared in the publications coauthored by Stebbins and Huffer in 1933 and 1934.

In beginning his discussion of the results, Stebbins first explicitly assumed that the reddening results from scattering by particles in the interstellar medium. But he noted that it was premature to discuss the nature of the particles, i.e. whether they are gas molecules or dust, because "… the first step is to find out just where and how much the reddening is." (Stebbins and Huffer, 1934: 244). But he did return eventually to the nature of the interstellar medium and the question of whether and to what extent the scattering medium is gaseous or particulate.

In regard to the 'where', the conclusions of the B-type star studies confirmed the globular cluster results but extended them across much more of the sky and allowed comparison with the band of the Milky Way where spiral nebulae were never seen—the 'zone of avoidance'. In fact, the reddening of B-type stars confirmed the

> … existence of a thin layer of dark scattering material near the median plane of the galaxy. The reddened stars are practically all within Hubble's zone of avoidance of the extra-galactic nebulae. (Stebbins and Huffer, 1934: 258).

They illustrated this in Figure 4, which shows three subsets of increasingly-reddened B-type stars in galactic coordinates. Hubble's 'zone of avoidance' (the irregular contours of which Stebbins took directly from Hubble) runs across the plot above and below the Galactic Equator, and

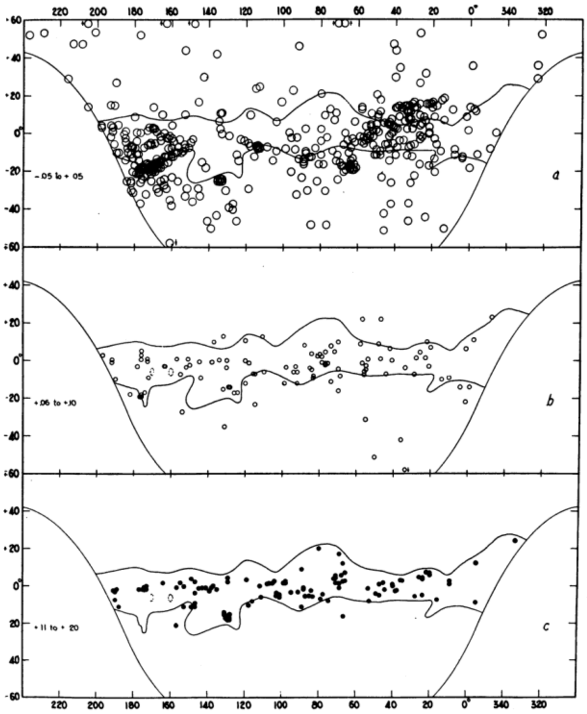


Figure 4: The more reddened B-type stars lie within the zone of avoidance (after Stebbins and Huffer, 1934: 242).

the curves cutting off the plot at right and left are the horizon cutoffs at the latitude of Washburn Observatory. Plot '*c*' (the lowest) shows the reddened group of stars with color indices between +0.11 and +0.20, nearly all of which fall within the 'zone'. Subsets of increasingly-reddened stars are plotted similarly in Figure 5. Stars of color indices from +0.21 to +0.30 (top plot) concentrate still more toward the Galactic Equator, and in the reddest range, +0.31 to +0.55, the stars fall very close to the Galactic Equator.

'How much' was partly addressed in the lowest plot of Figure 5, in which the scale of galactic longitude remains the same, but the vertical axis now represents the amount of reddening per kiloparsec. The reddening climbs toward a maximum approaching longitudes between 0 and 340° (near the center of the Galaxy), and descends to a minimum near the anticenter, near 180°. Despite these general trends, the distribution of space reddening, Stebbins and Huffer noted, is quite irregular as the reddening can be particularly strong in isolated regions. In fact, this is the first quantitative evidence for the extreme inhomogeneity of the general distribution of interstellar matter in the disk of our Galaxy. In addition, they pointed out that those areas of strongest reddening do not coincide with the visually-darker, more obscured, parts of the Milky Way but rather are found among the brighter star fields. They commented that although it is possible that the material causing the reddening might lie beyond the bright star fields, they thought it more likely that the material is in the spaces between the stars (Stebbins and Huffer, 1934: 248).

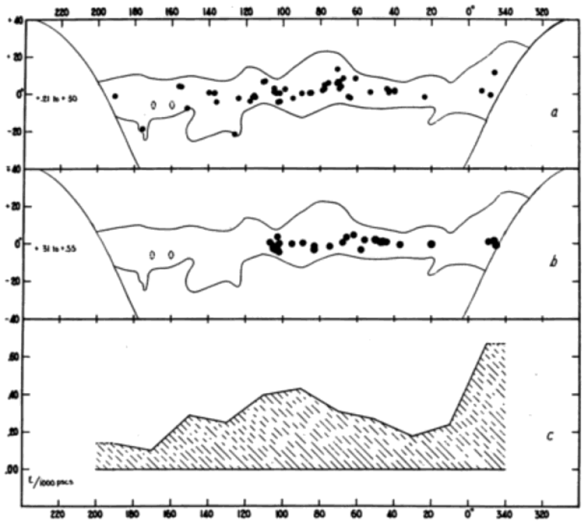


Figure 5: The most reddened stars and reddening along the Galactic Equator (after Stebbins and Huffer, 1934: 243).

With reddening as measured by B-type stars mapped, the authors then proceeded to compare those results with the reddening of globular clusters measured by Stebbins. To do so they reduced the color excesses of the globular clusters to the scale used for the B-type stars and plotted them together in the region near the center of our Galaxy (Figure 6). The shaded strip along the Galactic Equator, where no globular clusters are found, is where the most reddened B-type stars—indicated by crosses—are found; and the reddening of the globular clusters tends to be greater as they are closer to that strip. In Figure 6, the filled circles indicate reddened clusters and the bigger dots mean more reddening.

This has important implications for Shapley's general system, which located a number of the globular clusters

> … nearly in line with but far beyond the nucleus of the galaxy. On this view the light of the clusters comes through where the extragalactic nebulae are blotted out altogether. We think it more probable that the general region near the galactic center is opaque to the light of objects beyond the nucleus, and that the fainter globular clusters in that direction are between us and the center. (Stebbins and Huffer, 1934: 251).

So instead of seeing far across the entire expanse of a transparent Galaxy, as Shapley had thought he was doing, Stebbins and Huffer decided that we are actually seeing only objects on our side of the Galactic Center, and even those are very reddened. What is beyond is completely obscured by optically-opaque interstellar matter.

After a brief and inconclusive discussion of possible correlations between the reddening of B-type stars and the strength of interstellar calcium line absorption, Stebbins and Huffer implicitly turned their sights back to Shapley and the size of our Galaxy. Although the B-type stars had revealed space reddening to be extremely irregular, which makes calculations of distance liable to large uncertainties, multiple lines of evidence mean "… practically complete obscuration of distant objects near the galactic plane." (Stebbins and Huffer, 1934: 255). Without any doubt, the amount of absorption near the Galactic Plane meant that the inferred distances of objects must be reduced: "The largest absorption for B-stars is about two magnitudes, photographic, which means a division of the distances by 2.5." (Stebbins and Huffer, 1934: 259). Thus,

> The evidence from B-stars, from open and globular clusters, and from extra-galactic nebulae all agree in establishing the presence of the thin stratum of absorbing material near the galactic plane. There is every reason to conclude that this absorbing layer is quite similar to the dark lanes that we see in other galaxies that are viewed edge-on. When the absorbing effect of the dark material is properly allowed for it is expected that the hiatus between the dimensions of our galaxy and the other such systems will largely disappear. (ibid.).

With the confluence of the B-type star and globular cluster results, their case that interstellar matter has very important effects was now quite a strong one. Moreover, they made the point that our Galaxy would, if seen edge-on from outside, look similar to other spiral galaxies. Others had speculated in the same vein (for example, Curtis, 1917: 682; Trumpler, 1930b: 188), but unlike the others, Stebbins' comparison between our Galaxy and other spiral galaxies rested on new and solid evidence, and he presented it specifically as an alternative to the Shapley super-galaxy, both in terms of size and composition.

The aforementioned research was published first in *Proceedings of the National Academy of Sciences* (1933) and later in the *Publications of Washburn Observatory* (1934). For the most part, the two research papers parallel each other, and in many passages are identical. The Washburn Observatory version includes lengthy tables of stellar reddening data, which the *PNAS* paper omits. The only significant section that appears in the *PNAS* paper but was omitted from the Washburn Observatory version contains a discussion of the total mass of interstellar material responsible for the observed scattering. This discussion is very interesting as an early attempt to infer the amount of non-stellar mass in our Galaxy. There is no clue as to why it appears in only one version of the paper.

Stebbins and Huffer noted that they could go beyond earlier estimates of the mass of the interstellar absorbing material because the B-type star work had involved a survey of most of the plane of the Galaxy, whereas the earlier attempts by Anton Pannekoek (1873–1960) and Arthur Stanley Eddington (1882–1944) were based on an extrapolation from a small portion of sky in Taurus. So

> … now we have the whole mid-galactic layer filled with stuff and in a volume probably millions of times greater than the space in Taurus. (Stebbins and Huffer, 1933: 603).

Nevertheless, they noted that it remained premature to take the estimates very far because the ratio of total absorption to selective absorption was still unknown. Plunging ahead for the sake of illustration, they assumed the interstellar scattering through the entire absorbing layer along the line of sight perpendicular to the plane of the Galaxy to be of the same order as that produced by a column of terrestrial atmosphere looking toward the zenith, the cross-sectional mass of which they estimated at 1000 grams per square centimeter. Assuming the discoidal Galaxy to be 30,000 parsecs in diameter (much smalller than the Shapley super-galaxy), the total mass in the absorbing layer would be ~3 × 10^{15} solar masses. This much mass seemed unreasonable.[7] But the authors noted then that solid particles, compared to gas molecules, are more effective at scattering, per particle, by a factor of ~3 × 10^6, which implies a total scattering mass of 10^9 solar masses multiplied by the (unknown) ratio of the mass of a typical scattering particle to that of an air molecule. So although the total stellar mass of the Galaxy, they noted, was quite uncertain, "On any calculation it will not be surprising to find the dark material greater in mass than the total of the stars." (Stebbins and Huffer, 1933: 604). In the Shapley super-galaxy, the amount of matter between the stars was considered to be insignificant, but in the smaller 'Stebbins galaxy', the non-stellar mass might actually exceed the combined mass of all the stars!

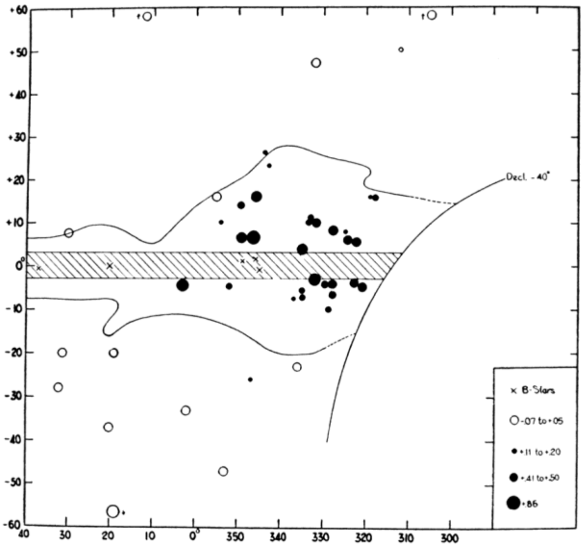


Figure 6: Reddened B-type stars (crosses) and globular clusters in and near the zone of avoidance in the region around Sagittarius (after Stebbins and Huffer, 1934: 251).

5.3 Taking the 'Hiatus' by Its Other End: The Diameter of the Andromeda Nebula

Stebbins pointed out that the 'hiatus'—that is, the apparent discrepancy between the estimated size of our Galaxy and the Andromeda Nebula —was quite large in the Shapley super-galaxy picture. It could amount to an order of magnitude, depending on which particular estimates of the sizes one takes. In his extensive study of that famous spiral nebula Hubble (1929: 156) concluded that "… the galactic system is five or six times the diameter of the spiral." In this estimate, he was depending on one of Shapley's results, based on globular cluster measurements, that the Galaxy was about 80,000 pc in diameter. Hubble realized that photographic limitations, such as sky brightness, probably caused the extent of the spiral to be underestimated, but his techniques could not correct for such factors. The Washburn astronomers' research had so far pointed to a considerable reduction in Shapley's size of our Galaxy, which had the effect of reducing the 'hiatus', but the true relative sizes of the two objects, and therefore the question of whether they are comparable objects or of different natures from each other, obviously depended also on the estimated size of that prominent nebulous object in Andromeda, which photography could not fully gauge. But the recently-developed amplifier photometer could do the job.

Stebbins and Whitford obtained photometric brightness profiles of the Andromeda Nebula using their amplifier outfit on the Mt. Wilson 100-in reflector in spring and summer of 1933, although Stebbins had experimented with the photometry of 'extra-galactic nebulae' at Mt. Wilson in previous years. The photometer vacuum tank, containing the Kunz photoelectric detector and amplifier, was mounted at the Newtonian focus of the telescope. A cable connected that instrument to the galvanometer—which measured the photocurrents—at the base of the telescope pier (see Figure 7).

The method, as was nearly always the case in Stebbins' photometric work, was to make differential measurements, comparing, in this case, the brightness measured at a place on the nebula, with that of a nearby spot of clear sky. The difference between the two deflections indicated by the galvanometer was the fundamental datum. By this differential method they generally avoided complications of varying air mass, minor variations in detector sensitivity owing to temperature and battery voltage, and so on. Their ability to directly subtract the sky background was a considerable improvement over photography in the detection of very low-contrast objects, such as the periphery of a spiral galaxy. On a given

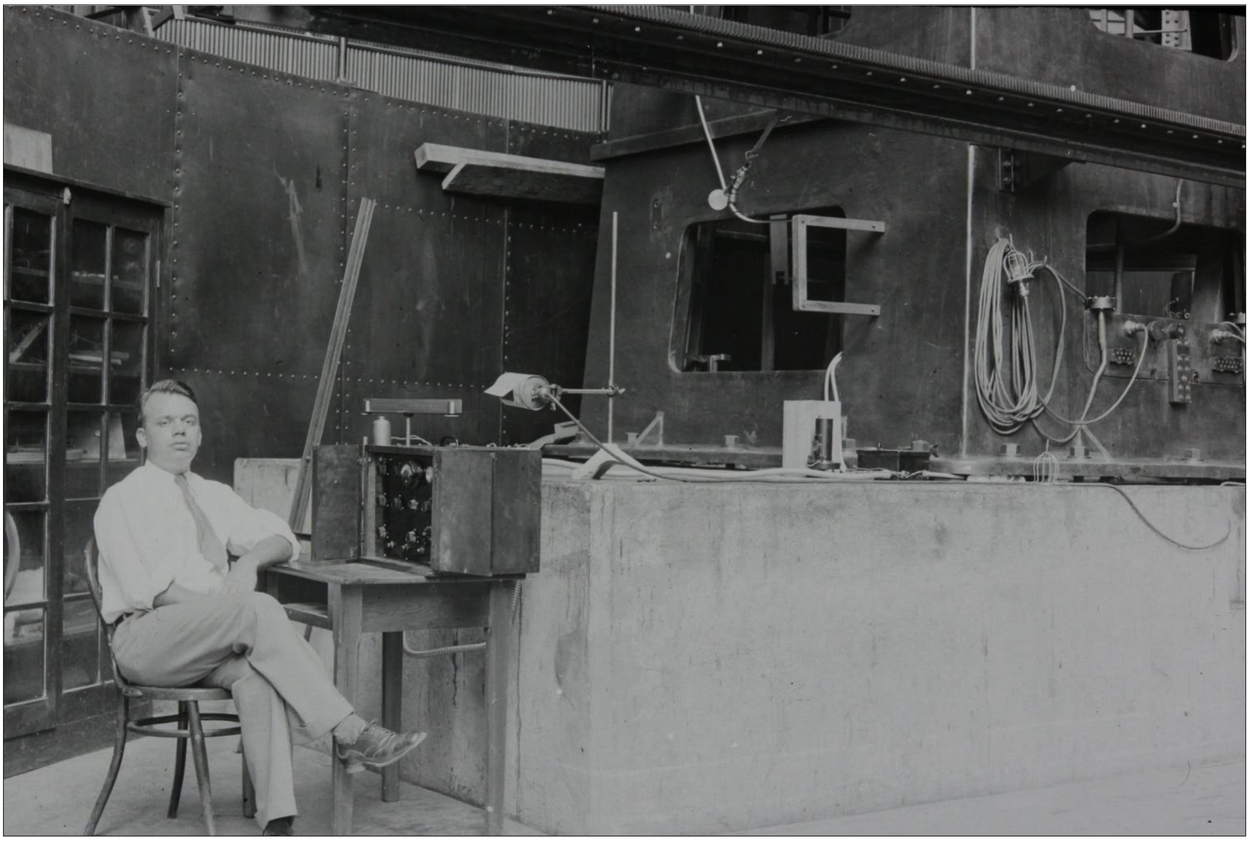


Figure 7: Albert Whitford at the readout position of his amplified photometer on the 100-in telescope. The galvanometer scale is the horizontal screen just above his table-top instrument cabinet, and the optical-lever galvanometer, the small dark vertical cylinder, sits on the top of the concrete platform half way between the galvanometer scale and the right edge of the photograph (courtesy: University of Wisconsin-Madison Department of Astronomy).

run they measured the differences between nebula and sky along linear paths crossing the nebula at increments of 10 arcmin in declination (see Figure 8).

In the paper setting out their results, published in 1934, Stebbins and Whitford established the context immediately as that of the notorious hiatus: "Any increase in the known size of extra-galactic nebulae is of course important in a comparison with the dimensions of our own galaxy." (Stebbins and Whitford, 1934: 93). After discussing the difficulty of comparing photographic measures of the dimensions, they concluded that their own measurements showed that the previously-accepted diameter of the Andromeda Nebula had to be at least doubled along the north-south extent, and that the same factor should probably also be applied to the perpendicular axis as well. Thus,

> The present work indicates that the diameter of the nebula may well be as much as 20,000 pc … [while] the figure for the [Milky Way] galaxy may have to be revised still further [downward] when the space absorption near the median plane is better determined … In fact, when the size of our galaxy is as well known as that of the Andromeda nebula, most of the inferred difference in scale between the two systems may disappear. (Stebbins and Whitford, 1934: 98).

They also were ready to speculate that this result is probably typical of other spiral nebulae: "The extension of the Andromeda nebula beyond the photographic limits is presumably typical of what may be found for other such objects." (ibid.).

After 1952 and Walter Baade's recalibration of the Cepheid period-luminosity curve, the distance, hence size, of the Andromeda Nebula based on Cepheids would be effectively doubled, confirming, as Stebbins expected, that it was comparable in size to our own Galaxy.

So the disturbing 'hiatus' introduced by the Shapley super-galaxy was unraveling at both ends because Stebbins and his colleagues had new data to cut it down to size. The intuition that there ought to be some uniformity in the nature of the spiral nebulae, and the disquiet at locating ourselves in a very special assembly of stars—the Shapley super-galaxy—had found new empirical support in the research program of the Washburn astronomers.

5.4 Finishing off the Shapley Galaxy: Back to the Globular Clusters

As the B-type star work continued at Madison, and the Andromeda Nebula measurements were in progress in 1933 on the 100-in telescope at Mt. Wilson (during which time Whitford was a National Research Council Fellow at Mt. Wilson), Stebbins and Whitford began using the same equipment on the 100-inch to begin new measurements of the colors of globular clusters. The result was a considerable expansion and improvement over Stebbins' 'preliminary report' of 1933. In the paper they published in *Astrophysical Journal* in 1936, Stebbins and Whitford reported colors of 68 globular clusters (increased from 47 in the 1933 paper). The new observations, acquired between 1933 and 1935, employed new filters (4340Å and 4670Å), which reduced the color index 'leverage' from 500Å, as in the earlier globular cluster and B-type star

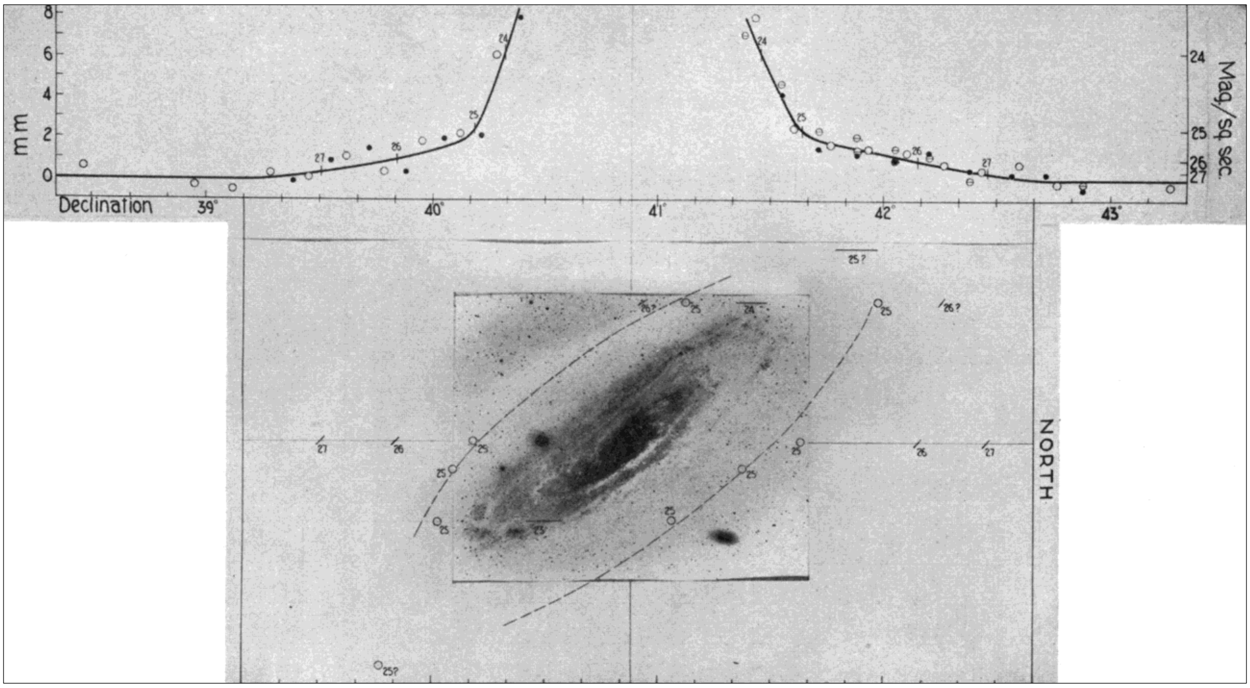


Figure 8: Illustration of photometric brightness contour along a north-south line through the nucleus of the Andromeda nebula. (after Stebbins and Whitford, 1934: 96).

work, to 330Å. The authors explained that these choices produce equal deflections about spectral type G.

The effect of moving the filter centers closer to the peak sensitivity of the potassium hydride Kunz cell (about 4500Å) meant greater sensitivity, important for the work on dim globular clusters. The lower noise levels of the photoelectric amplifier compared to the older electrometer rig compensated for the loss of leverage. The clearest indications of the technical advance were that the photoelectric amplifier could measure colors (on a given telescope) for objects a full magnitude dimmer than could be reached by the electrometer instrument, and that the probable error of the color measurements (as estimated by Stebbins) ranged from ±0.01 to ±0.04 mag with the new instrument compared to ±0.055 with the older one.

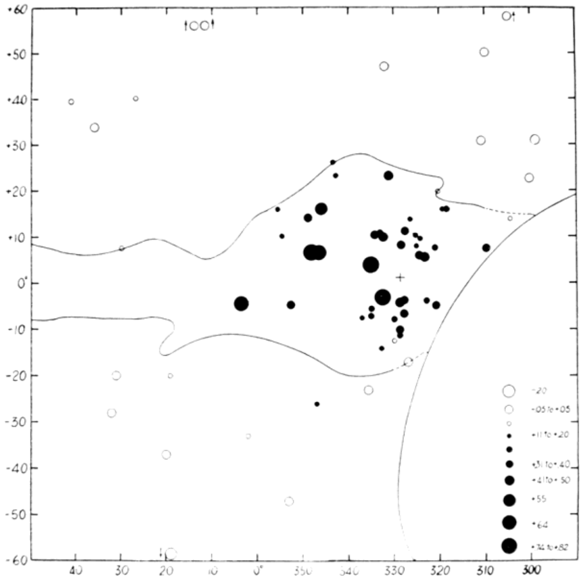


Figure 9: Color distribution of globular clusters. Reddened clusters are filled dots, with larger dots indicating greater color excess (after Stebbins and Whitford, 1936: 145).

In discussing the results, Stebbins and Whitford first compared their globular cluster colors with two other measures expected to be correlated with interstellar absorption: the number of nebulae in a given area of sky and the richness of the star fields. They acknowledged Baade in this comparison, who assisted them by examining his plates "… taken with the large reflectors …" for the areas around a subset of the globular clusters.[8] For each cluster, Baade had characterized the number of nebulae on the plate as 'normal', 'less than normal' or 'none', and he had characterized each star field as 'normal', 'partially obscured' or 'heavily obscured'. When the globular clusters were ranked in order of increasing color index (increasing redness), there emerged a fairly abrupt transition in the nebula counts at about color excess +0.19: plates containing clusters less reddened than +0.19 almost all showed 'normal' nebula counts in the area around the cluster, while those redder than +0.19 show 'none'. Only three of the 43 clusters with color excesses near +0.19, were found in areas with 'less than normal' nebulae. This was exactly what one would expect if the reddening of the clusters was a result of selective scattering by interstellar matter. As they wrote, "The close correlation of the colors with the numbers of nebulae is striking." (Stebbins and Whitford, 1936: 145).

Less striking was the relationship of star scarcity to cluster reddening, which showed only a general tendency for fewer stars in areas with more reddened clusters, which is consistent with the lack of a strong correlation that they had found between B-type star reddening and stellar density. The authors noted that rich star fields could lie in front of absorbing regions, which would blur the correlation, but they observed that whenever there was a relative scarcity of stars at low galactic latitudes, the globular clusters were strongly colored. In any case, the hypothesis that globular cluster reddening was caused by selective absorption in interstellar space was consistent with the rough measures of nebulae and star counts.

Stebbins and Whitford introduced their discussion of the general system of globular clusters with a diagram that plots the locations of clusters in galactic coordinates near the Galactic Center and indicates their degree of reddening (see Figure 9). This is very similar to the diagram published with the B-type star work (see Figure 6 above), but redrawn with more globular clusters and no B-type stars. The curve on the right is the horizon cut-off at the latitude of Mt. Wilson, and the Galactic Equator runs horizontally through the middle. Hubble's 'zone of avoidance' in the region of the center of the Galaxy contains nearly all of the reddened globular clusters, and the lower the latitude the redder the cluster. But along the Galactic Equator itself are no globular clusters are to be found. Putting this together with the correlation between cluster reddening, nebula counts and star counts, they declared: "There is now no doubt that Shapley's first distances of clusters must be corrected for absorption." (Stebbins and Whitford, 1936: 148). Figure 10 provides a modern illustration of the reddening effect.

What kind of correction should be made for the interstellar reddening? The choice was really between some kind of model for a coefficient of absorption, such as a cosecant law, as Stebbins discussed in his 1933 globular cluster paper, or applying individual corrections to each cluster according to how reddened it appeared. Stebbins and Whitford cited the attempt by Baade to model the absorption as a cosecant function of

Figure 10a: Three-color composite image of globular cluster M71 as it appears to us reddened by selective extinction in the interstellar medium. This cluster lies very close to the galactic plane and is so obscured that it was not even recognized to be a globular until the 1970s. For this reason M71 was not among the objects observed by Stebbins (courtesy: Bob Franke/Focal Pointe Observatory).

Figure 10b: The above image of globular cluster M71 processed to remove the calculated reddening, giving an impression of how it would look if seen through empty space (courtesy: Bob Franke/Focal Pointe Observatory). More information on these images is available at http://apod.nasa.gov/apod/ap141210.html.

galactic latitude, which came to the conclusion that "… practically all globular clusters are contained within a sphere of 20,000 pc radius." (Baade, 1935: 410). They modified Baade's numbers to derive a distance to the center of the system of globular clusters of about 8,000 parsecs. Nevertheless,

> Other considerations, especially the distribution of colored B stars, have convinced us that the simple assumption of a uniform layer of absorbing material near the plane of the galaxy will not suffice … at least there should be a dependence upon the longitude. (Stebbins and Whitford, 1936: 149–151).

The distribution of the reddening, as shown in Figure 9, demonstrates how 'spotted' is the pattern of reddening, with contrasting color excesses mingling within the zone of avoidance. After the B-type star work, this was yet another empirical demonstration of the extreme patchiness in the distribution of our Galaxy's interstellar matter, as well as an indication of how tricky it might be to model the absorption mathematically. So rather than a simple cosecant law, Stebbins and Whitford proposed to take account of the irregularity of the absorption by using the reddening of the individual clusters to find the amount of absorption in the line-of-sight to each individual cluster, with the explicit assumption that

Table 1: Comparison of distances to the center of our Galaxy derived from different assumptions about interstellar absorption (after Stebbins and Whitford, 1936: 156).

Photographic Optical Thickness (mag.)	Distance to Center (kpc)	Basis
0.0	16.4	Shapley, original moduli
0.32	10.0	Colors of globular clusters
0.50	8.0	Hubble's count of nebulae
0.8	5.5	Van de Kamp, Harvard counts of nebulae

> … the ratio of the selective to the general absorption is constant, that the relative proportion of the light-scattering particles and the light-obstructing particles is the same throughout the space considered. (Stebbins and Whitford, 1936: 151).

Establishing the value of this ratio was, however, not an easy task, because it involved comparing estimates of the 'photographic' absorption (as a measure of the total absorption) with the selective absorption (measured by reddening). The former came from counts by others (primarily Hubble (1934) and van de Kamp (1932; 1933)) of nebulae made in moderate to high latitudes, while the latter came from their reddened globular clusters, mostly at low latitudes. The details of the arguments are somewhat tedious, but in the end, Stebbins and Whitford (1936: 153) concluded that the value

> … for the total photographic absorption, derived from the counts of nebulae, is three or four times the absorption we might infer from the reddening alone.

The authors turned immediately to the nature of the absorbing matter itself, repeating a conclusion from their paper on B-type stars:

> In a discussion of the total amount of interstellar matter which causes space reddening it is necessary, in order to avoid an impossibly large mass, to suppose that the scattering material is composed largely of solid particles rather than gas molecules. It would indeed be surprising if some of the particles were not too large to scatter according to the Rayleigh law, and therefore merely obscure without reddening. (Stebbins and Whitford, 1936: 154).

Having recalculated the Shapley distance to each cluster according to the estimated total absorption, Stebbins and Whitford proceeded to test whether these new distances produce the expected 'system' of clusters symmetrically condensed about a distant center. But in fact, plotted this way, the grouping of clusters is still elongated, as Shapley had concluded, along the *x*-axis (the radius from the Sun toward the center of the Galaxy), which is both unsatisfying and unlikely (since it would seem to imply that the radius to the Sun is a special direction for the globular clusters). This suspicious elongation had been noted by others, including, for example, van de Kamp (1931) and Boris Vorontsov-Velyaminov (1930). Van de Kamp considered absorption a prime suspect. After calculating the corrections from colors of individual clusters, Stebbins and Whitford were so confident that the elongation resulted from systematic error that they concluded:

> … the proper corrections cannot be made either from the cosecant law or from the colors, or else the original uncorrected distances are uncertain. (Stebbins and Whitford, 1936: 154).

They chose the last of these three options: Shapley's use of apparent diameters for judging the distances of the faintest clusters was subject to very large uncertainties, which were exacerbated, they pointed out, especially at low galactic latitude, by the effects of total absorption, which Shapley explicitly neglected. Nevertheless, one could still try to use the centroid of the distribution of the clusters to estimate the distance to the center of the system. So Stebbins and Whitford concluded their paper by presenting a short comparison of values of distances to the center of the system of globular clusters (and hence presumably the Galaxy) derived from different assumed values of total interstellar absorption (see Table 1). The first distance is from Shapley, whose cluster distances neglected any interstellar absorption. The second is the value arrived at by Stebbins and Whitford on the basis of the reddening of the globular clusters. The third and fourth distances were deduced from the estimates of total absorption by Hubble and van de Kamp respectively. All three of the results that take into account some degree of interstellar absorption put most of the globular clusters within a sphere 30,000 to 40,000 pc in diameter (as determined by the maximum extent of the globular cluster system). In a final reply to Shapley, Stebbins and Whitford (1936: 157) wrote:

> Our galaxy is a large one; but when its apparent dimensions are corrected for space absorption, and the extension of the Andromeda nebula, both in stars and in clusters, is considered, the two systems seem to be of the same order of size.

6 CONCLUSION

As we have seen, Stebbins and his Washburn Observatory colleagues were working to address the provocative cosmological implications of the super-galaxy, that is, they wanted to put the 'hiatus' on trial, to test whether our Galaxy was, as Shapley held, a monstrous continent among mere islands, or whether our Galaxy was, as intuition and evidence was telling many astronomers, something more typical. Shapley's location of the Sun far from the center of the Galaxy is sometimes portrayed as a triumph of the 'Copernican Principle', which had presumably been offended by our star's more central location in the Kapteyn galaxy. But if so, then the Copernican Principle should have been just as offended by the special status of the super-galaxy. Or, as Eddington (1933: 5) put it:

> According to the present measurements the spiral nebulae, though bearing a general resemblance to our Milky Way system, are distinctly smaller. It has been said that if the spiral nebulae are islands, our own galaxy is a continent. I suppose that my humility has become a middle-class pride, for I rather dislike the imputation that we belong to the aristocracy of the universe.

Probably many astronomers agreed, and that would have been part of what fueled the 'Great Debate' as well as its aftermath.

What was emerging from the investigations provoked by Shapley's grand vision was a new concept of our Galaxy, much larger than Kapteyn's but much smaller than Shapley's, full of a lumpy distribution of non-stellar matter perhaps comparable in mass to the collective stellar mass; and comparable in size, structure and composition to neighboring galaxies. The new view of our Galaxy, outlined clearly in the work of Stebbins and others in the 1930s, included the interstellar matter that would later be recognized as essential not only for absorption and scattering of light, but for stars to form and spiral structures to emerge. Perhaps most importantly, the emerging concept was of a Galaxy not fundamentally different from the neighboring galaxies, but rather enough like them to allow astronomers to study structures and processes that operate in our own Galaxy but tend to remain cloaked in the complex interstellar medium. If our Galaxy was a continent, astronomers were now gazing across the cosmic oceans onto the shores of countless other galactic continents.

Beyond resizing our own Galaxy and others, the work of the Washburn astronomers had yielded the first mapping and measurement of interstellar matter and generated some early insights into the nature of the interstellar medium. They would extend their work to include measurements of interstellar matter's extreme inhomogeneity and determination of the 'law of interstellar reddening', which is to say, the behavior of interstellar scattering as a function of wavelength.

The dismissal by Shapley of any significant interstellar absorption remains somewhat puzzling. As noted earlier, he was fully aware that interstellar absorption could undermine his methods, so he attempted to estimate its effects and, as we saw, deemed them negligible. Why did he find no reddening in the globular clusters and thus decide that interstellar absorption was a non-issue while Stebbins found, quite to the contrary, significant reddening? In part, the answer stems from Stebbins's decades of effort in developing his photoelectric techniques. Shapley had to depend on conventional photographic color indices derived from individual, faint cluster stars. But it is precisely here that photoelectric photometry had a considerable advantage over photographic photometry, because Stebbins could work with the integrated light of the entire cluster. In addition there was the thoroughness and methodical approach that Stebbins was known for: while Shapley dismissed the extincttion problem after checking three globular clusters located in parts of the sky unlikely to show much absorption, Stebbins measured every globular cluster visible from Mt. Wilson. Moreover, he tested his cluster conclusions by checking the reddening results via the laborious B-type star program and also against, for example, Baade's counts of nebulae and star fields. Shapley's personal style seems to have been to forge on to grand hypotheses and leave their trials to others.

Even with the 'Great Debate' about the nature of the spiral nebulae resolved by Hubble, the apparent gulf in size between our Galaxy and the spiral nebulae, typified by the nearby Andromeda Nebula, remained a serious problem. Stebbins and his colleagues directed their efforts to the solution. But, as I have argued, there was more involved than a question of calibration and spatial dimensions, because the resolution of the 'hiatus' required the recognition and understanding of the phenomena caused by interstellar matter, and that took Washburn Observatory's astronomers toward new investigations and a modern understanding of galaxies.

7 NOTES

1. An important early study of the Andromeda Nebula was by Hubble (1929), cited by both Shapley and Stebbins, but a common assumption was that if the spirals were 'island universes' then they would be at most the size of the Kapteyn Universe, which might be very roughly 10,000 parsecs in diameter.
2. Modern values disagree but locate the center of our Galaxy between 6,700 and 8,500 pc from the Sun.
3. It does not have sharp edges, of course, but modern estimates put the diameter of the baryonic matter in the Galaxy at between 100,000 and 120,000 ly.
4. This method predates both the six-color system developed by Stebbins and Whitford and the Johnson-Morgan UBV color indices of stars.
5. Some of these papers appear twice in the literature, once as a *Publication of the National Academy of Sciences*, from which Stebbins received occasional funding, and again as a *Contribution from Mt. Wilson Observatory*. I have cited the *PNAS* versions unless otherwise noted.
6. Relative reddening is equivalent to a more positive color index, hence 'color excess'.
7. It amounts to about a thousand times the modern estimated baryonic mass of the Galaxy.
8. Only 43 of the 68 for which they had colors appear on this list. Stebbins and Whitford gave no explanation for this, but perhaps Baade did not have plates on hand for all the clusters.

8 ACKNOWLEDGEMENTS

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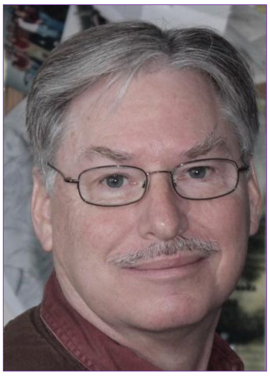

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BURMESE SHADOW CALCULATIONS

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Abstract: The methods of calculation of shadow lengths of the Sun and the Moon seem to be a specific for Burmese astronomy and have many original features. The present paper gives a detailed exposition of these methods with an analysis of an example taken from a Burmese manuscript.

Keywords: Burmese astronomy, solar shadow length, lunar shadow length

1 INTRODUCTION

Some of the traditional calculation procedures of South-East Asia appear at first sight to be impenetrable, a complicated jumble of figures accompanied by obscure labels usually of Pali derivation and of no explanatory value. With some application and perseverance, however, and a constant awareness of error in the arithmetic, it is often possible to unravel the reckoning, a process that involves constructing what in modern terms would be the 'right' answers as a means of isolating and being able to replicate what their 'wrong' answers were. In the course of analysis one becomes aware that in a pre-telescopic age number was power and also that the procedures were cast in such a way that their mechanical operation led to results whose theoretical basis went without challenge. But so did whatever anomalies and inconsistencies might creep into the reckoning. A prime example of this is where in the procedure leading to the mean reckoning of the Sun and the Moon it was the practice to subtract 3′ from the Sun's value and 40′ from the Moon's value. This adjustment can clearly be seen to have been a longitudinal correction based upon Ujjain, the ancient Greenwich, and as a correction it was roughly appropriate for Burma; but it was used routinely and hence without comprehension across South-East Asia (see Eade, 1995). An exception is the more modern *Thandeikhta* that only has a lunar correction of –52′ and so deviates from this pattern.

One of the more complex and interesting sets of procedure can be found in various Burmese documents that detail how the Sun's shadow length is to be calculated (for the purpose of casting horoscopes) and by extension how a similar process is applied to the Moon. The Moon's shadow length appears early on (in the fifteenth century) in the ancient Burmese capital of Pagan (Site 479, 21° 9′ 42″ N, 94° 54′ 11″ E, Burmese Era 767 Kason 7 waning (20 April 1405): "Monday, early morning cock crow 3 times, shadow of Moon 6 1/2 feet plus 4 hands, son born."), and at a time well before the revision of the system that displaced the *Makaranta* procedures by the *Thandeikhta*. The evidence we have comes from a period that must postdate this reform since consistently the shadow calculation adjusts for precession, though how far back the procedure stretches beyond the printed form in which some of the data is available cannot be assessed. In what follows we give an account of the correct procedures in modern terminology, together with an indication of what was actually done.

About ten years ago we discovered in a Burmese astronomical text (Mauk, 1971) a strange numerical table that was obviously connected with a shadow calculation. The calculation was, however, badly corrupted and full of errors. Other texts that appeared also were corrupt. One obstacle was also that, as we eventually discovered, the gnomon height was 7 units while the standard length for example in India is 8 or 12 (Pingree, 1978). Finally we obtained a printed text (Thi, 1936) that had a list of intermediate calculation results that were sound and enabled us to recreate the calculation procedure.

Our Burmese informant (Ko Ko Aung, pers. comm., June 2011) indicates that many Burmese villages in older times had a gnomon set up and when a child was born the gnomon would have been consulted for the shadow length, then used as the basis for casting a horoscope. There was a corresponding calculation procedure for the Moon, although given the difficulty of measuring in practice such shadows, one imagines that 'Moon shadow' values were purely notional. The calculation system has the merit that it can be applied at any time irrespective of physical conditions, to say nothing of its assumed superior accuracy because you are then juggling with numbers and not using measurement.

2 FUNDAMENTALS

In order to calculate the relation between time and shadow length you need some fundamental data. First you need to know the date in order to calculate the longitudes of the Sun and the Moon. Since Burmese astronomy, as in all parts of South-East Asian and India, uses sidereal longitudes, you have, in the more ‘modern’ versions that we have investigated, to correct for precession.

For your particular location you need also to know its latitude and the lengths of the day and night and finally the rising times for the different zodiacal signs at that place. Time in Burmese astronomy, as in Hindu astronomy, is measured in *nadis* and *vinadis* (Burmese *nayi* and *bizana*), 60 *nadis* being a day and night and 60 *vinadis* being a *nadi*.

3 THE LONGITUDES

As the calculation of true longitudes is somewhat complex we have placed an example in the Appendix.

4 PRECESSION

The Burmese used the Hindu system, where the difference between the tropical and sidereal longitudes is represented by a linear zigzag function with an amplitude of 27° and a period of 7,200 years, the zero being in AD 412. For years between AD 412 and AD 2212 it is +54″ per year. The Burmese allowed for precession by using the following algorithm, valid for the time interval above:

1) Convert the Burmese year to the Kaliyuga era by adding 3,739.
2) Add the era constant, 88.
3) Divide the result by 1,800 and save the remainder.
4) Multiply by 9 and divide by 10.
5) Divide the integer part of the result by 60. The integer part of the result is the degrees of the precession; the remainder is the arc minutes.
6) Multiply the remainder of the result in 4) by 6 to get the precession in arc seconds.

For details see the sample calculation below.

5 LENGTH OF DAY AND NIGHT

Using modern mathematical language, the ascensional difference or the difference A (plus or minus) in half a day from 6 hours/15 nadis is given by

$$\sin A = \tan \varphi \tan \delta \qquad (1)$$

where φ is the geographical latitude of the location and δ is the declination of the luminary, the Sun or the Moon. A here is given in degrees with 90° = 6 hours = 15 *nadis*.

The declination, δ, above is given by

$$\sin \delta = \sin \lambda \sin \varepsilon \qquad (2)$$

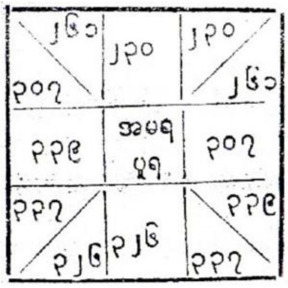
where λ is the true longitude of the luminary, corrected for precession, and ε is the obliquity of the ecliptic, with the Hindu value of 24°. The Moon is treated as though it has zero latitude.

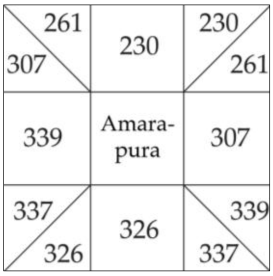
In practice the value of A, in *vinadis*, is given for a number of fixed locations in Burma as the three values for $\lambda = 30°$, 60° and 90° and intermediate values are calculated by linear Interpolation. See the Appendix for an example.

Once we know the difference, A, we can calculate the length of one half day, D, by adding to or subtracting A from 6 hours or 15 *nadis*.

6 RISING TIMES

The rising times of the zodiacal signs can be calculated once we know the location, and again this is pre-calculated and displayed in graphical form as a diagram of rising times (see Figure 1 and Table 1). Figure 1 is set up for Amarapura, formerly a capital of Burma, and now in the southern part of the Mandalay conurbation.





261 307	230	230 261
339	Amara-pura	307
337 326	326	339 337

Figure 1 (left): Rising time diagram.
Table 1 (right): Translation of numbers in Figure 1.

In modern language these numbers are differences of oblique ascension. The Appendix shows how to calculate these numbers.

The top segment is Aries and the other signs follow in anti-clockwise order. Each sign segment gives the rising time of that sign expressed in *vinadis*.

7 THE SOLAR SHADOW CALCULATION

The Burmese shadow calculation uses a gnomon height, G, of 7 ‘feet’, which usually is further divided into 420 smaller units. The equinoctial noon shadow, S_{eq}, is given by $G \tan \varphi$ for the gnomon and is displayed as a number associated with each listed location (see the Appendix).

The first part of the procedure is to calculate the noon shadow, S_{noon}, for the particular date.

This is given by the expression

$$S_{noon} = \left| G \tan(\varphi - \delta) \right| \qquad (3)$$

The vertical bars denote absolute value, skipping the sign.

ဘဝါးတွက်ရန်ဇယား

နတနာရီ	၂	၄	၆	၈	၁၀	၁၂	၁၄	၁၆	၁၈
မိန်-မိဿ-ကန်-တူ	၄	၅	၆	၆	၆	၅	၄ ၂၀	×	×
ပြိဿ-သိန်	၇	၇	၇	၇	၆	၆	၅	၄	×
မေထုန် ကြဋ်	၈	၈	၈	၇ ၃၀	၇	၇	၆	၅ ၃၀	၄
ဗြိစ္ဆာ ဓနု မကရ ကုံ	၂	၃	၄	၅	၅ ၄၀	၅ ၄၀	၅	×	×

Figure 2: Table in Mauk (1971: 154).

The Burmese method consists of giving a table of the *phawâ*, the differences between the noon shadow and the equinoctial noon shadow. The table gives the value of this difference of either luminary at longitudes 30°, 60°, 90° and 270°, 300° and 330°, with symmetries 60° = 120°, 30° = 150°, 210° = 330° and 240° = 300°. Intermediate values are interpolated. Once the *phawâ* is calculated, the noon shadow can be computed by subtracting the *phawâ* from the equinoctial noon shadow if the longitude of the luminary is <180°, or else by adding it to the equinoctial noon shadow.

The next step in the procedure is highly interesting. Doing an exact calculation of the relation between time and shadow is very complicated, and remarkably the Burmese resort to a theoretical model. As is usual in South-East Asian reckoning, theory becomes embedded in —effectively buried in—tables. Before the tables are examined it will be useful briefly to consider the model in general terms.

At noon the shadow is shortest and of course equal to the noon shadow. The change in length of the shadow at other times, H, being the time counted from noon, will be zero at noon and infinite at sunset/rise. The change can be modelled by the mathematical expression

$H / (D - H)$

where D is the time from noon to sunrise/set. This expression is clearly zero when $H = 0$ and infinite when $H = D$, i.e., has the correct values as its boundaries. We can multiply this expression by a multiplier, M, without distorting the boundary values.

The Burmese model is now that the total shadow, S, is given by

$$S = S_{noon} + [(M \times H) / (D - H)] \qquad (4)$$

with a value of M suitably chosen to approximate the real shadow length for all times from noon to sunrise/set.

Table 2: Translation of the numbers shown in Figure 2.

			Nadis	2	4	6	8	10	12	14	16	18
Pisces	Aries	Virgo	Libra	4	5	6	6	6	5	4:20		
	Taurus	Leo		7	7	7	7	6	6	5	4	
	Gemini	Cancer		8	8	8	7:30	7	7	6	5:30	4
Scorpius	Sagittarius	Capricorn	Aquarius	2	3	4	5	5:40	5:40	5		

ဘဝါးရဟိတာဇယား။

နတနာရီ		၁	၂	၃	၄	၅	၆	၇	၈	၉	၁၀	၁၁	၁၂	၁၃	၁၄	၁၅	၁၆
မကရ		၆၁	၁၂၄	၁၆၈	၂၁၆	၂၅၁	၂၈၀	၃၀၇	၃၂၅	၃၃၈	၃၄၅	၃၄၉	၃၅၀	၃၂၅			
ကုန်	ဓနု	၆၃	၁၃၃	၁၇၆	၂၂၀	၂၅၀	၂၈၀	၃၀၅	၃၂၁	၃၃၁	၃၃၅	၃၃၇	၃၃၇	၃၁၀			
မိန်	ဗြိစ္ဆာ	၇၉	၁၃၄	၁၈၇	၂၃၂	၂၆၇	၂၉၁	၃၀၉	၃၂၀	၃၂၄	၃၂၅	၃၂၀	၃၁၂	၃၀၁	၂၈၈		
မိဿ	တူ	၈၉	၁၆၂	၂၃၆	၂၈၃	၃၁၂	၃၃၀	၃၃၉	၃၄၀	၃၃၅	၃၂၈	၃၁၇	၃၀၃	၂၈၆	၂၆၇	၂၆၈	
ပြိဿ	ကန်	၁၇၈	၃၀၄	၃၆၃	၃၉၅	၄၀၈	၄၁၅	၄၀၂	၃၉၁	၃၇၅	၃၁၃	၃၃၈	၃၁၈	၂၉၆	၃၀၉	၂၅၁	
မေထုန်	သိဟ်	၅၇၁	၅၉၉	၅၈၂	၅၆၃	၅၉၀	၅၀၉	၄၈၄	၄၅၆	၄၃၀	၄၀၉	၃၇၅	၃၄၉	၃၂၂	၃၀၁	၂၇၀	၂၂၉
ကြဋ်		၄၅၅	၅၂၂	၅၃၉	၅၃၀	၅၁၅	၄၉၄	၄၇၁	၄၅၀	၄၂၇	၄၀၂	၃၇၂	၃၅၁	၃၂၆	၃၀၂	၂၆၇	၂၄၁

Figure 3: Table in Thi (1936: 12).

Table 3: Translation of numbers in Figure 3.

Nadis		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Capricorn		61	124	168	216	251	280	307	325	338	345	349	350	325			
Aqu	Sag	63	133	176	220	250	280	305	321	331	335	337	337	310			
Pis	Sco	79	134	187	232	267	291	309	320	324	325	320	312	301	288		
Aries	Libra	89	162	236	283	312	330	339	340	335	328	317	303	286	267	268	
Tau	Virgo	178	304	363	395	408	415	402	391	375	313	338	318	296	309	251	
Gem	Leo	571	599	582	563	590	509	484	456	430	409	375	349	322	301	270	229
Cancer		455	522	539	530	515	494	471	450	427	402	372	351	326	302	267	241

The multiplier, M, can be determined empirically or theoretically by inverting this expression where all the quantities in the right hand member can be calculated or measured to give

$$M = [(S - S_{\text{noon}}) \times (D - H)] \ / \ H \qquad (5)$$

You would expect, for reasons of scale, that M would be of the order of the gnomon height, 7 or 420, depending on the units used. Unfortunately, it turns out that the multiplier, M, which may be expected to be constant, is in fact a function dependent on the geographical latitude, φ, the time, H, and the longitude, λ, of the luminary. The latitude dependence is rather slow and the Burmese use an M that is a reasonable average, approximately valid for any location in Burma; but they still have to deal with the dependence on time and longitude. The Burmese solve this by having a double-entry multiplier table, the entries being time difference from noon in the horizontal and longitude of the luminary in the vertical.

We had available two printed text variants of this table, one by Mauk (1971: 154) and shown in Figure 2 (see, also, Table 2), and the other by Thi (1936: 12), which is shown in Figure 3 (and see Table 3 as well). The table in Mauk is by comparison crude and condensed, with only four entries for longitude and entries for time only for every second *nadi*. The value for M in this table varies between 2 and 8. The other version of the table uses a unit for M that is 60 times larger (G = 420) and has more entries for both longitude and time.

We do not know the original procedures used to create these tables, but we did a computer calculation of a table using Formula (5), above, and real shadow lengths for geographic latitude 22°. The generated result, Table 4, is quite similar to the Burmese table, the differences being small enough to suggest only minor variation in the original reckoning.

Given the existence of a table for the multiplier, M, the aim of the astrologer is to calculate time from the shadow. If we solve Equation (4) above for the time H we get:

$$H = [(S - S_{\text{noon}}) \times D] \ / \ [(S - S_{\text{noon}}) + M] \qquad (6)$$

M now appears as an additional term.

There is an obvious problem with the relation above. M is a function of H, so to calculate H we need to know the value of H in order to know M. The Burmese solution is to start with a default value of M = 7 and calculate a preliminary time H and then use this time H to get a better value of M from the table, insert it Formula (6) to get an improved value of H. This is an interesting application of successive approximations.

In practice a mathematically-equivalent expression is used for Formula (6):

$$H = D - \{(D \times M) \ / \ [(S - S_{\text{noon}}) + M]\} \qquad (6')$$

This mathematical procedure was turned into a series of steps to be learned by rote and in consequence some of the sources available to us go wildly astray in the elements they select for processing. But even from these confused calculations it was possible to arrive at a good estimate of how the original procedure must have looked and we could use the intermediary calculation values in a printed text (Thi, 1936) to vindicate our estimate.

The resulting time, H, is used to calculate back the shadow, in a reckoning that uses a modified, but mathematically-equivalent, version of Equation (4):

$$S = S_{\text{noon}} - [(D \times M) \ / \ (D - H)] - M \qquad (4')$$

8 THE LUNAR SHADOW CALCULATION

To begin with, this calculation is identical to that for the Sun. It tacitly ignores the latitude of the Moon, as was the case also with the planets in astronomical tables. Using the Moon's true longitude, corrected for precession, it is easy to calculate the length of the lunar 'day' and 'night'. Using the formulae above from a measured or notional Moon shadow, the Burmese could calculate the corresponding time from the lunar 'noon', the time of the culmination of the Moon. The problem is now to find the solar clock time of lunar noon.

Knowing the longitude of the Moon will determine the location in the rising time chart of moonrise and moonset. Lunar noon will be located midway in time from these points. As the difference, A, of the solar day is known, the interval in time from sunset to the time instant 45 *nadis* after midnight, or 6pm, is known. Also known is the longitude of the Sun, and thus the locations in the rising time chart of sunrise and sunset. This determines the point in the rising time chart

Table 4: Computer-generated multiplier table

Nadis		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Capricorn		69	128	178	219	254	281	304	321	335	346	354	359	363			
Aqu	Sag	69	127	176	216	249	275	296	312	324	333	339	343	346			
Pis	Sco	72	132	181	220	250	273	290	302	310	315	317	317	316	315		
Aries	Libra	92	165	220	258	284	301	311	316	318	317	313	309	303	296	288	
Tau	Virgo	168	273	329	356	368	371	369	363	355	346	335	325	313	302	290	
Gem	Leo	499	532	524	507	487	467	446	427	407	389	371	354	337	321	306	291
Cancer		449	506	509	498	481	464	445	427	409	391	374	358	342	327	312	298

corresponding to the time instant 6pm. Counting the rising times up to lunar noon will then give the clock-time instant of lunar noon. Knowing this and the value of *H* will finally give the clock time instant corresponding to the given shadow.

9 AN EXAMPLE

The results of a shadow calculation are presented in one of the available texts (Thi, 1936). On its last page (see Figure 4) the text gives a set of intermediary results of a Moon shadow calculation. The date, given in the text, is 1297 Pyatho 3 waning in the Burmese era, 9 January 1936. The location is Amurapura. A shadow length of 2 after lunar noon is also given in the text.

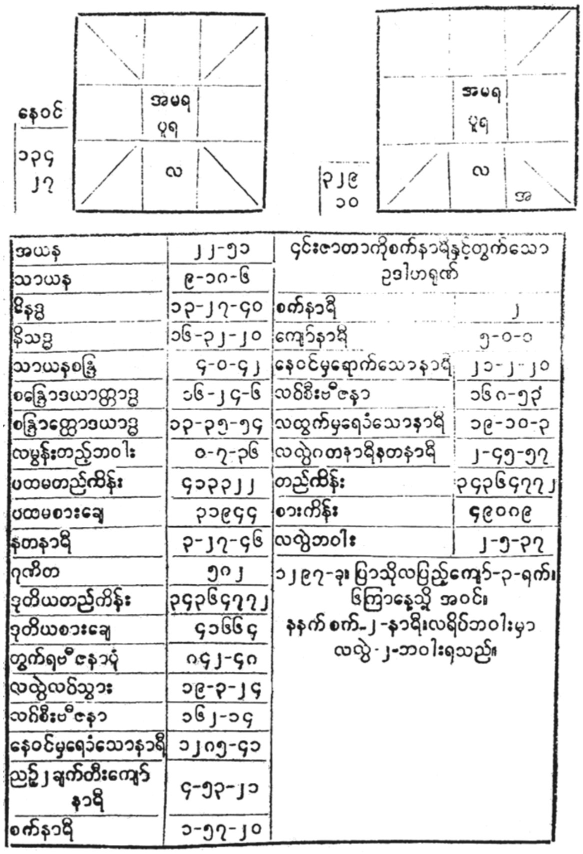


Figure 4: Moon shadow calculation (after Thi, 1936. 25).

Number format is sexagesimals, $a{:}b{:}c = a + b/60 + c/3600$, except for longitudes where $a{:}b{:}c = a$[zodiacal sign] + b[degrees] + c[arc minutes].

The rising time diagrams at the top have numbers 134:27 and 329:10 to their left. We label the lines in the lower square A, B … T and translate the numbers:

A	22:51	
B	9:18:6	
C	13:27:40	2
D	16:32:20	5:0:0
E	4:0:42	21:2:20
F	16:24:6	168:53
G	13:35:54	19:10:3
H	0:7:36	2:45:57
I	413322	34364772
J	31944	49089
K	3:27:46	2:5:37
L	582	
M	34364772	
N	41664	
O	842:48	
P	19:3:24	
Q	162:14	
R	1285:41	
S	4:53:21	
T	1:57:20	

The number in line A is the correction for precession. Using the algorithm given above we have:

$1297 + 3739 + 88 = 5124$
$5124 / 1800 = 2$, remainder 1524
$1524 \cdot 9 / 10 = 1471$, remainder 6
$1471 / 60 = \underline{22}$, remainder $\underline{51}$
$6 \cdot 6 = \underline{36}$

Thus the precession is 22:51:36, where the text has 22:51. The number in line B is the true longitude of the Sun corrected for precession, which is 9:18:6.

The differences of a half-day (in *vinadis*) for Amurapura are 48, 86 and 102, for solar longitudes 30°, 60° and 90° respectively. As the Sun is in sign 9 it will have 30° – 18:6° = 11:54° to reach sign 10. Sign 9 has (by symmetry) a day difference of 102, sign 10 has 86. Interpolation gives 86 + 11:54/30·(102 – 86) = 86 + 6:20:48 = 92:20:48 = 1:32:21.

A half-day is then 15:0:0 – 1:32:21 = 13:27:41, and line C in the text has 13:27:40.

A half-night is 30:0:0 – 13:27:41 = 16:32:19, and line D has 16:32:20.

The number in E is the Moon's true longitude, corrected for precession, 4:0:42.

Calculating the half lunar day and night as for the Sun gives 16:25:7 and 13:34:53, while the text has 16:24:6 and 13:36:54 for lines F and G.

The complete *phawâ* table for Amurapura using the symmetries is shown in Table 5.

The Moon's longitude is 4:0:42. Interpolating in the *phawâ* column gives 157:26. The equinoctial noon shadow for Amurapura is 165, giving a noon shadow of 165 – 157:26 = 7:34, and the text in line H is 0:7:36. The Moon shadow is 2:0:0 and the time is after the Moon's culmination or lunar noon. The Burmese start with a preliminary multiplier, *M* = 7, and they calculate a preliminary time, *H*, using Equation (6′). The half lunar day, *D*, according to the text is 16:24:6.

$D \cdot M = 16{:}24{:}6 \cdot 7 \cdot 3600 = 413322$, line I
$S - S_{noon} + M = (2{:}0{:}0 - 0{:}7{:}36 + 7) \cdot 3600 = 31944$, line J
$413322 / 31944 = 12{:}56{:}20$
$H = D - 12{:}56{:}20 = 16{:}24{:}6 - 12{:}56{:}20 = 3{:}27{:}46$, line K

This is the preliminary shadow time. Entering the multiplier table above with sign 4 and time 3 gives a multiplier 582, line L.

Repeating the calculation:

$D \cdot M = 16{:}24{:}6 \cdot 582 \cdot 3600 = = 34364772$, line M
$S - S_{noon} + M = ((2{:}0{:}0 - 0{:}7{:}36) \cdot 60 + 582) \cdot 60 = 41664$, line N.
$34364772 / 41664 = 824{:}48$

The text has 842:48 in line O but uses 824:48 for the following calculations:

$824{:}48 = 13{:}44{:}48$
$H = D - 13{:}44{:}48 = 16{:}24{:}6 - 13{:}44{:}48 = 2{:}39{:}18$.

This is the final time in *nadis* after lunar noon. To obtain the time, T, from moonrise we have

$T = D + 2{:}39{:}18 = 16{:}24{:}6 + 2{:}39{:}18 = 19{:}3{:}24$, line P.

The Moon has a longitude 4:0:42 or Leo 0:42. The rising time of the sign Leo is 337 *vinadis*. Thus moonrise is 0:42 / 30 337 = 7:52 *vinadis* into Leo and has 337 – 7:52 = 329: 8 left of that sign. The rising time diagram in the text has 329:10 and thus 7:50 instead of 7:52.

The shadow time 19:3:24 is then 19:3:24 + 0:7:50 = 19:11:14 from the beginning of Leo. Subtracting subsequent rising times: Leo 337, Virgo 326, Libra 326 tells us that the shadow time is 162:14 *vinadis* into Scorpio, line Q.

The Sun has a longitude of 9:18:6, and the opposite point on the ecliptic is 3:18:6, or Gemini 18:6. The rising time for Gemini is 339 *vinadis*, thus sunset is 18:6/30·339 = 204:32 *vinadis* into Gemini and remaining 339 – 204:32 = 134:28 to the beginning of Leo. The rising time diagram in the text has 134:27.

Thus the shadow time interval from sunset is 134:27 + 7:50 + 19:3:24 = 1285:41, line R. The difference from 15 *nadis* of half a solar day is 1:32:20. Thus, sunset occurs at 45:0:0 – 1:32:20 = 43:27:40 *nadis* from solar midnight. Adding the remaining part of Cancer from sunset tells us that the end of Cancer corresponds to 43:27:40 + 134:27 = 45:42:7 *nadis* from solar midnight.

Moonrise corresponds to 45:42:7 + 7:50 = 45:49:57 *nadis* from solar midnight. Adding the half lunar day 16:24:6 and the shadow time interval 2:39:18 after lunar noon gives us 45:49:57 + 16:24:6 + 2:39:18 = 64:53:21 = 4:53:21; the text has 4:53:21 in line S. This is the shadow time in *nadis* after solar midnight. The number in line T in the text is this time converted to hours:minutes:seconds.

The right-hand column of numbers is the back calculation, time to shadow.

D: The shadow time is rounded to 5:0:0, which is 6:39 *vinadis* later than the time in item S. 5:0:0 *nadis* after midnight corresponds to 2 a.m. in line C (right).
E: 21:2:21 is a misprint for 21:32:21 and is R (left) + 6:39.
F: 168:53 = Line Q (left) + 6:39.
G: 19:10:3 = Line P (left) + 6:39.
H: 2:45:57 is the shadow time after lunar noon 2:39:18 increased by 6:39.

Using Equation (4′) we now calculate shadow from time. With $H = 2{:}45{:}57 \approx 3$ and a lunar longitude 4:0:42 ≈ 4 we get a multiplier $M = 582$.

$D = 16{:}24{:}6$, $D \cdot M \cdot 3600 = 354364772$, line I.
$(D - H) \cdot 3600 = (16{:}24{:}6 - 2{:}45{:}57) \cdot 3600 = 49089$, line J.
$D \cdot M / (D - H) = 354364772 / 49089 = 700{:}3{:}1$
$D \cdot M / (D - H) - M = 700{:}3{:}1 - 582 = 118{:}3{:}1 = 1{:}58{:}3$
$S = S_{noon} + D \cdot M / (D - H) - M$ (Equation 4') $= 1{:}58{:}3 + 0{:}7{:}34 = 2{:}5{:}37$, line K.

This value is close to the shadow value we started with and gives a check that the calculation is correct.

Table 5: *Phawâ* table (after Thi, 1936: 24).

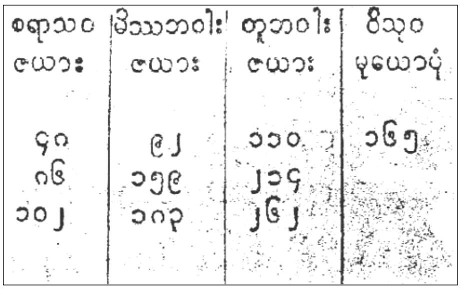
Sign		Phawâ
9		262
10	8	214
11	7	110
0	6	0
1	5	92
2	4	159
3		183

10 DISCUSSION

The original mode of astronomical reckoning in South-East Asia, found in Cambodia as far back as the seventh century AD, was inherited from India, with AD 78 as its epoch (Pingree, 1978). In the late thirteenth century this system was replaced in Burma and Thailand by a canon with an epoch of AD 638, which also was from India. This system, known in Burma as *Makaranta*, was eventually modified into the *Thandeikhta* mode in the mid-eighteenth century. While reference to solar and lunar shadow length occasionally can be found in Burmese records of the fifteenth century, the tradition reflected in our printed texts is from a somewhat later period and is distinctive in its routine use of an adjustment for precession and its adoption of successive approximation for shadow calculation.

This latter technique, although historically of great antiquity elsewhere, is not evident for instance in the reform the Thais made to their calculation of eclipses (assigning an epoch of AD 1142); and the precision and sophistication adopted in shadow reckoning was not, to our knowledge, adopted in other allied procedures. Indeed, it is symptomatic of both the Burmese and the Thai systems that more precise modes of reckoning were adopted only when a particular isolated need for them arose. The Thais continue to use their more approximate method of computation for day-to-day reckoning, and the Burmese use successive approximation for shadow length while at the same time not adjusting for the Moon's considerable motion between rising and setting (see Eade, 1995).

It is also symptomatic of the hold that traditional thinking still retains today in Thailand that there is a market for calendars that use the 638 canon to locate the Sun and the Moon (the annual 'Diary Hon'), while in Burma, as we have found, a complicated text has to posit even in its twentieth century printed form that the shadows of the Sun and of the Moon are more readily accessible than a clock time of day.



စရာသ၀ ဇယား	မိဿဘ၀ါး ဇယား	တူဘ၀ါး ဇယား	၀ိသု၀ မှုယောပုံ
၄၈	၉၂	၁၁၀	၁၆၅
၈၆	၁၅၉	၂၁၄	
၁၀၂	၁၈၃	၂၆၂	

Figure 5: Data table for Amurapura (after Thi, 1936: 24).

Table 6: Translation of the numbers in Figure 5.

48	92	110	165
86	159	214	
102	183	262	

According to modern conception, the underlying theory encapsulated in a formula is in general of more importance than the results that it happens to generate. In the tradition to which our texts belong, once an expert has devised a procedure and embodied it in a series of mechanically-implemented steps and in tables, the number eventually arrived at takes on quasi-magical properties. Our concern has been with what it was that the theorist was doing in an ingenious procedure whose rationale lies well below the surface: the purchasers of his text would be concerned, by contrast, with what painfully-acquired and life-controlling number the procedure would generate.

11 ACKNOWLEDGEMENTS

We are extremely grateful to Dr Ko Ko Aung of Yangoon (Myanmar) who provided us with copies of original Burmese texts and also with much valuable information on some Burmese calculations that enabled us to solve the shadow calculation procedures.

12 REFERENCES

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13 APPENDICES

13.1 Data Table for Amurapura

In Table 6 (see, also Figure 5) the first column displays the difference in day length for longitudes 30˚, 60˚ and 90˚ expressed in *vinadis*. For a translation of the numbers, see the table section. The second column shows the *phawâ* for the same longitudes and by symmetry also for 150˚ and 120˚. The third column shows *phawâs* for longitudes 210˚, 240˚ and 270˚ and by symmetry also for 330˚ and 300˚. The last column shows the equinoctial noon shadow for a gnomon with height 7·60 = 420 units. The value 165 corresponds to geographical latitude 21.45˚.

13.2 Longitude Calculations

A basic quantity that is used for the longitudes is the *ahargaṇa* of date, *a*, the number of expired days since the epoch. We use mainly corresponding Sanskrit terms for the quantities involved in the calculation.

Denoting by *y*, the Burmese year, and by *s*, the *sutin*, the number of elapsed days in that year we have (Irwin, 1909):

$$a = \{[(y - 233) \times 29227] + [(y - 233)/193] + 17742\}/800 + 1 + s \tag{7}$$

For the Sun we also calculate the *kyamat* of the date:

$$k = \text{remainder}\{[(y - 233) \times 29227] + [(y - 233)/193] + 17742\}/800 \times s \tag{8}$$

The mean longitude of the sun in arc minutes is then

$$\lambda_{\text{sun}} = [(1000 \times k) - (6 \times s)] / 13528 \tag{9}$$

The Sun's apogee ω_{sun} is assumed to be located at $\omega_{\text{sun}} = 2:17:18$.

The anomaly, α_{sun}, of the Sun is

$$\alpha_{\text{sun}} = \lambda_{\text{sun}} - \omega_{\text{sun}} \tag{10}$$

To calculate the elongation of the Moon from the Sun we first calculate the *avaman*, *A*, and *khaya*, *K*, of the date:

$\{[(a \times 11) - (y - 233)] / 25 + 175\} / 692$

$$= K{:}A \qquad (13)$$

K is the integer part of the division and A the remainder.
The Moon’s elongation is then

$$\eta = A + (7 \times A) / 173 + 12 \times [(a + K) \bmod 30] \times 60 - 52' \qquad (14)$$

and the mean longitude of the Moon is

$$\lambda_{moon} = \lambda_{sun} + \eta \qquad (15)$$

The Moon’s apogee is moving and its location is calculated by first calculating

$$u = (a + 316) \bmod 3232 \qquad (16)$$

and the Moon’s apogee then is

$$\omega_{moon} = (3 \times u) / 808 - 0:4:24 \qquad (17)$$

The anomaly is

$$\alpha_{moon} = \lambda_{moon} - \omega_{moon} \qquad (19)$$

The equation of centre, or the correction in arc minutes to the mean longitude, is given in tabular form as a *chaya.* It is a table with arguments of angle from 0˚ to 90˚ in 24 steps of 3.75˚. If the anomaly is larger than 180˚ we use as argument the 360˚ complement of the anomaly, and if this complement is larger than 90˚ the 180˚ complement of the complement is used.

The *chayas* are given in Table 7 below.

The *chaya* value is added to the mean longitude if the anomaly is larger than 180˚, otherwise subtracted from the mean longitude.

By way of an example, let us examine Burmese year 1297 Pyatho 3 waning, $y = 1297$, $s = 268$.

$$a = \{[(1297 - 233) \times 29227] + [(1297 - 233) / 193] + 17742\} / 800 + 1 + 268 = 72247$$

$$k = \text{remainder}\{[(1297 - 233) \times 29227] + [(1297 - 233)/193] + 17742\}/800 \times 268 = 21507$$

$$\{[(72247 \times 11) - (1297 - 233)] / 25 + 175\} / 692 = 1148 : 470$$

$$\lambda_{sun} = [(1000 \times 215078) - (6 \times 268)] / 13528 = 15898' = 6:24:58$$

$$\eta = 470 + (7 \times 470) / 173 + 12 \times [(72247 + 1148) \bmod 30] \times 60 - 52' = 11237'$$

$$\lambda_{moon} = 15898 + 11237 = 5535' \quad = 3:2:15$$

$$u = (72247 + 316) \bmod 3232 - 1459$$

$$\omega_{moon} = (3 \times 1459) / 808 - 0:4:24 = 5:12:30 - 0:4:24 = 5:8:6$$

We get:

$$\alpha_{sun} = 11260' = 6:7:40 \qquad \alpha_{moon} = 17649' = 9:24:9$$

These anomalies give respectively corrections of +17′ and +276′ and true longitudes are

$$\lambda_{sun} = 15915' = 8:25:15 \qquad \lambda_{moon} = 5811' = 3:6:51$$

The printed text (Thi, 1936: 25) has 3:7:51. Plus a precession value of 0:22:51 = 4:0:42 for the Moon.

Table 7: *Chayas* for the Sun and Moon (after Mauk, 1971: 85).

Sun		Moon	
Argument	Correction	Argument	Correction
0	0	0	0
1	9	1	20
2	17	2	40
3	26	3	60
4	34	4	79
5	43	5	98
6	51	6	116
7	58	7	134
8	66	8	152
9	73	9	169
10	80	10	185
11	87	11	200
12	93	12	214
13	99	13	228
14	104	14	241
15	109	15	252
16	113	16	262
17	117	17	272
18	121	18	280
19	124	19	287
20	126	20	293
21	128	21	297
22	129	22	300
23	130	23	302
24	131	24	303

12.3 Rising Times and Oblique Ascension

To calculate the rectascension, E, of the Sun given the longitude λ and the obliquity $\varepsilon = 24˚$:

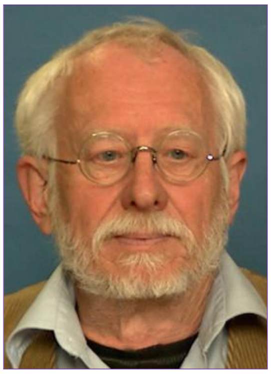
$$\tan E = \tan \lambda \cos \varepsilon \qquad (20)$$

Subtract the ascensional difference, A, calculated in the day length section above. The oblique ascension is the difference $\Omega = E - A$. The rising times of the zodiacal signs are then the differences between the oblique ascension for sequential signs. As there are 3600 *vinadis* to a solar day and night, a rotation of the Earth by 360˚, the conversion from degrees to *vinadis* is just simply multiplication by 10.

Table 8 shows the result of a calculation of the values in the rising time diagram.

Table 8. Rising times for Amurapura

Longitude (˚)	*E*	*A*	*E–A*	Difference
0	0	0	0	230
30	278	48	230	261
60	577	86	491	307
90	900	102	798	339
120	1223	86	1137	337
150	1522	48	1474	326
180	1800	0	1800	



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Dr Chris Eade has an M.A. from St Andrews and a Ph.D. from the Australian National University. In 1968 he retired from the Australian National University, where he had been a Research Officer in the Humanities Research Centre before moving to an affiliation with the Asian Studies Faculty, in order to pursue his interest in South-East Asian calendrical systems. In particular, research that he continued after retirement concerned dating in the Thai inscriptional record, in the horoscope record of the temples of Pagan and in the published record of Cambodia and Campa.

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THE DISCOVERY OF QUASARS AND ITS AFTERMATH

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Abstract: Although the extragalactic nature of quasars was discussed as early as 1960 by John Bolton and others it was rejected largely because of preconceived ideas about what appeared to be an unrealistically-high radio and optical luminosity. Following the 1962 observation of the occultations of the strong radio source 3C 273 with the Parkes Radio Telescope and the subsequent identification by Maarten Schmidt of an apparent stellar object, Schmidt recognized that the simple hydrogen line Balmer series spectrum implied a redshift of 0.16. Successive radio and optical measurements quickly led to the identification of other quasars with increasingly-large redshifts and the general, although for some decades not universal, acceptance of quasars as being by far the most distant and the most luminous objects in the Universe. However, due to an error in the calculation of the radio position, it appears that the occultation position played no direct role in the identification of 3C 273, although it was the existence of a claimed accurate occultation position that motivated Schmidt's 200-in Palomar telescope investigation and his determination of the redshift.

Curiously, 3C 273, which is one of the strongest extragalactic sources in the sky, was first catalogued in 1959, and the 13th magnitude optical counterpart was observed at least as early as 1887. Since 1960, much fainter optical counterparts were being routinely identified, using accurate radio interferometer positions which were measured primarily at the Caltech Owens Valley Radio Observatory. However, 3C 273 eluded identification until the series of lunar occultation observations led by Cyril Hazard. Although an accurate radio position had been obtained earlier with the Owens Valley Interferometer, inexplicably 3C 273 was misidentified with a faint galaxy located about one arc minute away from the true position. It appears that the Parkes occultation position played only an indirect role in the identification of the previously-suspected galactic star, which was only recognized as the optical counterpart after Schmidt's 200-in observations showed it to have a peculiar spectrum corresponding to a surprisingly-large redshift.

Keywords: quasars, radio stars, AGN, lunar occultation, redshift

1 HISTORICAL BACKGROUND

The discovery of quasars in 1963, and more generally, active galactic nuclei (AGN), revolutionized extragalactic astronomy. In early February 1963, Maarten Schmidt (b. 1929; Figure 1) at Caltech recognized that the spectrum of the 13th magnitude apparently stellar object identified with the radio source 3C 273 could be most easily interpreted by a redshift of 0.16. Subsequent work by Schmidt and others led to increasingly-large measured redshifts and the recognition of the broad class of active galactic nuclei (AGN) of which quasars occupy the high luminosity end. Schmidt's discovery changed extragalactic astronomy in a fundamental way. Within a few years redshifts as great as 2 or more were being routinely observed, making possible a new range of cosmological studies as well as the realization that supermassive black holes which power radio galaxies and quasars play a prominent role in the evolution of galaxies. But the path to this understanding was a slow, tortuous one, with missed turns that could have, and should have, earlier defined the nature of quasars.

The events leading up to the recognition of quasars as the extremely luminous nuclei of distant galaxies go back much earlier than 1963; indeed, one wonders why the extragalactic nature of quasars was not recognized well before 1963, and why 3C 273, which is the seventh brightest radio source in the northern sky away from the Galactic Plane, was not identified at least one or two years earlier based on the radio position determined by observations carried out at the Owens Valley Radio Observatory (henceforth OVRO), which was more accurate than the occultation position used by Schmidt to identify 3C 273 in December 1962.

In the remainder of this section we review the early arguments and evidence for powerful activity in the nuclei of galaxies. In Section 2, we briefly review the status of extragalactic radio astronomy prior to the identification of 3C 48, and

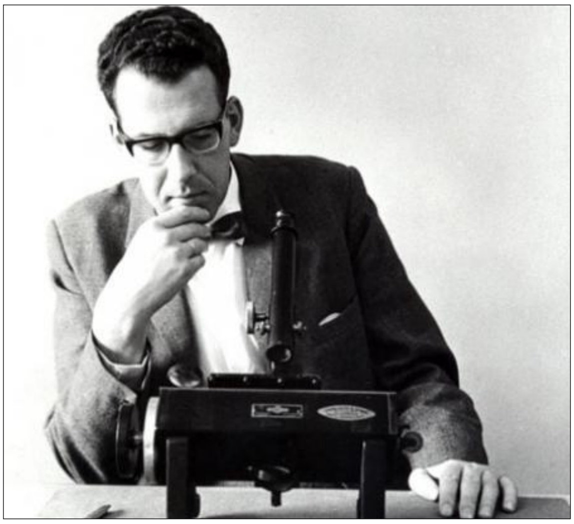


Figure 1: A photograph of Maarten Schmidt at work in 1965 (credit: James McClanahan, Engineering and Science, May, 1965; courtesy: Caltech Archives).

in Section 3, the identification of 3C 48, which might have been the first discovered quasar, but was unrecognized as such until the work on 3C 273 more than two years later, as described in Section 4. In Section 5 we return to the issues surrounding 3C 48, and in Sections 6 and 7 the implications for cosmology and the arguments for non-cosmological interpretations of quasar redshifts. Sections 8 and 9 describe the discovery of radio-quiet quasars. Finally, in Section 10 we summarize the history and highlight remaining issues and questions surrounding the discovery of quasars.

Probably the first person to note enhanced activity in the nucleus of a galaxy was Edward Arthur Fath (1880–1959) who reported on the nuclear emission line spectrum of NGC 1068 (Fath, 1909). Later observations of strong nuclear emission lines by Vesto Melvin Slipher (1875–1969) in 1917, Edwin Powell Hubble (1889–1953) in 1926, Milton Lasell Humason (1891–1972) in 1932, and Nicholas Ulrich Mayall (1906–1993) in 1934 and 1939 led Carl Keenan Seyfert (1911–1960; Figure 2) in 1943 to his now famous study of the enhanced activity in the nuclei of six galaxies (or as he called them, 'extragalactic nebulae'). Seyfert, and his predecessors, commented on the similarity with the emission line spectrum of planetary and other gaseous nebulae and noted that the lines are apparently Doppler broadened. There is no evidence that Seyfert ever continued this work, but nevertheless, galaxies containing a stellar nucleus with strong broad emission (including forbidden) lines have become known as 'Seyfert Galaxies'.


Figure 2: Carl Seyfert (dyer.vanderbilt.edu/about-us/history/).

Curiously, while the SAO/NASA Astrophysics Data System lists 365 citations to Seyfert's 1943 paper, the first one did not appear until a full eight years after Seyfert's 1943 publication during WWII. Even then, not much interest was shown in Seyfert Galaxies until Iosif Samuilovich Shklovsky (1916–1985) drew attention to the possible connection between Seyfert galaxies and radio galaxies (Shklovsky, 1962). Seyfert served three years on the board of Associated Universities Inc. during the critical period when AUI was overseeing the early years of the NRAO, and he had been nominated to serve as the first Director of the NRAO. Unfortunately, in 1960 he died in an automobile accident, but it is interesting to speculate on whether, if Seyfert had lived, his association with the radio astronomers at the NRAO might have led to an earlier appreciation of the relationship between radio emission and nuclear activity.

Even earlier, Sir James Hopwood Jeans (1877–1946) speculated that

> The centres of the nebulae are of the nature of 'singular points,' at which matter is poured into our universe from some other and entirely spatial dimension, so that to a denizen of our universe, they appear as points at which matter is being continually created. (Jeans, 1929: 360).

However, it was Victor Amazaspovich Ambartsumian (1908–1996) who championed the modern ideas that something special was going on in the nuclei of galaxies. At the 1958 Solvay Conference, Ambartsumian (1958: 266) proposed "... a radical change in the conception on the nuclei of galaxies ...", saying that "... apparently we must reject the idea that the nuclei of galaxies is [*sic*] composed of stars alone." He went on to conclude that, "... large masses of prestellar matter are present in nuclei."

In a prescient paper, Fred Hoyle (1915–2001) and William Alfred Fowler (1911–1995) considered

> ... the existence at the very center of galaxies of a stellar-type object of large mass … in which angular momentum is transferred from the central star to a surrounding disk of gas. (Hoyle and Fowler, 1963: 169).

2 BEFORE QUASARS

When discrete sources of radio emission were discovered, they were first thought to be due to stars in our Galaxy. Karl Guthe Jansky (1905–1950) and Grote Reber (1911–2002) had shown that the diffuse radio emission was associated with the Milky Way, and since the Milky Way is composed of stars, dust and gas, it seemed natural to suppose that the discrete radio sources were likely connected with stars. Indeed for many years they were called 'radio stars'.

The first hint that at least some radio sources might be extragalactic came from a series of observations made by John Gatenby Bolton (1922

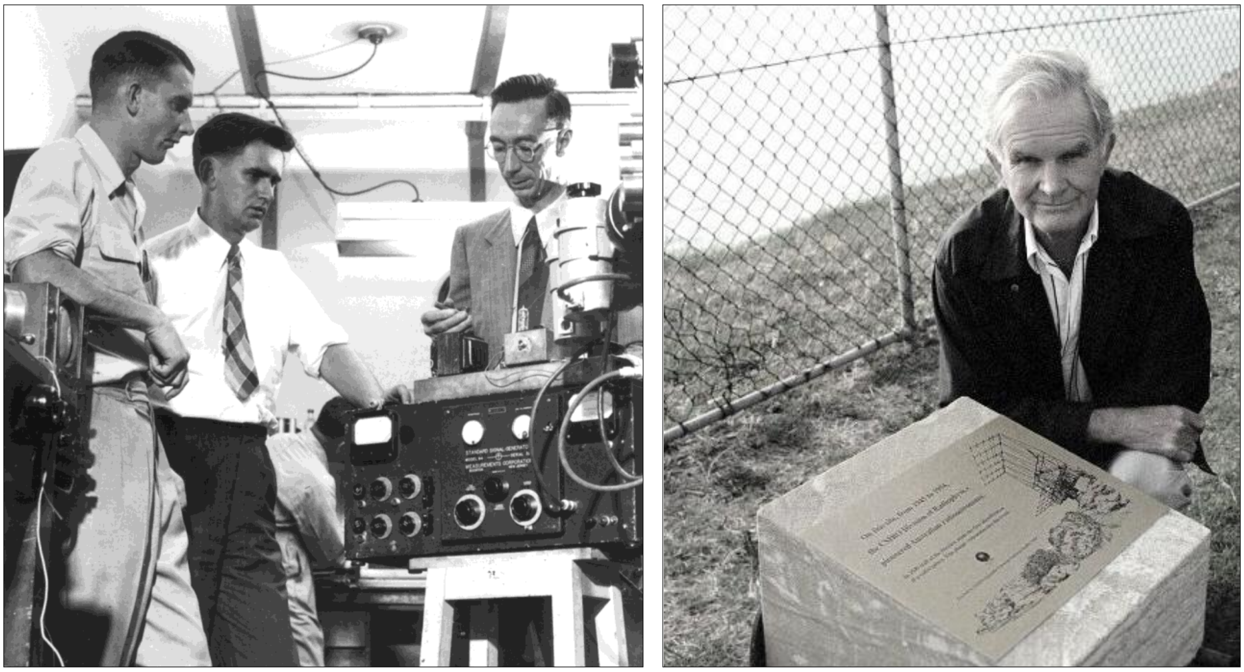


Figure 3: The left hand photograph shows (left to right) John Bolton, Gordon Stanley and the Head of the Radio Astronomy Group at the Division of Radiophysics, Dr Joe Pawsey, at the Radiophysics Laboratory during the late 1940s. The right hand photograph shows Bruce Slee during the unveiling of a commemorative plaque in 1989 at Rodney Reserve, the site of the Division's Dover Heights field Station (both photographs are adapted from originals in the CSIRO's Radio Astronomy Image Archive).

–1993), Gordon James Stanley (1921–2001) and Owen Bruce Slee (b. 1924) (see Figure 3) using cliff interferometers in Australia and New Zealand (see Robertson et al., 2014). After months of painstaking observations, Bolton and his colleagues succeeded in measuring the positions of three strong radio sources with an accuracy of better than half a degree.

For the first time it was possible to associate radio sources with known optical objects. Bolton, Stanley and Slee (1949) identified Taurus A, Centaurus A, and Virgo A with the Crab Nebula, NGC 5128 and M87 respectively. NGC 5128, with its conspicuous dark lane, and M87, with its prominent jet, were well known to astronomers as peculiar galaxies, but their paper, "Positions of Three Discrete Sources of Galactic Radio Frequency Radiation," which was published in *Nature*, mostly discussed the nature of the Crab Nebula. In a few paragraphs near the end of their paper, Bolton, Stanley and Slee commented:

> NGC 5128 and NGC 4486 (M87) have not been resolved into stars, so there is little direct evidence that they are true galaxies. If the identification of the radio sources are [*sic*] accepted, it would indicate that they are [within our own Galaxy].

As implied by the title, Bolton, Stanley and Slee dismissed the extragalactic nature of both Centaurus A and M87. When asked many years later why he did not recognize that he had discovered the first radio galaxies, Bolton (pers. comm., August 1989) responded that he knew they were extragalactic, but that he also realized that the corresponding radio luminosities would be orders of magnitude greater than that of our Galaxy and that he was concerned that in view of their apparent extraordinary luminosities, a conservative *Nature* referee might hold up publication of the paper. However, in a 1989 talk, Bolton (1990) commented that their 1949 paper marked the beginning of extra-galactic radio astronomy. Nevertheless, for the next few years the nature of discrete radio sources remained controversial within the radio astronomy community, and many workers, particularly those at the Cambridge University Cavendish Laboratory, continued to refer to 'radio stars'.

Following the 1954 identification of Cygnus A with a faint galaxy at z = 0.06, by Mount Wilson and Palomar astronomers, Wilhelm Heinrich Walter Baade (1893–1960; Figure 4a) and Rudolph Leo Bernard Minkowski (1895–1976; Figure 4b), it became widely appreciated that the high latitude radio sources were in fact very powerful 'radio galaxies', and that the fainter radio sources might be at much larger redshifts, even beyond the limits of the most powerful optical telescopes such as the Palomar 200 inch (Baade and Minkowski, 1954). In a footnote in their paper, Baade and Minkowski noted that Cygnus A previously had been identified with the same galaxy by Bernard Yarnton Mills (1920–2011) and Adin Thomas (1951) and by David Dewhirst (1926–2012) (see Mills and Thomas, 1951; Dewhirst, 1951), but Minkowski confessed that at the time he was not willing to accept the identification with such a faint and distant nebula. Over the next five years, many other radio galaxies were

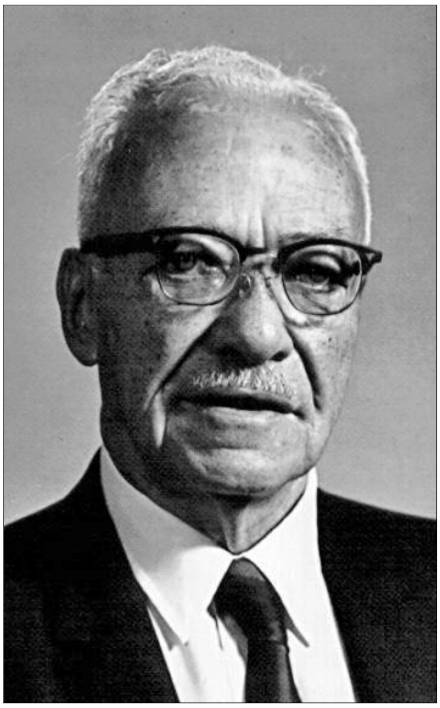


Figure 4a (left): Walter Baade (courtesy: Caltech Archives).
Figure 4b (right): Rudolf Minkowski (courtesy: Astronomical Society of the Pacific).

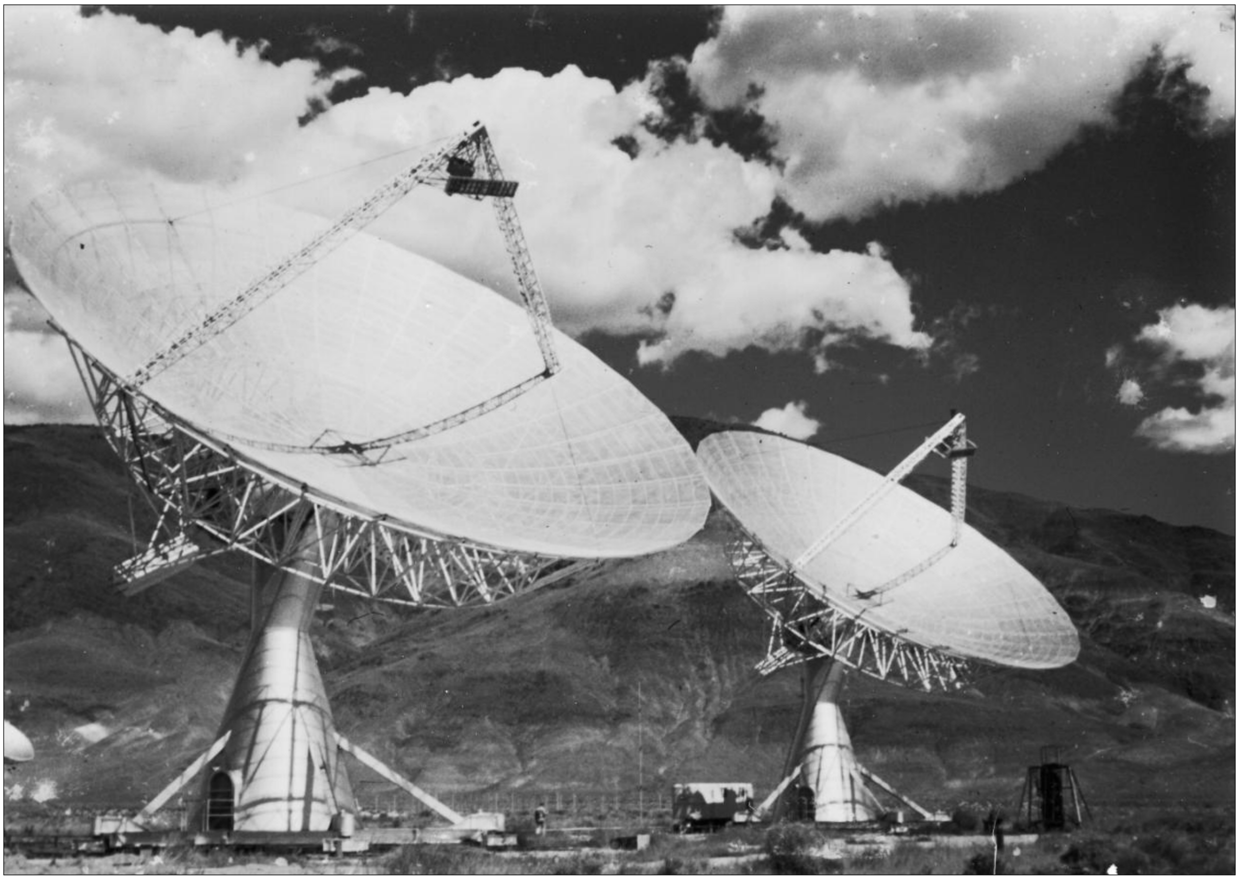
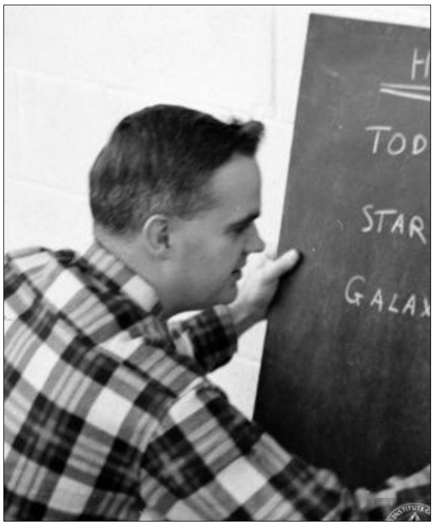
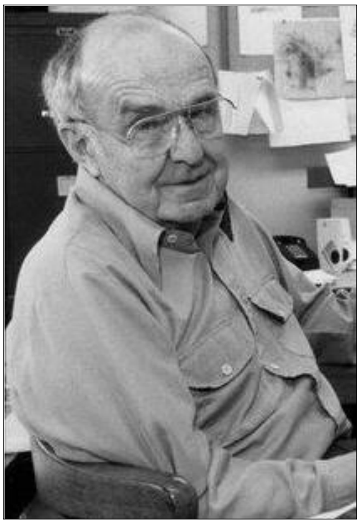


Figure 5: The two-element interferometer at the Owens Valley Radio Observatory (courtesy: Marshall Cohen).

identified, but many others were also misidentified due to inaccurately-measured radio positions.

In 1955, John Bolton came to Caltech from Australia to build a radio telescope specifically designed to accurately measure radio positions and to work with Caltech and Carnegie astronomers to identify and study their optical counterparts. Starting in early 1960, the Caltech OVRO (Figure 5) began to produce hundreds of radio source positions accurate up to ten seconds of arc and leading to new radio galaxy identifications





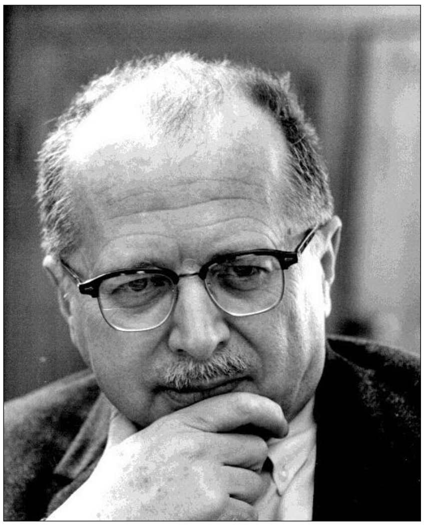


Figure 6a (left): Tom Matthews (courtesy: Caltech Archives).
Figure 6b (center): Alan Sandage (courtesy: Carnegie Observatories).
Figure 6c (right): Jesse Greenstein (courtesy: Caltech Archives).

(Greenstein 1961). Recognizing that radio galaxies were characteristically the brightest galaxy in a cluster (Bolton 1960c), it became clear to many that the search for distant galaxies needed to address the outstanding cosmological problems of the day and therefore should concentrate on galaxies identified with radio sources. Moreover, it was naturally assumed that the smaller radio sources were most likely to be the more distant, so emphasis was given to the smallest radio sources, whose dimensions were determined with the long baseline radio-linked interferometers at Jodrell Bank (Allen et al., 1960; 1962) and with Caltech's OVRO interferometer.

Much of this work was carried out within a collaboration of scientists at Caltech and at the Mount Wilson and Palomar Observatories. John Bolton, Thomas Arnold Matthews (Figure 6a), Alan Theodore Moffet, Richard B. Read and Per E. Maltby (1933–2006) at the OVRO provided accurate radio positions, angular sizes and optical identifications based on inspection of the 48-in Schmidt prints and plates. At the Mt Wilson and Palomar Observatories, Baade, Minkowski, and Allan Sandage (1926–2010; Figure 6b) teamed up with the Caltech radio astronomers to obtain 200-in photographs and spectra. At Caltech, Jesse Greenstein (1909–2002; Figure 6c), Guido Münch (b. 1921) and, after Minkowski's retirement in 1960, Maarten Schmidt, provided spectroscopic follow-up to determine the redshifts of the radio galaxies.

This program had a dramatic success, when, using the 200-in telescope during his last observing session before retiring, Minkowski (1960) found a redshift of 0.46 for the 20.5 magnitude galaxy which was identified by Matthews and Bolton with 3C 295. This made 3C 295 by far the largest known redshift. Although previous to Minkowski's observation, the largest measured spectroscopic redshift was less than 0.2, curiously, an unrelated foreground galaxy located only a few arcminutes from 3C 295 was observed by Minkowski to have a redshift of 0.24, making it the second-largest known redshift at the time. Yet, it would be another 15 years before a galaxy redshift greater than that of 3C 295 would be measured. Interestingly, 3C 295 was targeted not because of any special properties, but only because it was at a high declination, where an accurate declination could be measured with the OVRO interferometer, which until late 1960 had only an East-West base line.

3 3C 48: THE FIRST RADIO STAR

By late 1960, it was widely accepted that radio sources located away from the Galactic Plane were powerful distant radio galaxies (e.g., Bolton 1960c). However, Bolton's Caltech colleague, Jesse Greenstein, an acknowledged expert on exotic stars, offered a case of the best Scotch whisky to whoever found the first true radio star. Meanwhile, in the quest to find more distant galaxies, the Caltech identification program concentrated on small diameter sources selected from the early OVRO interferometer observations and from unpublished long-baseline interferometer observations at Jodrell Bank (Allen et al., 1962).

In 1960 Tom Matthews and John Bolton identified 3C 48 with what appeared to be a 16th magnitude star. Observations made by Sandage using the 200-in telescope in September 1960 showed a faint red wisp 3″ × 8″ in size. Spectroscopic observations by Sandage, Greenstein and Münch showed multiple emission and absorption lines as well as a strong continuum UV excess, but attempts to identify the lines were inconclusive. On 29 December, Sandage presented a late paper at the 107th meeting of the

American Astronomical society (AAS) in New York. The listed authors were Matthews, Bolton, Greenstein, Münch and Sandage (1960), which reflected the order of their involvement (Bolton, 1990). But, by this time, Bolton had left Caltech and returned to Australia to oversee the completion and operation of the 64-m Parkes Radio Telescope. Unfortunately, abstracts of late AAS papers were not published at that time, and the only remaining written record of the talk is a news article on the "First True Radio Star" which appeared in the February 1961 issue of *Sky and* Telescope (The first true ..., 1961) and a report in the annual report of the Carnegie Institution of Washington (see Report ..., 1960–1961: 80). Curiously, there is no record of the 107th meeting of the AAS at the American Institute of Physics Niels Bohr Library & Archives, although the records of the preceding and succeeding years still exist at the AIP.

Sky and Telescope (1961) cautiously reported that

> ... there is a remote possibility that [3C48] may be a distant galaxy of stars; but there is general agreement among the astronomers concerned that it is a relatively nearby star with most peculiar properties.

A few months later, Jesse Greenstein (1961) wrote an article in the Caltech *Engineering and Science* publication announcing "The First True Radio Star."

Subsequent study appeared to confirm the nature of 3C 48 as a true radio star, but with no proper motion as great as 0.05 arcsec/yr. Radio observations indicated angular dimensions less than 0.8 arcsec (Allen et al., 1962) but no measured radio variability (Matthews and Sandage, 1963). Observations by Sandage with the 200-in telescope showed that except for the faint 'wisp', most of the optical light was unresolved, that the color was 'peculiar' and that the optical counterpart varied by at least 0.4 mag over a time scale of months, thus supporting the notion that 3C 48 was a galactic star (Matthews and Sandage, 1963).

Meanwhile, Greenstein (1962) made an exhaustive study of the optical spectrum. After two years of analysis, he submitted a paper to the *Astrophysical Journal* with the title, "The Radio Star 3C48". In this paper, he concluded that 3C 48 was the stellar remains of a supernova, and that the spectrum reflected highly-ionized rare earth elements. The abstract states, "The possibility that the lines might be greatly redshifted forbidden emissions in a very distant galaxy is explored with negative results ...", and the first sentence of the paper states,

> The first spectra of the 16th magnitude stellar radio source 3C48 obtained in October 1960 by Sandage were sufficient to show that this object was not an extragalactic nebula of moderate redshift.

Greenstein discussed possible line identifications with several possible redshifts. Although he commented that "... except for 0.367 no red-shift explains the strongest lines of any single ionization ...", he maintained that, "... the case for a large redshift is definitely not proven." Nevertheless, with great prescience, he then went on to point out that if the 3C 48 spectrum is really the red-shifted emission spectrum of a galaxy, then for $\Delta\lambda/\lambda > 1$, Ly-α and other strong UV lines would be shifted into the visible spectrum. When asked years later why he rejected what appeared to be a very important and satisfactory interpretation in terms of a large redshift, Greenstein responded: "I had a reputation for being a radical and was afraid to go out on a limb with such an extreme idea." (Jesse Greenstein, pers. comm., January, 1995).

Subsequently, Matthews and Sandage (1963) succeeded in identifying two additional small-diameter radio sources, 3C 196 and 3C 286, with 'star-like' optical counterparts. But the nature of these 'star-like' counterparts to compact radio sources remained elusive until the investigation of 3C 273 showed them to be distant and unprecedentedly-powerful objects.

4 3C 273

3C 273 is the seventh-brightest source in the 3C catalogue. The flux density is comparable to that of 3C 295, so 3C 273 was naturally included in the Caltech program to measure accurate radio positions with the goal of finding optical counterparts for several hundred sources from the 3C catalogue. Typical positional accuracy of the OVRO interferometer was better than 10″ for the stronger sources. Right ascensions were measured by Tom Matthews and others. The declination measurements were part of Richard Read's 1962 Caltech Ph.D. thesis and were submitted for publication in the *Astrophysical Journal* (Read, 1963) in December 1962. The right ascensions were not published until later (Fomalont et al., 1964), but the interferometer positions of many sources, including 3C 273, were available to Caltech astronomers by 1961.

Based on his measured declinations and right ascensions measured by other Caltech radio astronomers, Read (1962) discussed likely identifications of four sources, including 3C 273, with faint galaxies seen only in 200-in plates. Read's declination differed by only 1″ from the currently-accepted position of the quasar. An unpublished contemporaneous right ascension measured by the Caltech radio astronomers was within 2″ of the correct position (see Papers ...). But, the faint galaxy mentioned by Read, which Maarten Schmidt attempted to observe in May 1962, was inexplicably about 1′ west of 3C 273. Interestingly, in his published paper, Read (1963) uses the exact same wording to describe the four identified sources as used in his thesis, but 3C 273 is replaced by 3C 286.

The breakthrough occurred in 1962 as a result of a series of lunar occultations of 3C 273 which were predicted to be observable with the 64-m Parkes Radio Telescope in Australia. Earlier, Cyril Hazard (b. 1928; Figure 7) had used the Jodrell Bank 250-ft Radio Telescope to observe a lunar occultation of the radio source 3C 212. Hazard (1961; 1962) was able to determine the position of 3C 212 with an accuracy of 3″, but his inspection of Palomar Sky Survey plates failed to recognize the 19th magnitude stellar identification which later turned out to be a quasar. Although unresolved by the OVRO interferometer (Moffet, 1962), 3C 273 was known from interferometer measurements at Jodrell Bank (Allen et al., 1962) and Nançay (Lequeux, 1962) to be resolved on longer baselines so it was not on the Caltech list of high-priority small sources that might lead to an identification of a more distant galaxy than 3C 295.

A full occultation of 3C 273, including both immersion and emersion, was predicted to occur on 5 August 1962 and was observed at Parkes at both 136 and 400 MHz. According to Hazard (1977; 1985; Interview ..., 2013) and Bolton (1990), Rudolph Minkowski had a Polaroid copy of a 48-in Schmidt image which indicated the incorrect faint galaxy identification which Schmidt had tried to observe in May of that year. According to Bolton (1990), earlier position measurements made with the Parkes Radio Telescope had established a tentative identification in between a 13th magnitude stellar object and an elongated feature, like an edge-on galaxy, on Minkowski's photograph. However, Bolton claimed that the position accuracy was insufficient to determine whether the radio source was associated with the 'star' or with the elongated feature, so hopefully the occultation would resolve the uncertainty.

The first occultation, on 15 May,[1] when only the immersion was visible, showed diffraction fringes characteristic of a very small source, but was not adequate to derive a position. The 5 August event was more promising as both immersion and emersion were visible, but there was a catch. The emersion of the radio source from behind the Moon was predicted to occur uncomfortably close to the 60° zenith angle limit of the Parkes Radio Telescope (Figure 8). To make sure that the event would not be missed due to an inaccurate position—as had occurred with some earlier predicted occultations—Bolton removed a ladder from the Radio Telescope and ground down part of the gear box in order to extend the length of time the telescope could track. However, as it turned out, the occultation took place at precisely the predicted time, and so the rather drastic alteration of the Radio Telescope's gear box proved unnecessary. But it was a good story which Bolton enjoyed telling and retelling.

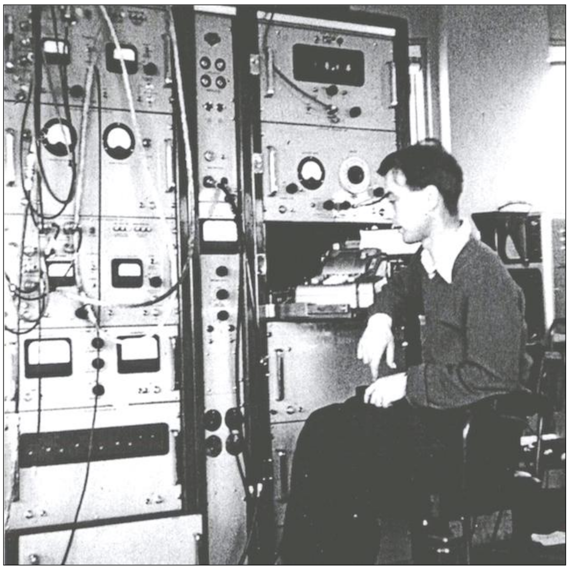


Figure 7: Cyril Hazard observing at Jodrell Bank in the 1950s (courtesy: Miller Goss).

From analysis of the diffraction pattern at 136 and 410 MHz obtained from the immersion (see Figure 9) and emersion of the source from behind the Moon, Hazard et al. (1963) showed that 3C 273 was a complex source consisting of a small flat spectrum component (B) and an elongated steep spectrum component (A). Even before the occultation, Hazard (Interview ..., 1973) was aware of the observations by James Lequeux (1962) using the Nançay interferometer which showed that 3C 273 was a double source with an E-W separation of 14″ between the two components, which was precisely the value derived from the occultation.

On 20 August, just two weeks after the occultation, John Bolton (1962) wrote to Maarten Schmidt at Caltech discussing the Parkes program of radio source identifications and request-

Figure 8: The 64-m Parkes Radio Telescope (photograph: K.I. Kellermann).

Figure 9: Chart record showing the immersion of the radio source 3C 273 behind the Moon on 5 August 1962 at 410 MHz. Time runs from right to left. The right hand (early) part of the curve shows the Fresnel diffraction pattern as the smaller component B is occulted, followed by the disappearance of the larger component, A (after Hazard et al., 1963; reproduced with permission).

ing optical follow-up from Palomar on a radio source located at –28° declination. Somewhat parenthetically, or as an afterthought, he gave the occultation positions of 3C 273 components A and B, and asked Schmidt to pass them along to Tom Matthews, but Bolton made no mention of the obvious optical counterparts in his letter. Moreover, due to a mathematical error by Hazard the positions communicated by Bolton were in error by about 15″. Although Hazard later recounted that Minkowski had tentatively identified 3C 273 with the nebulosity which he assumed to be an edge-on galaxy (Bolton, 1962), in January 1963 Hazard wrote to Schmidt: "I have heard … that *you* have succeeded in identifying the radio source 3C 273 ..." (Hazard, 1963; my italics), so it appears likely that even five months after the occultation neither Hazard nor anyone in Australia was fully convinced of what should have been the obvious association with the bright star that was known to be close to the position of 3C 273. It was probably Tom Matthews (Schmidt, 1963) who provided the precise optical coordinates which showed that the 13th magnitude stellar counterpart was coincident with radio component B, and that the fainter jet was coincident with radio component A. But, this was only after Schmidt had already observed the spectrum of the stellar object.

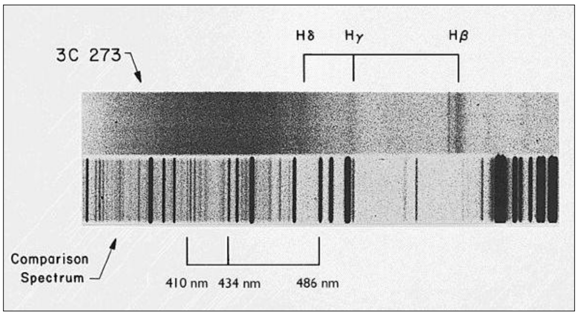


Figure 10: The spectrum of 3C 273 obtained with the 200-in Palomar telescope (courtesy: Maarten Schmidt).

Unfortunately, 3C 273 was too close to the Sun to attempt any spectroscopy until December 1962, when Schmidt used the 200-in telescope to observe the spectrum. Based on the faint optical counterparts that were being associated with other radio sources, Schmidt (1983; 2011) has explained that, like Minkowski, he assumed that the correct optical counterpart was the faint nebulosity. Although at the time there were already three radio sources, 3C 48, 3C 196, and 3C 286, which had been identified with stellar counterparts, Schmidt (ibid.) assumed that that the 13th magnitude stellar object was far too bright to be associated with the radio source. Nevertheless, in order to eliminate the stellar object from further consideration, Schmidt decided to first obtain a spectrum of the 'star'. Having spent most of his 200-in experience observing very faint objects, Schmidt overexposed the spectrum on the first night. Although he obtained a properly-exposed spectrum on 29 December 1962 (Figure 10), it was only on 6 February 1963 that he recognized the simple Balmer series bands of Hβ, Hγ, and Hδ, with a redshift of 0.158 and a corresponding optical luminosity some hundred times brighter than the typical galaxies previously identified with radio sources. Applying that redshift led Schmidt (1963) to recognize the observed band at 3239 Å to be Mg II with a rest wavelength of 2798 Å and another line at a rest wavelength of 5007 Å to be [O III] (Schmidt, 1983). A low-resolution infra-red observation by John Beverley Oke (1928–2004) showed the Hα line shifted to 7599 Å, which confirmed Schmidt's redshift determination (Oke, 1963).

Re-inspection of the spectrum of 3C 48 by Schmidt and Greenstein immediately identified the broad line at 3832 Å to be Mg II redshifted by 0.3679. Using this value of the redshift, the other 3C 48 lines fell into place as [Ne V], [O II], and [Ne III]. Greenstein (1996) recalled that Matthews had earlier suggested "... the possibility of a 37% redshift ..." so the 3C 48 paper was authored by Greenstein and Matthews (1963), but no mention was made of any involvement by John Bolton.[2] However, the high luminosity implied by the observed redshifts along with the small size implied by Sandage's observation of variability was quite remarkable, and was not immediately universally accepted.

The four, now classic, papers by Hazard et al. (1963), Schmidt (1963), Oke (1963), and Greenstein and Matthews (1963) were published as consecutive papers in the 16 March 1963 issue of *Nature*. Whether by error or intentionally, Hazard's name appeared in *Nature* with a CSIRO[3] Radiophysics Laboratory affiliation, even though he was affiliated with the University of Sydney. At the time relations between the University of Sydney and the Radiophysics Laboratory were already strained, and this incident further exacerbated the existing tensions. Hazard had been invited by John Bolton, Edward George ('Taffy') Bowen (1912–1991) and Joseph Lade Pawsey (1908–1962) to use the Parkes Radio Telescope to observe the occultation. As a non-staff member, Hazard was not familiar with the operation of the Radio Telescope or the instrumentation at Parkes, and so following standard practice for non-Radiophysics observers, CSIRO staff members Albert John Shimmins and Brian Mackey were added to the observing team to provide telescope and instrumental support respectively (Bolton, 1990). Characteristically, Bolton (ibid.) declined to put his name on the paper, stating that he merely "... was just doing his job as Director." Haynes and Haynes (1993) attribute the error to an unintentional mistake on the part of the journal due to the change from a letter format, as submitted, to an article format, as published, although the manuscript submitted by the Radiophysics publications office has the word, 'delete' handwritten in next to Hazard's University of Sydney address.

5 3C 48 REVISITED

In 1989 John Bolton gave a talk to the Astronomical Society of Australia in which he reminisced about the period 1955–1960 when he was setting up the radio astronomy program at Caltech. In this talk, Bolton recalled that back in 1960, a full two years before the redshifts of 3C 273 and 3C 48 were announced, he had discussed a possible 3C 48 redshift of 0.37. Bolton (1990) subsequently wrote:

> The best fit I could find for the one broad line and one narrow line which Jesse [Greenstein] had measured were with Mg II λ2798 and [Ne V] λ3426, and a redshift of 0.37.

Since a quarter of a century had passed before his 1989 talk, Bolton's assertion was naturally viewed with skepticism and was emphatically rejected by Greenstein (1996) as a fabrication. However, Fred (later Sir Fred) Hoyle (1915–2001) later recalled that, at the time, John Bolton had told him "I think there's a big redshift in the spectrum." (Hoyle, 1981) Bolton's claim is also supported by a handwritten letter from Bolton to Joe Pawsey dated 16 November, 1960, just one month before Bolton left Caltech for Australia to take charge of the Parkes Radio Telescope, and more than a month before Sandage's AAS paper. Bolton (1960a) wrote:

> I thought we had a star. It is not a star. Measurements on a high dispersion spectrum suggest the lines are those of Neon [V], Argon [III] and [IV] and that the redshift is 0.367. The absolute photographic magnitude is –24 which is two magnitudes greater than anything known. … I don't know how rare these things are going to be, but one thing is quite clear – we can't afford to dismiss a position in the future because there is nothing but stars.

But, just a month later, on 19 December, Bolton (1960b) wrote to Pawsey from the *SS Orcades*: "The latest news on 3C 48 as I left Caltech was – It is most likely a star." Bolton's letter was mailed from Honolulu where the ship stopped while *en route* to Australia. Apparently, between 16 November and the time he sailed for Australia on 12 December, Bolton had discussed 3C 48 with Ira Sprague Bowen (1898–1973), the then Director of the Mt Wilson and Palomar Observatories who was an expert on spectroscopy. Bowen and Greenstein had inexplicably argued that the dispersion of only three to four angstroms in the calculated rest wavelengths of different lines was too great to accept the large redshift and the corresponding extraordinary absolute magnitude of –24. Indeed, in a paper submitted on 8 December 1962, several months before Schmidt's 3C 273 breakthrough, Matthews and Sandage (1963) had written that they were not able to find "... any plausible combination of red-shifted emission lines." Apparently Matthews had forgotten that earlier he had suggested to Greenstein that 3C 48 might have a 37% redshift. The paper was published in July 1963, with a section discussing "3C 48 as a Galaxy" added in proof after its redshift had been determined by Greenstein and Schmidt.

6 QUASARS AND COSMOLOGY

The discovery of quasars with their large redshifts and corresponding unprecedented-large radio and optical luminosities generated a wide range of observational and theoretical investigations as well as a plethora of conferences, particularly the series of Texas Symposia on Relativistic Astrophysics and Cosmology (e.g., Robinson, Schild and Schucking 1965). Motivated by the possibility of extending the Hubble relation to higher redshifts and determining the value of the deceleration constant, q_0, for years there was an intense competition to find the highest redshifts. Within two years of the 3C 273 breakthrough, redshifts as high as 2 were reported by Schmidt (1965) and others; but redshifts >3 were not observed until 1973 (Carswell and Strittmatter 1973).

In his classic paper written only five years after he determined the redshift of 3C 273, Schmidt (1968) used a sample of forty quasi-stellar radio sources to derive their luminosity functions and to show that the space density dramatically evolves with cosmic time much in the same manner as powerful radio galaxies. A few years later, Schmidt (1970) extended the study to include optically-selected, e.g., radio quiet, quasars. Now fifty years later, quasar and AGN research have become part of mainstream astronomy with numerous AGN and quasar conferences held each year, along with many books and probably thousands of papers having been published. Supermassive black holes which were first introduced to power quasars (Lynden-Bell, 1969) are now thought to play a major role in galaxy formation and evolution.

7 NON-COSMOLOGICAL REDSHIFTS

In view of the apparent extraordinary properties of quasars, a number of well-respected astronomers have argued that the large observed quasar redshifts are intrinsic and not due to cosmological shifts that reflect the expansion of the Universe. The possibility that the observed shifts might be gravitational redshifts was considered very early, but Schmidt and Greenstein (1964) showed that an interpretation in terms of gravitational red-shifts was unrealistic.

Nevertheless, there were a number of observations which appeared to challenge the cosmological interpretation of the large observed redshifts (e.g., Hoyle, 1966; Hoyle and Burbidge, 1966). These included:

(1) *The absence of any redshift-magnitude (Hubble) relation for either the radio or optical data*, now understood in terms of the wide range of apparent quasar luminosities.

(2) *QSO clustering near galaxies*: For many years, Fred Hoyle, Geoffrey Ronald Burbidge (1925–2010), Halton Christian ('Chip') Arp (1927–2013) and others maintained that the density of quasars in the vicinity of galaxies significantly exceeded that found in random fields. Thus, they argued that quasars were ejected from galaxies, but it was difficult to understand the absence of blue shifts in such a model. One not very convincing explanation was that light was emitted only in the opposite direction from the motion in the manner of an exhaust, hence only redshifts were observed. In a variation on this interpretation, James Terrell (1964) suggested that quasars were ejected from the center of our Galaxy and had all passed the Earth, hence we only saw redshifts from the receding objects.

(3) *Distribution of observed redshifts*: Analysis of the distribution of observed quasar redshifts suggested that there were preferred values with peaks near 1.955 (Burbidge and Burbidge, 1967) and at multiples of 0.061 (Burbidge, 1968).

(4) *Radio variability*: The discovery of radio variability and especially rapid inter-day variability in some quasars suggested such correspondingly-small linear dimensions, so if the quasars were at cosmological redshifts the brightness temperature would exceed the inverse Compton limit of 10^{12} K (Hoyle and Burbidge, 1966; Kellermann and Pauliny-Toth, 1969). This issue was addressed with the discovery of apparent superluminal motion which is most easily understood as the effect of relativistic beaming which can increase the observed brightness temperature to well above the inverse Compton limit.

(5) *Superluminal motion*: Although relativistic beaming satisfactorily addresses the inverse Compton problem, it was still argued that the observed large angular speed could be more easily understood if quasar redshifts were not cosmological, and the corresponding linear speeds sub-luminal. Indeed, Hoyle, Burbidge and others argued that the relativistic beaming interpretation still required velocities unrealistically close to the speed of light. Still today, the physics of the process by which highly-relativistic motions are attained and maintained remains elusive.

The arguments for non-cosmological redshifts lasted for several decades, and many conferences were held and books written to debate the issues. The apparent anomalies were argued to be the result of *a posteriori* statistics and in the case of redshift distributions, selection effects due to the limited number of strong quasar emission lines that could be observed combined with the narrow range of the observable optical window, and the blocking of certain spectral regions by night-sky lines. The arguments for non-cosmological redshifts only died when the proponents died or at least retired, but from time to time they still surface (e.g., Lopez-Corredoira, 2011).

8 INTERLOPERS, BLUE STELLAR OBJECTS, AND QUASI STELLAR GALAXIES

Soon after the discovery of quasars, it was realized that the optical counterparts were unusually blue. This suggested that quasars might be identified by their blue color only, without the need for very precise radio positions. In pursuing radio source identifications with 'blue stellar objects' (BSOs), Sandage (1965) noticed many BSOs that were not coincident with known radio sources, which he called 'interlopers' or 'quasi-stellar galaxies' (or 'QSGs'). In a paper received at the *Astrophysical Journal* on 15 May, 1965, Sandage estimated that the density of interlopers or QSGs was about 10^3 times greater than that of 3C radio sources. The Editor of the *Astrophysical Journal* was apparently so impressed that he did not send the paper to any referee and by delaying publication was able to rush the paper into publication in the 15 May issue of the *Journal*. Sandage's paper was received with skepticism, no doubt in part generated by what was perceived as privileged treatment of his paper.

Characteristically, Fritz Zwicky (1898–1974; Figure 11) immediately pointed out that

> All of the five quasi-stellar galaxies described individually by Sandage (1965) evidently belong to the subclass of compact galaxies with pure emission spectra previously discovered and described by the present writer. (Zwicky, 1965: 1293).

A few years later, Zwicky was less circumspect and wrote:

> In spite of all these facts being known to him in 1964, Sandage attempted one of the most astounding feats of plagiarism by announcing the existence of a major new component of the Universe: the quasi-stellar galaxies ... Sandage's earthshaking discovery consisted in nothing more than renaming compact galaxies, calling them 'interlopers' and quasistellar galaxies, thus playing the interloper himself. (Zwicky and Zwicky, 1971: xix).

Zwicky (1963) in fact did report at the April 1963 meeting of the AAS that the 'radio stars' are thought to lie at the most luminous end of the sequence of compact galaxies. However, his paper on the same subject was rejected by Subrahmanyan Chandrasekhar (1910–1995), the Editor of the *Astrophysical Journal* editor, who wrote that, "Communications of this character are outside the scope of this journal." (Zwicky and Zwicky, 1971).

Tom Kinman (1965), working at Lick, and Roger Lynds and C. Villere (1965) working at Kitt Peak, each concluded that most of Sandage's BSOs were just that, blue stellar objects, located in our Galaxy and not compact external galaxies. Today we do recognize that there is indeed a population of so called 'radio quiet' quasars, but they are only about an order of magnitude more numerous and three to four orders of magnitude less radio luminous than 'radio loud' quasars.

Interestingly, subsequent investigations later identified several extragalactic radio sources, such as 1219+285, 1514–241 and 2200+420, which had previously been erroneously catalogued as the galactic stars W Comae, AP Lib, and BL Lac respectively.

9 NOMENCLATURE

For the lack of any other name Schmidt and Matthews (1964) adopted the term 'quasi stellar radio sources'. This was quite a mouthful, so in a *Physics Today* review article Hong-Yee Chiu (1964) coined the term 'quasar'. This became widely used in oral discussions and in the popular media, but it was not accepted by the *Astrophysical Journal* until, in his 1970 paper on the "Space Distribution and Luminosity Function of Quasars," Schmidt (1970) wrote:

> We use the term "quasar" for the class of objects of starlike appearance (or those containing a dominant starlike component) that exhibit redshifts much larger than those of ordinary stars in the Galaxy. QSOs are quasars selected on the basis of purely optical criteria, while QSSs are quasars selected on both the optical and radio criteria.

Chandrasekhar, the Editor of the *Astrophysical Journal*, responded with a footnote saying:

> The *Astrophysical Journal* has until now not recognized the term "quasar"; and it regrets that it must now concede: Dr. Schmidt feels that, with his precise definition, the term can no longer be ignored.

The term 'quasar' has caught on and is now commonly used in both the popular and professional literature. However, as observations have been extended to cover the entire electromagnetic spectrum, and as improvements in technology have resulted in increasingly-detailed descriptions of both continuum and line spectra, variability, and morphology, quasars have become classified and sub-classified based on their line spectra, as well as their radio, optical, and high-energy spectral distribution. Optical spectroscopy and photometry have defined QSO1s, QSO2s, Broad Absorption Line quasars (BALs), LINERS, and BL Lacs, collectively referred to as QSOs. Radio astronomers have defined Flat Spectrum and Steep Spectrum Radio Quasars, Radio Loud and Radio Quiet Quasars. Radio Quiet quasars have been referred to as In-

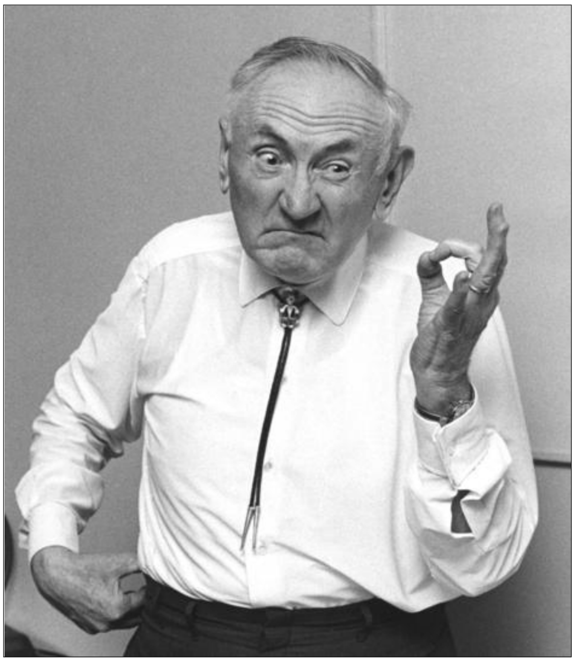


Figure 11: Fritz Zwicky (photograph: Floyd Clark; courtesy: Caltech Archives).

terlopers, QSGs, and BSOs. Relativistically-beamed quasars are known as blazars; X-ray and gamma-ray observations have defined High and Low Spectral Peaked Quasars. Collectively they are all known as Active Galactic Nuclei (AGN), although the term AGN was originally defined to describe the low luminosity counterpart to powerful quasars.

Further background on the early controversies surrounding the discovery of radio galaxies and their implications for cosmology can be found in the excellent books by Edge and Mulkay (1976) and Sullivan III (2009). Shields (1999) and Collin (2006) have given other accounts of the history of quasars and AGN, in particular the subsequent extensive development of the field over the past half century.

10 SUMMARY, UNCERTAINTIES, AND SPECULATIONS

Quasars and AGN are now a fundamental part of astrophysics and cosmology. The understanding that they are powered by accretion onto a supermassive black hole has had a profound impact on theories of galaxy formation and evolution, and also has motivated extensive research on black hole physics.

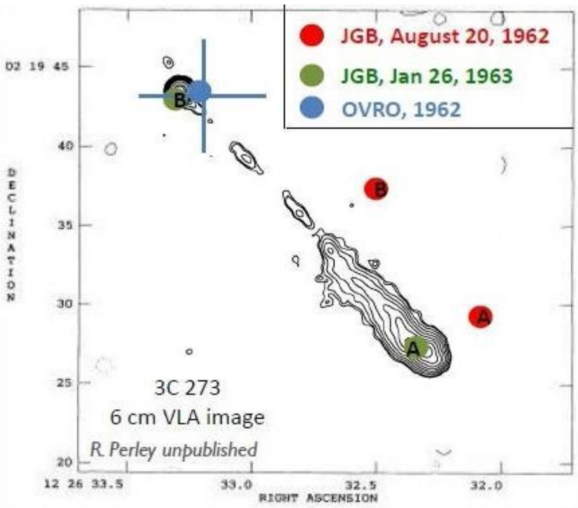


Figure 12: A 6-cm image of 3C 273 obtained with the VLA. Red dots show the location of components A and B as reported to Maarten Schmidt by John Bolton in a letter dated 20 August 1962. Green dots show the location of components A and B as reported by Bolton in his 26 January 1963 letter to Schmidt. The blue point with error bars represents the then-unpublished OVRO interferometer position.

Although both radio and optical astronomers were concentrating on small-diameter radio sources in their quest to locate high-redshift galaxies, the break-through occultation observations of 3C 273 in 1962 were unrelated to the quest for distant galaxies. Indeed, the known relatively-large size of the 3C 273 radio source apparently discouraged further optical investigation until the 1962 series of occultations. Although Bolton (1990) later claimed that the goal of the occultation observation was to determine whether the radio source was associated with the 'star' or the nebulosity, when writing to Schmidt in August 1962 about the occultation, why did he only communicate the radio positions, and uncharacteristically make no mention of the likely obvious optical counterparts. Indeed, he asked Schmidt to "... pass on to Tom [Matthews] the following positions." In his classic paper reporting the redshift, Schmidt (1963) thanked Tom Matthews for drawing his attention to the 13th magnitude 'star', although in a 2012 interview with the author, Matthews denied any involvement in the 3C 273 saga.

It remains unclear why the strong radio source 3C 273 was not identified earlier with its 13th magnitude counterpart. Clearly, Caltech was measuring sufficiently accurate radio source positions as much as two years earlier and had the resources to identify 3C 273 as early as 1961. Although the possibility of identification with apparent stellar objects was already well established with the identifications of the faint optical counterparts 3C 48, 3C 196 and 3C 286, the association with a 13th magnitude stellar object apparently was too extreme to seriously consider. The 19.5 magnitude galaxy first thought to be the optical counterpart of 3C 273 was observed by Schmidt in May 1962, although it was about 1′ west of the true position. Schmidt and the Caltech radio astronomers must have believed that the position error was not more than a few arc seconds, as that kind of accuracy would be required to accept an identification with a barely-detectable galaxy.

An accurate radio position was known among the Caltech radio astronomers perhaps as early as 1961, and certainly prior to Schmidt's May and December 1962 observations made with the 200-in telescope. It seems that somewhere along the line there may have been an error in conveying the OVRO radio position to the Caltech optical astronomers. Ironically, the position conveyed to Schmidt by Bolton on 20 August 1962 which was the basis of the spectrum taken by Schmidt in December was in error by about 15″ due to a wrong calculation by Hazard in determining the time of immersion and emersion during the August occultation. The correct position was not known by Schmidt until he received Bolton's 26 January 1963 letter, more than a month after he obtained the spectrum of the QSO on 29 December, 1962 (see Figure 12).

Thus it appears that the Parkes occultation position played no direct role in the identification of the quasar, which was only recognized as the optical counterpart after Schmidt's 200-in observations showed it to have a peculiar spectrum. Because it was known to be well resolved, 3C 273 had not been on the Caltech list of high-priority sources that might be at high redshift, so it would not have been observed by Schmidt in December were it not for John Bolton's August letter that motivated Schmidt to take the spectrum as the object rose just before the December morning twilight.

Sooner or later, probably sooner, 3C 273 would have been identified on the basis of the OVRO interferometer position, and should have been at least a year or two earlier. Interestingly, it was possible to recognize the 'large' redshift of 3C 273, not because it was large, but because it was so 'small' that the Balmer series was still seen within the small classical optical window. 3C 273 is probably unique in being the only quasar whose spectrum can be so easily determined without prior knowledge of the line identification. It is also somewhat unique in that the radio and optical morphologies are nearly identical, much as in the case of M 87. 3C 273 is the brightest quasar in the radio, IR and optical sky. It is widely believed that the apparent bright radio luminosity is due to relativistic beaming. Does that suggest that the IR and optical emission is also beamed?

The possibility that 3C 48 was a distant galaxy had been discussed by Bolton, Greenstein, Matthews and Bowen at least two full years before the identification of 3C 273. Bolton (1990) later claimed that he and the others apparently rejected the redshift because of a very small 3 to 4 Angstrom discrepancy in the calculated rest wavelengths of the broad emission lines. But, considering the broad nature of the emission lines this seems very unlikely. More probably, they were unwilling to accept the implied huge luminosity, just as Bolton, Stanley and Slee rejected the extragalactic nature of radio galaxies in 1949, and Minkowski later rejected the identification of Cygnus A. It was just too big a step to accept the paradigm-changing radio luminosity until it was forced by Schmidt's interpretation of the 3C 273 spectrum.

It may be relevant that while others were looking for distant galaxies, Bolton may have wanted to believe that he had discovered the first 'radio star' and collect on Greenstein's offer of a case of Scotch, and so 3C 48 played no direct role in the discovery of quasar redshifts. In the end, Greenstein (1963) offered Bolton a beer, but there is no record that Bolton ever accepted. Prior to Schmidt's February 1963 realization of the 3C 273 redshift, Greenstein along with Matthews and Sandage, had submitted separate papers to the *Astrophysical Journal* interpreting the 3C 48 spectrum as a galactic star. After Schmidt's discovery, Greenstein withdrew his paper, while Matthews and Sandage (1963) added a section based on the 0.37 redshift reported by Greenstein and Matthews (1963). Interestingly, on 25 January 1963, just one day prior to his communicating the revised occultation position to Maarten Schmidt, John Bolton gave a lecture to a group of undergraduate students on "Observing Radio Sources". Ron Ekers attended this lecture and his notes show that Bolton stated that "4 genuine radio stars have been identified." (pers. comm., March 2013).[4] At that time only three 'radio stars' were known, 3C 48, 3C 196 and 3C 286, so yet a month after Schmidt had obtained his spectrum Bolton apparently still considered 3C 273 to be among the class of galactic radio stars.

It is curious that John Bolton waited nearly 30 years before making a public claim to have recognized the redshift of 3C 48 two years before the series of *Nature* papers. It is also hard to understand, why Greenstein, apparently having been convinced that 3C 48 was his long sought 'first radio star', used only in-house Caltech publications, *Scientific American* and media releases to announce his claim to the 'first radio star' and did not publish in a refereed journal until after Maarten Schmidt's 1963 breakthrough.

The subsequent search for ever-larger redshifts following the 1963 understanding of the 3C 48 and 3C 273 spectra was highly competitive, particularly among the large optical observatories, but it also contributed to the increasing tensions between Caltech and Carnegie astronomers in Pasadena (see Waluska, 2007).

Currently, the largest-known quasar redshift belongs to ULAS J1120+064 with a redshift of 7.1 (Mortlock et al., 2011). However, it is now gamma-ray bursts and ULIRGs (Ultra Luminous Infra-Red Galaxies), not quasars, that are the most distant and the most luminous objects in the Universe, and gravitational lensing has enabled the detection of a starburst galaxy with a probable redshift of close to 10 (Zheng et al., 2012), well in excess of any known quasar. The controversy over cosmological redshifts was intense and personal and has had a lasting impact on the sociology of astronomy and astronomers.

11 NOTES

1. The date is erroneously given as 15 April in the Hazard et al. paper in *Nature*.
2. In his letter Greenstein (1996) claimed that Bolton played no role in the 3C 48 story and that it was Tom Matthews who first suggested that 3C 48 might have a high redshift. In an interview with the author on 28 April 2012, Matthews (Interview ..., 2012) explained that his early suggestion of a large redshift was based simply on the small angular size of the

radio source, but that once they had the optical identification, he too assumed it was a galactic star. See Section 5.

3. The 'CSIRO' is the Federal Government-funded Commonwealth Scientific and Industrial Research Organisation, and one of it's show-case Divisions was the Division of Radiophysics, based in Sydney, which was a world-leader in radio astronomy.
4. Papers of K.I. Kellermann (NRAO Archives).

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THE DISCOVERY OF QUASARS AND ITS AFTERMATH

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Abstract: Although the extragalactic nature of quasars was discussed as early as 1960 by John Bolton and others it was rejected largely because of preconceived ideas about what appeared to be an unrealistically-high radio and optical luminosity. Following the 1962 observation of the occultations of the strong radio source 3C 273 with the Parkes Radio Telescope and the subsequent identification by Maarten Schmidt of an apparent stellar object, Schmidt recognized that the simple hydrogen line Balmer series spectrum implied a redshift of 0.16. Successive radio and optical measurements quickly led to the identification of other quasars with increasingly-large redshifts and the general, although for some decades not universal, acceptance of quasars as being by far the most distant and the most luminous objects in the Universe. However, due to an error in the calculation of the radio position, it appears that the occultation position played no direct role in the identification of 3C 273, although it was the existence of a claimed accurate occultation position that motivated Schmidt's 200-in Palomar telescope investigation and his determination of the redshift.

Curiously, 3C 273, which is one of the strongest extragalactic sources in the sky, was first catalogued in 1959, and the 13th magnitude optical counterpart was observed at least as early as 1887. Since 1960, much fainter optical counterparts were being routinely identified, using accurate radio interferometer positions which were measured primarily at the Caltech Owens Valley Radio Observatory. However, 3C 273 eluded identification until the series of lunar occultation observations led by Cyril Hazard. Although an accurate radio position had been obtained earlier with the Owens Valley Interferometer, inexplicably 3C 273 was misidentified with a faint galaxy located about one arc minute away from the true position. It appears that the Parkes occultation position played only an indirect role in the identification of the previously-suspected galactic star, which was only recognized as the optical counterpart after Schmidt's 200-in observations showed it to have a peculiar spectrum corresponding to a surprisingly-large redshift.

Keywords: quasars, radio stars, AGN, lunar occultation, redshift

1 HISTORICAL BACKGROUND

The discovery of quasars in 1963, and more generally, active galactic nuclei (AGN), revolutionized extragalactic astronomy. In early February 1963, Maarten Schmidt (b. 1929; Figure 1) at Caltech recognized that the spectrum of the 13th magnitude apparently stellar object identified with the radio source 3C 273 could be most easily interpreted by a redshift of 0.16. Subsequent work by Schmidt and others led to increasingly-large measured redshifts and the recognition of the broad class of active galactic nuclei (AGN) of which quasars occupy the high luminosity end. Schmidt's discovery changed extragalactic astronomy in a fundamental way. Within a few years redshifts as great as 2 or more were being routinely observed, making possible a new range of cosmological studies as well as the realization that supermassive black holes which power radio galaxies and quasars play a prominent role in the evolution of galaxies. But the path to this understanding was a slow, tortuous one, with missed turns that could have, and should have, earlier defined the nature of quasars.

The events leading up to the recognition of quasars as the extremely luminous nuclei of distant galaxies go back much earlier than 1963; indeed, one wonders why the extragalactic nature of quasars was not recognized well before 1963, and why 3C 273, which is the seventh brightest radio source in the northern sky away from the Galactic Plane, was not identified at least one or two years earlier based on the radio position determined by observations carried out at the Owens Valley Radio Observatory (henceforth OVRO), which was more accurate than the occultation position used by Schmidt to identify 3C 273 in December 1962.

In the remainder of this section we review the early arguments and evidence for powerful activity in the nuclei of galaxies. In Section 2, we briefly review the status of extragalactic radio astronomy prior to the identification of 3C 48, and

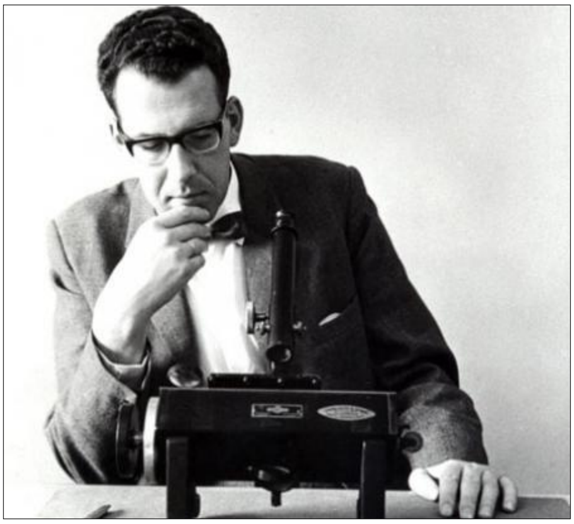

Figure 1: A photograph of Maarten Schmidt at work in 1965 (credit: James McClanahan, Engineering and Science, May, 1965; courtesy: Caltech Archives).

in Section 3, the identification of 3C 48, which might have been the first discovered quasar, but was unrecognized as such until the work on 3C 273 more than two years later, as described in Section 4. In Section 5 we return to the issues surrounding 3C 48, and in Sections 6 and 7 the implications for cosmology and the arguments for non-cosmological interpretations of quasar redshifts. Sections 8 and 9 describe the discovery of radio-quiet quasars. Finally, in Section 10 we summarize the history and highlight remaining issues and questions surrounding the discovery of quasars.

Probably the first person to note enhanced activity in the nucleus of a galaxy was Edward Arthur Fath (1880–1959) who reported on the nuclear emission line spectrum of NGC 1068 (Fath, 1909). Later observations of strong nuclear emission lines by Vesto Melvin Slipher (1875–1969) in 1917, Edwin Powell Hubble (1889–1953) in 1926, Milton Lasell Humason (1891–1972) in 1932, and Nicholas Ulrich Mayall (1906–1993) in 1934 and 1939 led Carl Keenan Seyfert (1911–1960; Figure 2) in 1943 to his now famous study of the enhanced activity in the nuclei of six galaxies (or as he called them, 'extragalactic nebulae'). Seyfert, and his predecessors, commented on the similarity with the emission line spectrum of planetary and other gaseous nebulae and noted that the lines are apparently Doppler broadened. There is no evidence that Seyfert ever continued this work, but nevertheless, galaxies containing a stellar nucleus with strong broad emission (including forbidden) lines have become known as 'Seyfert Galaxies'.


Figure 2: Carl Seyfert (dyer.vanderbilt.edu/about-us/history/).

Curiously, while the SAO/NASA Astrophysics Data System lists 365 citations to Seyfert's 1943 paper, the first one did not appear until a full eight years after Seyfert's 1943 publication during WWII. Even then, not much interest was shown in Seyfert Galaxies until Iosif Samuilovich Shklovsky (1916–1985) drew attention to the possible connection between Seyfert galaxies and radio galaxies (Shklovsky, 1962). Seyfert served three years on the board of Associated Universities Inc. during the critical period when AUI was overseeing the early years of the NRAO, and he had been nominated to serve as the first Director of the NRAO. Unfortunately, in 1960 he died in an automobile accident, but it is interesting to speculate on whether, if Seyfert had lived, his association with the radio astronomers at the NRAO might have led to an earlier appreciation of the relationship between radio emission and nuclear activity.

Even earlier, Sir James Hopwood Jeans (1877–1946) speculated that

> The centres of the nebulae are of the nature of 'singular points,' at which matter is poured into our universe from some other and entirely spatial dimension, so that to a denizen of our universe, they appear as points at which matter is being continually created. (Jeans, 1929: 360).

However, it was Victor Amazaspovich Ambartsumian (1908–1996) who championed the modern ideas that something special was going on in the nuclei of galaxies. At the 1958 Solvay Conference, Ambartsumian (1958: 266) proposed "... a radical change in the conception on the nuclei of galaxies ...", saying that "... apparently we must reject the idea that the nuclei of galaxies is [*sic*] composed of stars alone." He went on to conclude that, "... large masses of prestellar matter are present in nuclei."

In a prescient paper, Fred Hoyle (1915–2001) and William Alfred Fowler (1911–1995) considered

> ... the existence at the very center of galaxies of a stellar-type object of large mass … in which angular momentum is transferred from the central star to a surrounding disk of gas. (Hoyle and Fowler, 1963: 169).

2 BEFORE QUASARS

When discrete sources of radio emission were discovered, they were first thought to be due to stars in our Galaxy. Karl Guthe Jansky (1905–1950) and Grote Reber (1911–2002) had shown that the diffuse radio emission was associated with the Milky Way, and since the Milky Way is composed of stars, dust and gas, it seemed natural to suppose that the discrete radio sources were likely connected with stars. Indeed for many years they were called 'radio stars'.

The first hint that at least some radio sources might be extragalactic came from a series of observations made by John Gatenby Bolton (1922

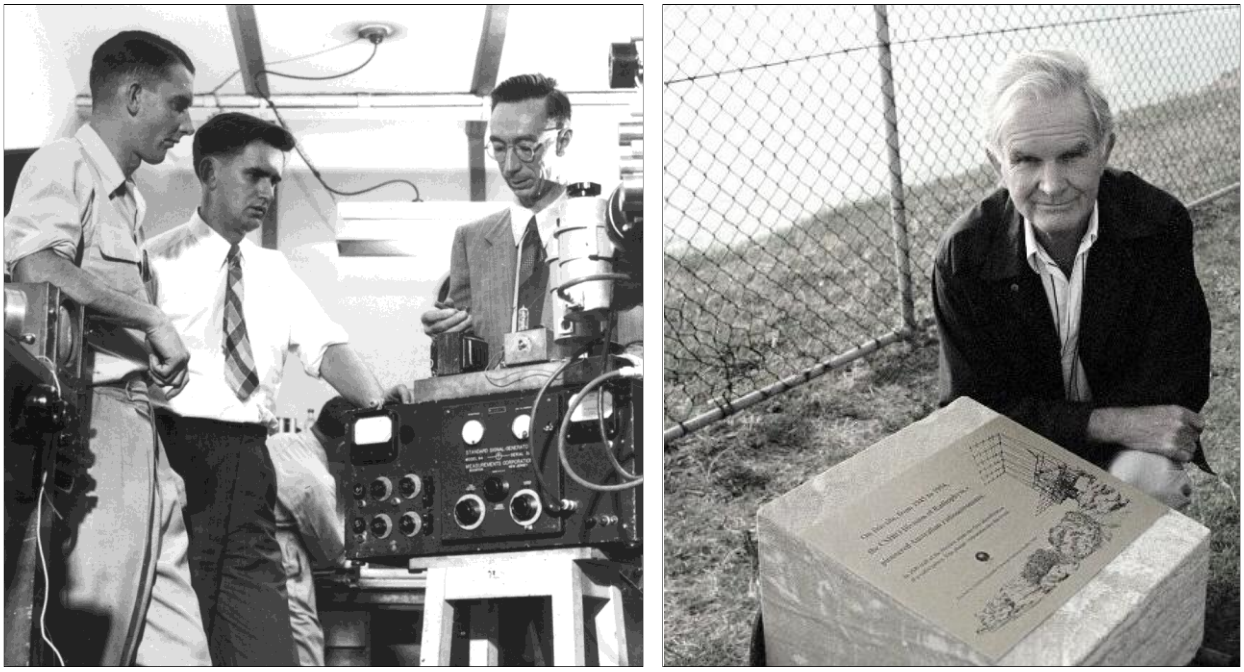

Figure 3: The left hand photograph shows (left to right) John Bolton, Gordon Stanley and the Head of the Radio Astronomy Group at the Division of Radiophysics, Dr Joe Pawsey, at the Radiophysics Laboratory during the late 1940s. The right hand photograph shows Bruce Slee during the unveiling of a commemorative plaque in 1989 at Rodney Reserve, the site of the Division's Dover Heights field Station (both photographs are adapted from originals in the CSIRO's Radio Astronomy Image Archive).

–1993), Gordon James Stanley (1921–2001) and Owen Bruce Slee (b. 1924) (see Figure 3) using cliff interferometers in Australia and New Zealand (see Robertson et al., 2014). After months of painstaking observations, Bolton and his colleagues succeeded in measuring the positions of three strong radio sources with an accuracy of better than half a degree.

For the first time it was possible to associate radio sources with known optical objects. Bolton, Stanley and Slee (1949) identified Taurus A, Centaurus A, and Virgo A with the Crab Nebula, NGC 5128 and M87 respectively. NGC 5128, with its conspicuous dark lane, and M87, with its prominent jet, were well known to astronomers as peculiar galaxies, but their paper, "Positions of Three Discrete Sources of Galactic Radio Frequency Radiation," which was published in *Nature*, mostly discussed the nature of the Crab Nebula. In a few paragraphs near the end of their paper, Bolton, Stanley and Slee commented:

> NGC 5128 and NGC 4486 (M87) have not been resolved into stars, so there is little direct evidence that they are true galaxies. If the identification of the radio sources are [*sic*] accepted, it would indicate that they are [within our own Galaxy].

As implied by the title, Bolton, Stanley and Slee dismissed the extragalactic nature of both Centaurus A and M87. When asked many years later why he did not recognize that he had discovered the first radio galaxies, Bolton (pers. comm., August 1989) responded that he knew they were extragalactic, but that he also realized that the corresponding radio luminosities would be orders of magnitude greater than that of our Galaxy and that he was concerned that in view of their apparent extraordinary luminosities, a conservative *Nature* referee might hold up publication of the paper. However, in a 1989 talk, Bolton (1990) commented that their 1949 paper marked the beginning of extra-galactic radio astronomy. Nevertheless, for the next few years the nature of discrete radio sources remained controversial within the radio astronomy community, and many workers, particularly those at the Cambridge University Cavendish Laboratory, continued to refer to 'radio stars'.

Following the 1954 identification of Cygnus A with a faint galaxy at $z = 0.06$, by Mount Wilson and Palomar astronomers, Wilhelm Heinrich Walter Baade (1893–1960; Figure 4a) and Rudolph Leo Bernard Minkowski (1895–1976; Figure 4b), it became widely appreciated that the high latitude radio sources were in fact very powerful 'radio galaxies', and that the fainter radio sources might be at much larger redshifts, even beyond the limits of the most powerful optical telescopes such as the Palomar 200 inch (Baade and Minkowski, 1954). In a footnote in their paper, Baade and Minkowski noted that Cygnus A previously had been identified with the same galaxy by Bernard Yarnton Mills (1920–2011) and Adin Thomas (1951) and by David Dewhirst (1926–2012) (see Mills and Thomas, 1951; Dewhirst, 1951), but Minkowski confessed that at the time he was not willing to accept the identification with such a faint and distant nebula. Over the next five years, many other radio galaxies were

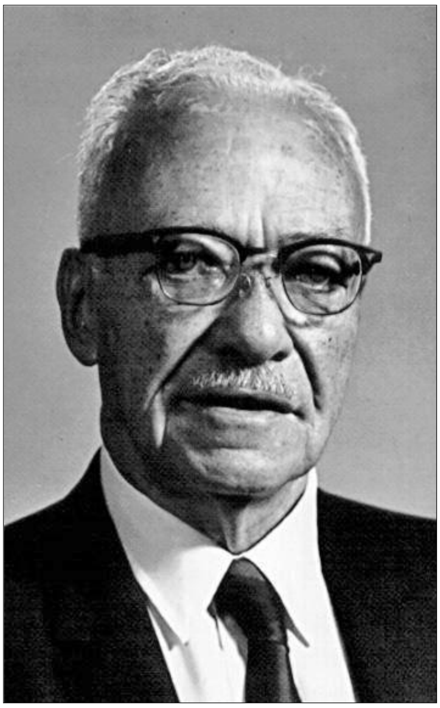

Figure 4a (left): Walter Baade (courtesy: Caltech Archives).
Figure 4b (right): Rudolf Minkowski (courtesy: Astronomical Society of the Pacific).

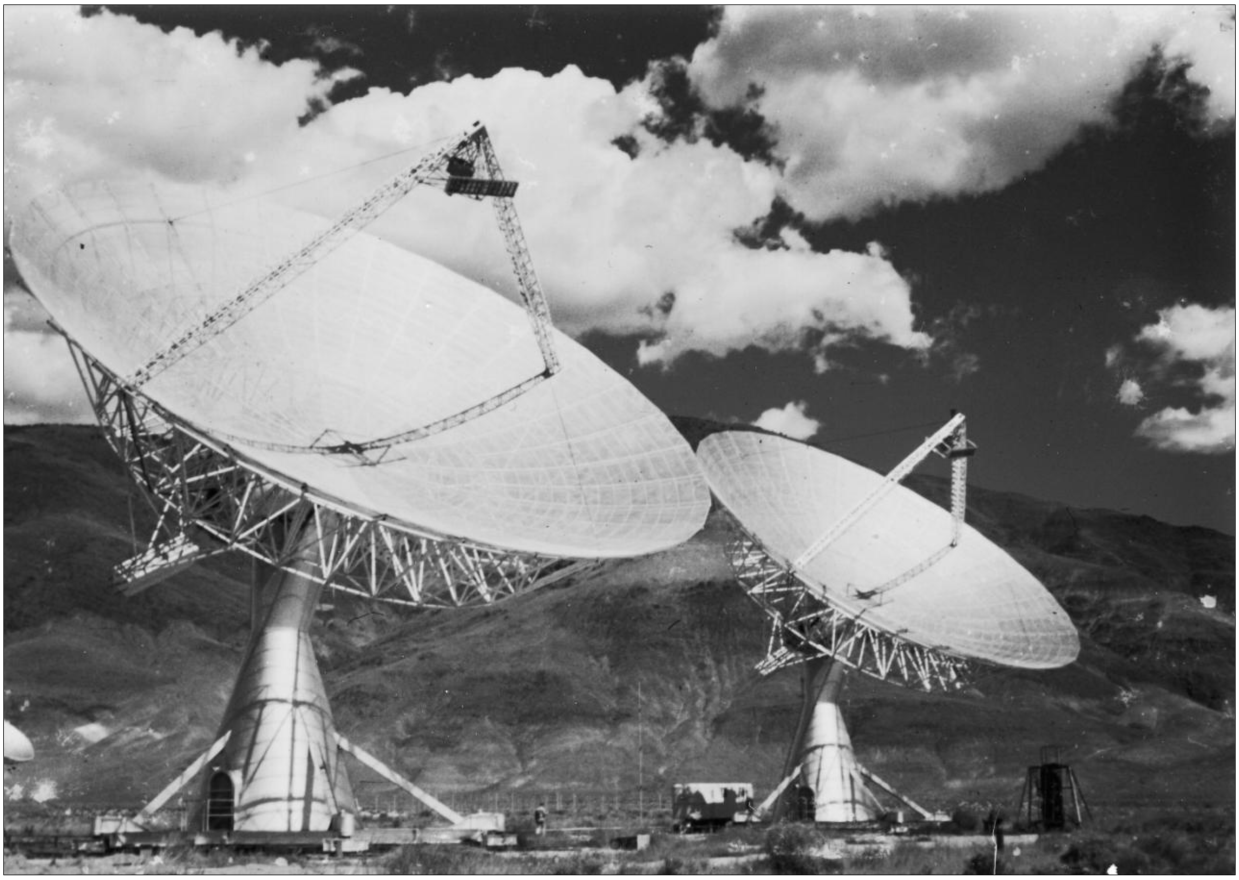

Figure 5: The two-element interferometer at the Owens Valley Radio Observatory (courtesy: Marshall Cohen).

identified, but many others were also misidentified due to inaccurately-measured radio positions.

In 1955, John Bolton came to Caltech from Australia to build a radio telescope specifically designed to accurately measure radio positions and to work with Caltech and Carnegie astronomers to identify and study their optical counterparts. Starting in early 1960, the Caltech OVRO (Figure 5) began to produce hundreds of radio source positions accurate up to ten seconds of arc and leading to new radio galaxy identifications

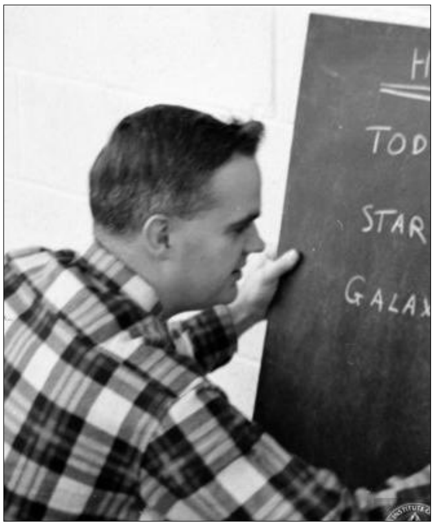
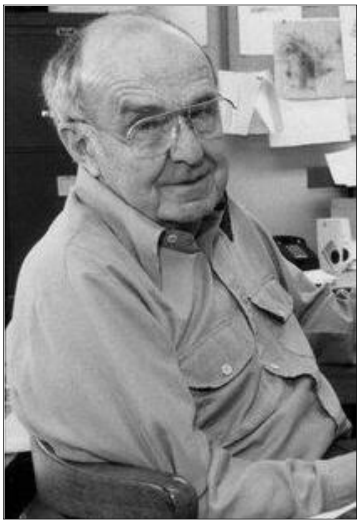
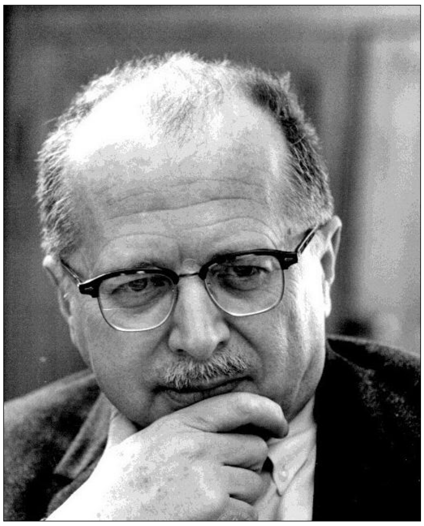

Figure 6a (left): Tom Matthews (courtesy: Caltech Archives).
Figure 6b (center): Alan Sandage (courtesy: Carnegie Observatories).
Figure 6c (right): Jesse Greenstein (courtesy: Caltech Archives).

(Greenstein 1961). Recognizing that radio galaxies were characteristically the brightest galaxy in a cluster (Bolton 1960c), it became clear to many that the search for distant galaxies needed to address the outstanding cosmological problems of the day and therefore should concentrate on galaxies identified with radio sources. Moreover, it was naturally assumed that the smaller radio sources were most likely to be the more distant, so emphasis was given to the smallest radio sources, whose dimensions were determined with the long baseline radio-linked interferometers at Jodrell Bank (Allen et al., 1960; 1962) and with Caltech's OVRO interferometer.

Much of this work was carried out within a collaboration of scientists at Caltech and at the Mount Wilson and Palomar Observatories. John Bolton, Thomas Arnold Matthews (Figure 6a), Alan Theodore Moffet, Richard B. Read and Per E. Maltby (1933–2006) at the OVRO provided accurate radio positions, angular sizes and optical identifications based on inspection of the 48-in Schmidt prints and plates. At the Mt Wilson and Palomar Observatories, Baade, Minkowski, and Allan Sandage (1926–2010; Figure 6b) teamed up with the Caltech radio astronomers to obtain 200-in photographs and spectra. At Caltech, Jesse Greenstein (1909–2002; Figure 6c), Guido Münch (b. 1921) and, after Minkowski's retirement in 1960, Maarten Schmidt, provided spectroscopic follow-up to determine the redshifts of the radio galaxies.

This program had a dramatic success, when, using the 200-in telescope during his last observing session before retiring, Minkowski (1960) found a redshift of 0.46 for the 20.5 magnitude galaxy which was identified by Matthews and Bolton with 3C 295. This made 3C 295 by far the largest known redshift. Although previous to Minkowski's observation, the largest measured spectroscopic redshift was less than 0.2, curiously, an unrelated foreground galaxy located only a few arcminutes from 3C 295 was observed by Minkowski to have a redshift of 0.24, making it the second-largest known redshift at the time. Yet, it would be another 15 years before a galaxy redshift greater than that of 3C 295 would be measured. Interestingly, 3C 295 was targeted not because of any special properties, but only because it was at a high declination, where an accurate declination could be measured with the OVRO interferometer, which until late 1960 had only an East-West base line.

3 3C 48: THE FIRST RADIO STAR

By late 1960, it was widely accepted that radio sources located away from the Galactic Plane were powerful distant radio galaxies (e.g., Bolton 1960c). However, Bolton's Caltech colleague, Jesse Greenstein, an acknowledged expert on exotic stars, offered a case of the best Scotch whisky to whoever found the first true radio star. Meanwhile, in the quest to find more distant galaxies, the Caltech identification program concentrated on small diameter sources selected from the early OVRO interferometer observations and from unpublished long-baseline interferometer observations at Jodrell Bank (Allen et al., 1962).

In 1960 Tom Matthews and John Bolton identified 3C 48 with what appeared to be a 16th magnitude star. Observations made by Sandage using the 200-in telescope in September 1960 showed a faint red wisp 3″ × 8″ in size. Spectroscopic observations by Sandage, Greenstein and Münch showed multiple emission and absorption lines as well as a strong continuum UV excess, but attempts to identify the lines were inconclusive. On 29 December, Sandage presented a late paper at the 107th meeting of the

American Astronomical society (AAS) in New York. The listed authors were Matthews, Bolton, Greenstein, Münch and Sandage (1960), which reflected the order of their involvement (Bolton, 1990). But, by this time, Bolton had left Caltech and returned to Australia to oversee the completion and operation of the 64-m Parkes Radio Telescope. Unfortunately, abstracts of late AAS papers were not published at that time, and the only remaining written record of the talk is a news article on the "First True Radio Star" which appeared in the February 1961 issue of *Sky and* Telescope (The first true ..., 1961) and a report in the annual report of the Carnegie Institution of Washington (see Report ..., 1960–1961: 80). Curiously, there is no record of the 107th meeting of the AAS at the American Institute of Physics Niels Bohr Library & Archives, although the records of the preceding and succeeding years still exist at the AIP.

Sky and Telescope (1961) cautiously reported that

> ... there is a remote possibility that [3C48] may be a distant galaxy of stars; but there is general agreement among the astronomers concerned that it is a relatively nearby star with most peculiar properties.

A few months later, Jesse Greenstein (1961) wrote an article in the Caltech *Engineering and Science* publication announcing "The First True Radio Star."

Subsequent study appeared to confirm the nature of 3C 48 as a true radio star, but with no proper motion as great as 0.05 arcsec/yr. Radio observations indicated angular dimensions less than 0.8 arcsec (Allen et al., 1962) but no measured radio variability (Matthews and Sandage, 1963). Observations by Sandage with the 200-in telescope showed that except for the faint 'wisp', most of the optical light was unresolved, that the color was 'peculiar' and that the optical counterpart varied by at least 0.4 mag over a time scale of months, thus supporting the notion that 3C 48 was a galactic star (Matthews and Sandage, 1963).

Meanwhile, Greenstein (1962) made an exhaustive study of the optical spectrum. After two years of analysis, he submitted a paper to the *Astrophysical Journal* with the title, "The Radio Star 3C48". In this paper, he concluded that 3C 48 was the stellar remains of a supernova, and that the spectrum reflected highly-ionized rare earth elements. The abstract states, "The possibility that the lines might be greatly redshifted forbidden emissions in a very distant galaxy is explored with negative results ...", and the first sentence of the paper states,

> The first spectra of the 16th magnitude stellar radio source 3C48 obtained in October 1960 by Sandage were sufficient to show that this object was not an extragalactic nebula of moderate redshift.

Greenstein discussed possible line identifications with several possible redshifts. Although he commented that "... except for 0.367 no red-shift explains the strongest lines of any single ionization ...", he maintained that, "... the case for a large redshift is definitely not proven." Nevertheless, with great prescience, he then went on to point out that if the 3C 48 spectrum is really the red-shifted emission spectrum of a galaxy, then for $\Delta\lambda/\lambda > 1$, Ly-α and other strong UV lines would be shifted into the visible spectrum. When asked years later why he rejected what appeared to be a very important and satisfactory interpretation in terms of a large redshift, Greenstein responded: "I had a reputation for being a radical and was afraid to go out on a limb with such an extreme idea." (Jesse Greenstein, pers. comm., January, 1995).

Subsequently, Matthews and Sandage (1963) succeeded in identifying two additional small-diameter radio sources, 3C 196 and 3C 286, with 'star-like' optical counterparts. But the nature of these 'star-like' counterparts to compact radio sources remained elusive until the investigation of 3C 273 showed them to be distant and unprecedentedly-powerful objects.

4 3C 273

3C 273 is the seventh-brightest source in the 3C catalogue. The flux density is comparable to that of 3C 295, so 3C 273 was naturally included in the Caltech program to measure accurate radio positions with the goal of finding optical counterparts for several hundred sources from the 3C catalogue. Typical positional accuracy of the OVRO interferometer was better than 10″ for the stronger sources. Right ascensions were measured by Tom Matthews and others. The declination measurements were part of Richard Read's 1962 Caltech Ph.D. thesis and were submitted for publication in the *Astrophysical Journal* (Read, 1963) in December 1962. The right ascensions were not published until later (Fomalont et al., 1964), but the interferometer positions of many sources, including 3C 273, were available to Caltech astronomers by 1961.

Based on his measured declinations and right ascensions measured by other Caltech radio astronomers, Read (1962) discussed likely identifications of four sources, including 3C 273, with faint galaxies seen only in 200-in plates. Read's declination differed by only 1″ from the currently-accepted position of the quasar. An unpublished contemporaneous right ascension measured by the Caltech radio astronomers was within 2″ of the correct position (see Papers ...). But, the faint galaxy mentioned by Read, which Maarten Schmidt attempted to observe in May 1962, was inexplicably about 1′ west of 3C 273. Interestingly, in his published paper, Read (1963) uses the exact same wording to describe the four identified sources as used in his thesis, but 3C 273 is replaced by 3C 286.

The breakthrough occurred in 1962 as a result of a series of lunar occultations of 3C 273 which were predicted to be observable with the 64-m Parkes Radio Telescope in Australia. Earlier, Cyril Hazard (b. 1928; Figure 7) had used the Jodrell Bank 250-ft Radio Telescope to observe a lunar occultation of the radio source 3C 212. Hazard (1961; 1962) was able to determine the position of 3C 212 with an accuracy of 3″, but his inspection of Palomar Sky Survey plates failed to recognize the 19th magnitude stellar identification which later turned out to be a quasar. Although unresolved by the OVRO interferometer (Moffet, 1962), 3C 273 was known from interferometer measurements at Jodrell Bank (Allen et al., 1962) and Nançay (Lequeux, 1962) to be resolved on longer baselines so it was not on the Caltech list of high-priority small sources that might lead to an identification of a more distant galaxy than 3C 295.

A full occultation of 3C 273, including both immersion and emersion, was predicted to occur on 5 August 1962 and was observed at Parkes at both 136 and 400 MHz. According to Hazard (1977; 1985; Interview ..., 2013) and Bolton (1990), Rudolph Minkowski had a Polaroid copy of a 48-in Schmidt image which indicated the incorrect faint galaxy identification which Schmidt had tried to observe in May of that year. According to Bolton (1990), earlier position measurements made with the Parkes Radio Telescope had established a tentative identification in between a 13th magnitude stellar object and an elongated feature, like an edge-on galaxy, on Minkowski's photograph. However, Bolton claimed that the position accuracy was insufficient to determine whether the radio source was associated with the 'star' or with the elongated feature, so hopefully the occultation would resolve the uncertainty.

The first occultation, on 15 May,[1] when only the immersion was visible, showed diffraction fringes characteristic of a very small source, but was not adequate to derive a position. The 5 August event was more promising as both immersion and emersion were visible, but there was a catch. The emersion of the radio source from behind the Moon was predicted to occur uncomfortably close to the 60° zenith angle limit of the Parkes Radio Telescope (Figure 8). To make sure that the event would not be missed due to an inaccurate position—as had occurred with some earlier predicted occultations—Bolton removed a ladder from the Radio Telescope and ground down part of the gear box in order to extend the length of time the telescope could track. However, as it turned out, the occultation took place at precisely the predicted time, and so the rather drastic alteration of the Radio Telescope's gear box proved unnecessary. But it was a good story which Bolton enjoyed telling and retelling.

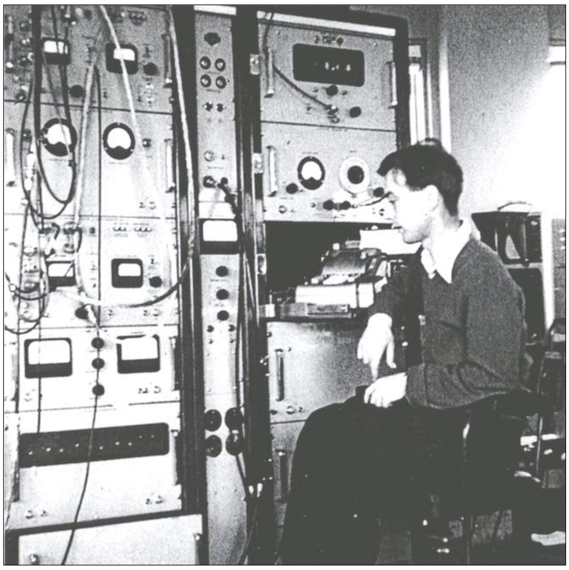

Figure 7: Cyril Hazard observing at Jodrell Bank in the 1950s (courtesy: Miller Goss).

From analysis of the diffraction pattern at 136 and 410 MHz obtained from the immersion (see Figure 9) and emersion of the source from behind the Moon, Hazard et al. (1963) showed that 3C 273 was a complex source consisting of a small flat spectrum component (B) and an elongated steep spectrum component (A). Even before the occultation, Hazard (Interview ..., 1973) was aware of the observations by James Lequeux (1962) using the Nançay interferometer which showed that 3C 273 was a double source with an E-W separation of 14″ between the two components, which was precisely the value derived from the occultation.

On 20 August, just two weeks after the occultation, John Bolton (1962) wrote to Maarten Schmidt at Caltech discussing the Parkes program of radio source identifications and request-

Figure 8: The 64-m Parkes Radio Telescope (photograph: K.I. Kellermann).

Figure 9: Chart record showing the immersion of the radio source 3C 273 behind the Moon on 5 August 1962 at 410 MHz. Time runs from right to left. The right hand (early) part of the curve shows the Fresnel diffraction pattern as the smaller component B is occulted, followed by the disappearance of the larger component, A (after Hazard et al., 1963; reproduced with permission).

ing optical follow-up from Palomar on a radio source located at –28° declination. Somewhat parenthetically, or as an afterthought, he gave the occultation positions of 3C 273 components A and B, and asked Schmidt to pass them along to Tom Matthews, but Bolton made no mention of the obvious optical counterparts in his letter. Moreover, due to a mathematical error by Hazard the positions communicated by Bolton were in error by about 15″. Although Hazard later recounted that Minkowski had tentatively identified 3C 273 with the nebulosity which he assumed to be an edge-on galaxy (Bolton, 1962), in January 1963 Hazard wrote to Schmidt: "I have heard … that *you* have succeeded in identifying the radio source 3C 273 ..." (Hazard, 1963; my italics), so it appears likely that even five months after the occultation neither Hazard nor anyone in Australia was fully convinced of what should have been the obvious association with the bright star that was known to be close to the position of 3C 273. It was probably Tom Matthews (Schmidt, 1963) who provided the precise optical coordinates which showed that the 13th magnitude stellar counterpart was coincident with radio component B, and that the fainter jet was coincident with radio component A. But, this was only after Schmidt had already observed the spectrum of the stellar object.

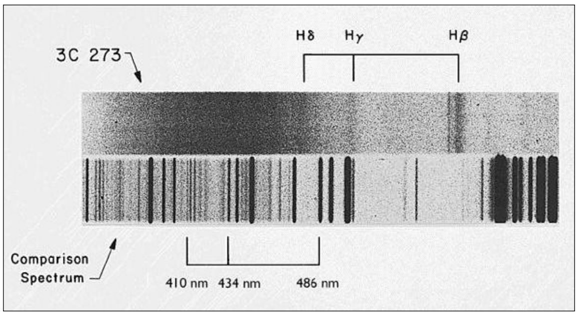

Figure 10: The spectrum of 3C 273 obtained with the 200-in Palomar telescope (courtesy: Maarten Schmidt).

Unfortunately, 3C 273 was too close to the Sun to attempt any spectroscopy until December 1962, when Schmidt used the 200-in telescope to observe the spectrum. Based on the faint optical counterparts that were being associated with other radio sources, Schmidt (1983; 2011) has explained that, like Minkowski, he assumed that the correct optical counterpart was the faint nebulosity. Although at the time there were already three radio sources, 3C 48, 3C 196, and 3C 286, which had been identified with stellar counterparts, Schmidt (ibid.) assumed that that the 13th magnitude stellar object was far too bright to be associated with the radio source. Nevertheless, in order to eliminate the stellar object from further consideration, Schmidt decided to first obtain a spectrum of the 'star'. Having spent most of his 200-in experience observing very faint objects, Schmidt overexposed the spectrum on the first night. Although he obtained a properly-exposed spectrum on 29 December 1962 (Figure 10), it was only on 6 February 1963 that he recognized the simple Balmer series bands of Hβ, Hγ, and Hδ, with a redshift of 0.158 and a corresponding optical luminosity some hundred times brighter than the typical galaxies previously identified with radio sources. Applying that redshift led Schmidt (1963) to recognize the observed band at 3239 Å to be Mg II with a rest wavelength of 2798 Å and another line at a rest wavelength of 5007 Å to be [O III] (Schmidt, 1983). A low-resolution infra-red observation by John Beverley Oke (1928–2004) showed the Hα line shifted to 7599 Å, which confirmed Schmidt's redshift determination (Oke, 1963).

Re-inspection of the spectrum of 3C 48 by Schmidt and Greenstein immediately identified the broad line at 3832 Å to be Mg II redshifted by 0.3679. Using this value of the redshift, the other 3C 48 lines fell into place as [Ne V], [O II], and [Ne III]. Greenstein (1996) recalled that Matthews had earlier suggested "... the possibility of a 37% redshift ..." so the 3C 48 paper was authored by Greenstein and Matthews (1963), but no mention was made of any involvement by John Bolton.[2] However, the high luminosity implied by the observed redshifts along with the small size implied by Sandage's observation of variability was quite remarkable, and was not immediately universally accepted.

The four, now classic, papers by Hazard et al. (1963), Schmidt (1963), Oke (1963), and Greenstein and Matthews (1963) were published as consecutive papers in the 16 March 1963 issue of *Nature*. Whether by error or intentionally, Hazard's name appeared in *Nature* with a CSIRO[3] Radiophysics Laboratory affiliation, even though he was affiliated with the University of Sydney. At the time relations between the University of Sydney and the Radiophysics Laboratory were already strained, and this incident further exacerbated the existing tensions. Hazard had been invited by John Bolton, Edward George ('Taffy') Bowen (1912–1991) and Joseph Lade Pawsey (1908–1962) to use the Parkes Radio Telescope to observe the occultation. As a non-staff member, Hazard was not familiar with the operation of the Radio Telescope or the instrumentation at Parkes, and so following standard practice for non-Radiophysics observers, CSIRO staff members Albert John Shimmins and Brian Mackey were added to the observing team to provide telescope and instrumental support respectively (Bolton, 1990). Characteristically, Bolton (ibid.) declined to put his name on the paper, stating that he merely "... was just doing his job as Director." Haynes and Haynes (1993) attribute the error to an unintentional mistake on the part of the journal due to the change from a letter format, as submitted, to an article format, as published, although the manuscript submitted by the Radiophysics publications office has the word, 'delete' handwritten in next to Hazard's University of Sydney address.

5 3C 48 REVISITED

In 1989 John Bolton gave a talk to the Astronomical Society of Australia in which he reminisced about the period 1955–1960 when he was setting up the radio astronomy program at Caltech. In this talk, Bolton recalled that back in 1960, a full two years before the redshifts of 3C 273 and 3C 48 were announced, he had discussed a possible 3C 48 redshift of 0.37. Bolton (1990) subsequently wrote:

> The best fit I could find for the one broad line and one narrow line which Jesse [Greenstein] had measured were with Mg II λ2798 and [Ne V] λ3426, and a redshift of 0.37.

Since a quarter of a century had passed before his 1989 talk, Bolton's assertion was naturally viewed with skepticism and was emphatically rejected by Greenstein (1996) as a fabrication. However, Fred (later Sir Fred) Hoyle (1915–2001) later recalled that, at the time, John Bolton had told him "I think there's a big redshift in the spectrum." (Hoyle, 1981) Bolton's claim is also supported by a handwritten letter from Bolton to Joe Pawsey dated 16 November, 1960, just one month before Bolton left Caltech for Australia to take charge of the Parkes Radio Telescope, and more than a month before Sandage's AAS paper. Bolton (1960a) wrote:

> I thought we had a star. It is not a star. Measurements on a high dispersion spectrum suggest the lines are those of Neon [V], Argon [III] and [IV] and that the redshift is 0.367. The absolute photographic magnitude is –24 which is two magnitudes greater than anything known. … I don't know how rare these things are going to be, but one thing is quite clear – we can't afford to dismiss a position in the future because there is nothing but stars.

But, just a month later, on 19 December, Bolton (1960b) wrote to Pawsey from the *SS Orcades*: "The latest news on 3C 48 as I left Caltech was – It is most likely a star." Bolton's letter was mailed from Honolulu where the ship stopped while *en route* to Australia. Apparently, between 16 November and the time he sailed for Australia on 12 December, Bolton had discussed 3C 48 with Ira Sprague Bowen (1898–1973), the then Director of the Mt Wilson and Palomar Observatories who was an expert on spectroscopy. Bowen and Greenstein had inexplicably argued that the dispersion of only three to four angstroms in the calculated rest wavelengths of different lines was too great to accept the large redshift and the corresponding extraordinary absolute magnitude of –24. Indeed, in a paper submitted on 8 December 1962, several months before Schmidt's 3C 273 breakthrough, Matthews and Sandage (1963) had written that they were not able to find "... any plausible combination of red-shifted emission lines." Apparently Matthews had forgotten that earlier he had suggested to Greenstein that 3C 48 might have a 37% redshift. The paper was published in July 1963, with a section discussing "3C 48 as a Galaxy" added in proof after its redshift had been determined by Greenstein and Schmidt.

6 QUASARS AND COSMOLOGY

The discovery of quasars with their large redshifts and corresponding unprecedented-large radio and optical luminosities generated a wide range of observational and theoretical investigations as well as a plethora of conferences, particularly the series of Texas Symposia on Relativistic Astrophysics and Cosmology (e.g., Robinson, Schild and Schucking 1965). Motivated by the possibility of extending the Hubble relation to higher redshifts and determining the value of the deceleration constant, q_0, for years there was an intense competition to find the highest redshifts. Within two years of the 3C 273 breakthrough, redshifts as high as 2 were reported by Schmidt (1965) and others; but redshifts >3 were not observed until 1973 (Carswell and Strittmatter 1973).

In his classic paper written only five years after he determined the redshift of 3C 273, Schmidt (1968) used a sample of forty quasi-stellar radio sources to derive their luminosity functions and to show that the space density dramatically evolves with cosmic time much in the same manner as powerful radio galaxies. A few years later, Schmidt (1970) extended the study to include optically-selected, e.g., radio quiet, quasars. Now fifty years later, quasar and AGN research have become part of mainstream astronomy with numerous AGN and quasar conferences held each year, along with many books and probably thousands of papers having been published. Supermassive black holes which were first introduced to power quasars (Lynden-Bell, 1969) are now thought to play a major role in galaxy formation and evolution.

7 NON-COSMOLOGICAL REDSHIFTS

In view of the apparent extraordinary properties of quasars, a number of well-respected astronomers have argued that the large observed quasar redshifts are intrinsic and not due to cosmological shifts that reflect the expansion of the Universe. The possibility that the observed shifts might be gravitational redshifts was considered very early, but Schmidt and Greenstein (1964) showed that an interpretation in terms of gravitational red-shifts was unrealistic.

Nevertheless, there were a number of observations which appeared to challenge the cosmological interpretation of the large observed redshifts (e.g., Hoyle, 1966; Hoyle and Burbidge, 1966). These included:

(1) *The absence of any redshift-magnitude (Hubble) relation for either the radio or optical data*, now understood in terms of the wide range of apparent quasar luminosities.

(2) *QSO clustering near galaxies*: For many years, Fred Hoyle, Geoffrey Ronald Burbidge (1925–2010), Halton Christian ('Chip') Arp (1927–2013) and others maintained that the density of quasars in the vicinity of galaxies significantly exceeded that found in random fields. Thus, they argued that quasars were ejected from galaxies, but it was difficult to understand the absence of blue shifts in such a model. One not very convincing explanation was that light was emitted only in the opposite direction from the motion in the manner of an exhaust, hence only redshifts were observed. In a variation on this interpretation, James Terrell (1964) suggested that quasars were ejected from the center of our Galaxy and had all passed the Earth, hence we only saw redshifts from the receding objects.

(3) *Distribution of observed redshifts*: Analysis of the distribution of observed quasar redshifts suggested that there were preferred values with peaks near 1.955 (Burbidge and Burbidge, 1967) and at multiples of 0.061 (Burbidge, 1968).

(4) *Radio variability*: The discovery of radio variability and especially rapid inter-day variability in some quasars suggested such correspondingly-small linear dimensions, so if the quasars were at cosmological redshifts the brightness temperature would exceed the inverse Compton limit of 10^{12} K (Hoyle and Burbidge, 1966; Kellermann and Pauliny-Toth, 1969). This issue was addressed with the discovery of apparent superluminal motion which is most easily understood as the effect of relativistic beaming which can increase the observed brightness temperature to well above the inverse Compton limit.

(5) *Superluminal motion*: Although relativistic beaming satisfactorily addresses the inverse Compton problem, it was still argued that the observed large angular speed could be more easily understood if quasar redshifts were not cosmological, and the corresponding linear speeds sub-luminal. Indeed, Hoyle, Burbidge and others argued that the relativistic beaming interpretation still required velocities unrealistically close to the speed of light. Still today, the physics of the process by which highly-relativistic motions are attained and maintained remains elusive.

The arguments for non-cosmological redshifts lasted for several decades, and many conferences were held and books written to debate the issues. The apparent anomalies were argued to be the result of *a posteriori* statistics and in the case of redshift distributions, selection effects due to the limited number of strong quasar emission lines that could be observed combined with the narrow range of the observable optical window, and the blocking of certain spectral regions by night-sky lines. The arguments for non-cosmological redshifts only died when the proponents died or at least retired, but from time to time they still surface (e.g., Lopez-Corredoira, 2011).

8 INTERLOPERS, BLUE STELLAR OBJECTS, AND QUASI STELLAR GALAXIES

Soon after the discovery of quasars, it was realized that the optical counterparts were unusually blue. This suggested that quasars might be identified by their blue color only, without the need for very precise radio positions. In pursuing radio source identifications with 'blue stellar objects' (BSOs), Sandage (1965) noticed many BSOs that were not coincident with known radio sources, which he called 'interlopers' or 'quasi-stellar galaxies' (or 'QSGs'). In a paper received at the *Astrophysical Journal* on 15 May, 1965, Sandage estimated that the density of interlopers or QSGs was about 10^3 times greater than that of 3C radio sources. The Editor of the *Astrophysical Journal* was apparently so impressed that he did not send the paper to any referee and by delaying publication was able to rush the paper into publication in the 15 May issue of the *Journal*. Sandage's paper was received with skepticism, no doubt in part generated by what was perceived as privileged treatment of his paper.

Characteristically, Fritz Zwicky (1898–1974; Figure 11) immediately pointed out that

> All of the five quasi-stellar galaxies described individually by Sandage (1965) evidently belong to the subclass of compact galaxies with pure emission spectra previously discovered and described by the present writer. (Zwicky, 1965: 1293).

A few years later, Zwicky was less circumspect and wrote:

> In spite of all these facts being known to him in 1964, Sandage attempted one of the most astounding feats of plagiarism by announcing the existence of a major new component of the Universe: the quasi-stellar galaxies ... Sandage's earthshaking discovery consisted in nothing more than renaming compact galaxies, calling them 'interlopers' and quasistellar galaxies, thus playing the interloper himself. (Zwicky and Zwicky, 1971: xix).

Zwicky (1963) in fact did report at the April 1963 meeting of the AAS that the 'radio stars' are thought to lie at the most luminous end of the sequence of compact galaxies. However, his paper on the same subject was rejected by Subrahmanyan Chandrasekhar (1910–1995), the Editor of the *Astrophysical Journal* editor, who wrote that, "Communications of this character are outside the scope of this journal." (Zwicky and Zwicky, 1971).

Tom Kinman (1965), working at Lick, and Roger Lynds and C. Villere (1965) working at Kitt Peak, each concluded that most of Sandage's BSOs were just that, blue stellar objects, located in our Galaxy and not compact external galaxies. Today we do recognize that there is indeed a population of so called 'radio quiet' quasars, but they are only about an order of magnitude more numerous and three to four orders of magnitude less radio luminous than 'radio loud' quasars.

Interestingly, subsequent investigations later identified several extragalactic radio sources, such as 1219+285, 1514–241 and 2200+420, which had previously been erroneously catalogued as the galactic stars W Comae, AP Lib, and BL Lac respectively.

9 NOMENCLATURE

For the lack of any other name Schmidt and Matthews (1964) adopted the term 'quasi stellar radio sources'. This was quite a mouthful, so in a *Physics Today* review article Hong-Yee Chiu (1964) coined the term 'quasar'. This became widely used in oral discussions and in the popular media, but it was not accepted by the *Astrophysical Journal* until, in his 1970 paper on the "Space Distribution and Luminosity Function of Quasars," Schmidt (1970) wrote:

> We use the term "quasar" for the class of objects of starlike appearance (or those containing a dominant starlike component) that exhibit redshifts much larger than those of ordinary stars in the Galaxy. QSOs are quasars selected on the basis of purely optical criteria, while QSSs are quasars selected on both the optical and radio criteria.

Chandrasekhar, the Editor of the *Astrophysical Journal*, responded with a footnote saying:

> The *Astrophysical Journal* has until now not recognized the term "quasar"; and it regrets that it must now concede: Dr. Schmidt feels that, with his precise definition, the term can no longer be ignored.

The term 'quasar' has caught on and is now commonly used in both the popular and professional literature. However, as observations have been extended to cover the entire electromagnetic spectrum, and as improvements in technology have resulted in increasingly-detailed descriptions of both continuum and line spectra, variability, and morphology, quasars have become classified and sub-classified based on their line spectra, as well as their radio, optical, and high-energy spectral distribution. Optical spectroscopy and photometry have defined QSO1s, QSO2s, Broad Absorption Line quasars (BALs), LINERS, and BL Lacs, collectively referred to as QSOs. Radio astronomers have defined Flat Spectrum and Steep Spectrum Radio Quasars, Radio Loud and Radio Quiet Quasars. Radio Quiet quasars have been referred to as In-

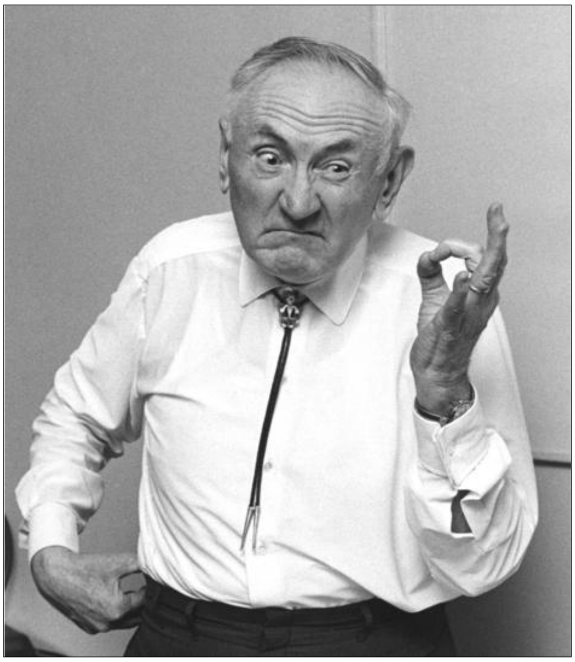

Figure 11: Fritz Zwicky (photograph: Floyd Clark; courtesy: Caltech Archives).

terlopers, QSGs, and BSOs. Relativistically-beamed quasars are known as blazars; X-ray and gamma-ray observations have defined High and Low Spectral Peaked Quasars. Collectively they are all known as Active Galactic Nuclei (AGN), although the term AGN was originally defined to describe the low luminosity counterpart to powerful quasars.

Further background on the early controversies surrounding the discovery of radio galaxies and their implications for cosmology can be found in the excellent books by Edge and Mulkay (1976) and Sullivan III (2009). Shields (1999) and Collin (2006) have given other accounts of the history of quasars and AGN, in particular the subsequent extensive development of the field over the past half century.

10 SUMMARY, UNCERTAINTIES, AND SPECULATIONS

Quasars and AGN are now a fundamental part of astrophysics and cosmology. The understanding that they are powered by accretion onto a supermassive black hole has had a profound impact on theories of galaxy formation and evolution, and also has motivated extensive research on black hole physics.

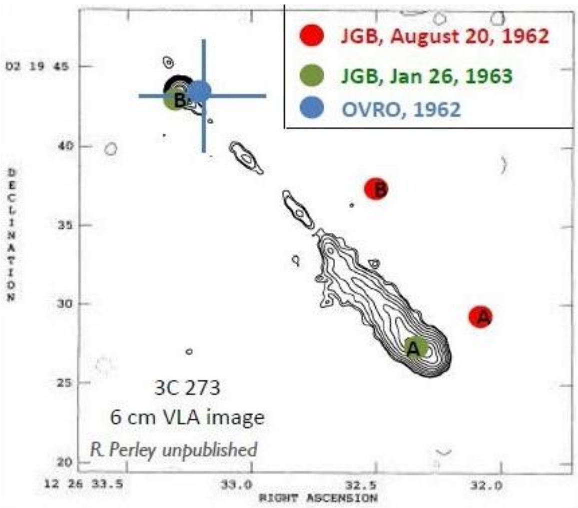

Figure 12: A 6-cm image of 3C 273 obtained with the VLA. Red dots show the location of components A and B as reported to Maarten Schmidt by John Bolton in a letter dated 20 August 1962. Green dots show the location of components A and B as reported by Bolton in his 26 January 1963 letter to Schmidt. The blue point with error bars represents the then-unpublished OVRO interferometer position.

Although both radio and optical astronomers were concentrating on small-diameter radio sources in their quest to locate high-redshift galaxies, the break-through occultation observations of 3C 273 in 1962 were unrelated to the quest for distant galaxies. Indeed, the known relatively-large size of the 3C 273 radio source apparently discouraged further optical investigation until the 1962 series of occultations. Although Bolton (1990) later claimed that the goal of the occultation observation was to determine whether the radio source was associated with the 'star' or the nebulosity, when writing to Schmidt in August 1962 about the occultation, why did he only communicate the radio positions, and uncharacteristically make no mention of the likely obvious optical counterparts. Indeed, he asked Schmidt to "... pass on to Tom [Matthews] the following positions." In his classic paper reporting the redshift, Schmidt (1963) thanked Tom Matthews for drawing his attention to the 13th magnitude 'star', although in a 2012 interview with the author, Matthews denied any involvement in the 3C 273 saga.

It remains unclear why the strong radio source 3C 273 was not identified earlier with its 13th magnitude counterpart. Clearly, Caltech was measuring sufficiently accurate radio source positions as much as two years earlier and had the resources to identify 3C 273 as early as 1961. Although the possibility of identification with apparent stellar objects was already well established with the identifications of the faint optical counterparts 3C 48, 3C 196 and 3C 286, the association with a 13th magnitude stellar object apparently was too extreme to seriously consider. The 19.5 magnitude galaxy first thought to be the optical counterpart of 3C 273 was observed by Schmidt in May 1962, although it was about 1′ west of the true position. Schmidt and the Caltech radio astronomers must have believed that the position error was not more than a few arc seconds, as that kind of accuracy would be required to accept an identification with a barely-detectable galaxy.

An accurate radio position was known among the Caltech radio astronomers perhaps as early as 1961, and certainly prior to Schmidt's May and December 1962 observations made with the 200-in telescope. It seems that somewhere along the line there may have been an error in conveying the OVRO radio position to the Caltech optical astronomers. Ironically, the position conveyed to Schmidt by Bolton on 20 August 1962 which was the basis of the spectrum taken by Schmidt in December was in error by about 15″ due to a wrong calculation by Hazard in determining the time of immersion and emersion during the August occultation. The correct position was not known by Schmidt until he received Bolton's 26 January 1963 letter, more than a month after he obtained the spectrum of the QSO on 29 December, 1962 (see Figure 12).

Thus it appears that the Parkes occultation position played no direct role in the identification of the quasar, which was only recognized as the optical counterpart after Schmidt's 200-in observations showed it to have a peculiar spectrum. Because it was known to be well resolved, 3C 273 had not been on the Caltech list of high-priority sources that might be at high redshift, so it would not have been observed by Schmidt in December were it not for John Bolton's August letter that motivated Schmidt to take the spectrum as the object rose just before the December morning twilight.

Sooner or later, probably sooner, 3C 273 would have been identified on the basis of the OVRO interferometer position, and should have been at least a year or two earlier. Interestingly, it was possible to recognize the 'large' redshift of 3C 273, not because it was large, but because it was so 'small' that the Balmer series was still seen within the small classical optical window. 3C 273 is probably unique in being the only quasar whose spectrum can be so easily determined without prior knowledge of the line identification. It is also somewhat unique in that the radio and optical morphologies are nearly identical, much as in the case of M 87. 3C 273 is the brightest quasar in the radio, IR and optical sky. It is widely believed that the apparent bright radio luminosity is due to relativistic beaming. Does that suggest that the IR and optical emission is also beamed?

The possibility that 3C 48 was a distant galaxy had been discussed by Bolton, Greenstein, Matthews and Bowen at least two full years before the identification of 3C 273. Bolton (1990) later claimed that he and the others apparently rejected the redshift because of a very small 3 to 4 Angstrom discrepancy in the calculated rest wavelengths of the broad emission lines. But, considering the broad nature of the emission lines this seems very unlikely. More probably, they were unwilling to accept the implied huge luminosity, just as Bolton, Stanley and Slee rejected the extragalactic nature of radio galaxies in 1949, and Minkowski later rejected the identification of Cygnus A. It was just too big a step to accept the paradigm-changing radio luminosity until it was forced by Schmidt's interpretation of the 3C 273 spectrum.

It may be relevant that while others were looking for distant galaxies, Bolton may have wanted to believe that he had discovered the first 'radio star' and collect on Greenstein's offer of a case of Scotch, and so 3C 48 played no direct role in the discovery of quasar redshifts. In the end, Greenstein (1963) offered Bolton a beer, but there is no record that Bolton ever accepted. Prior to Schmidt's February 1963 realization of the 3C 273 redshift, Greenstein along with Matthews and Sandage, had submitted separate papers to the *Astrophysical Journal* interpreting the 3C 48 spectrum as a galactic star. After Schmidt's discovery, Greenstein withdrew his paper, while Matthews and Sandage (1963) added a section based on the 0.37 redshift reported by Greenstein and Matthews (1963). Interestingly, on 25 January 1963, just one day prior to his communicating the revised occultation position to Maarten Schmidt, John Bolton gave a lecture to a group of undergraduate students on "Observing Radio Sources". Ron Ekers attended this lecture and his notes show that Bolton stated that "4 genuine radio stars have been identified." (pers. comm., March 2013).[4] At that time only three 'radio stars' were known, 3C 48, 3C 196 and 3C 286, so yet a month after Schmidt had obtained his spectrum Bolton apparently still considered 3C 273 to be among the class of galactic radio stars.

It is curious that John Bolton waited nearly 30 years before making a public claim to have recognized the redshift of 3C 48 two years before the series of *Nature* papers. It is also hard to understand, why Greenstein, apparently having been convinced that 3C 48 was his long sought 'first radio star', used only in-house Caltech publications, *Scientific American* and media releases to announce his claim to the 'first radio star' and did not publish in a refereed journal until after Maarten Schmidt's 1963 breakthrough.

The subsequent search for ever-larger redshifts following the 1963 understanding of the 3C 48 and 3C 273 spectra was highly competitive, particularly among the large optical observatories, but it also contributed to the increasing tensions between Caltech and Carnegie astronomers in Pasadena (see Waluska, 2007).

Currently, the largest-known quasar redshift belongs to ULAS J1120+064 with a redshift of 7.1 (Mortlock et al., 2011). However, it is now gamma-ray bursts and ULIRGs (Ultra Luminous Infra-Red Galaxies), not quasars, that are the most distant and the most luminous objects in the Universe, and gravitational lensing has enabled the detection of a starburst galaxy with a probable redshift of close to 10 (Zheng et al., 2012), well in excess of any known quasar. The controversy over cosmological redshifts was intense and personal and has had a lasting impact on the sociology of astronomy and astronomers.

11 NOTES

1. The date is erroneously given as 15 April in the Hazard et al. paper in *Nature*.
2. In his letter Greenstein (1996) claimed that Bolton played no role in the 3C 48 story and that it was Tom Matthews who first suggested that 3C 48 might have a high redshift. In an interview with the author on 28 April 2012, Matthews (Interview ..., 2012) explained that his early suggestion of a large redshift was based simply on the small angular size of the

radio source, but that once they had the optical identification, he too assumed it was a galactic star. See Section 5.

3. The 'CSIRO' is the Federal Government-funded Commonwealth Scientific and Industrial Research Organisation, and one of it's show-case Divisions was the Division of Radiophysics, based in Sydney, which was a world-leader in radio astronomy.
4. Papers of K.I. Kellermann (NRAO Archives).

12 ACKNOWLEDGEMENTS

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Dr Ken Kellermann is a Senior Scientist at the U.S. National Radio Astronomy Observatory where he does research on radio galaxies, quasars, cosmology and the history of radio astronomy. He did his undergraduate work at MIT and received his Ph.D. in physics and astronomy from Caltech in 1963, after which he spent two years in Australia at the CSIRO Division of Radiophysics. Aside from a two-year stint as a Director at the Max Planck Institute for Radio Astronomy in Bonn, Germany, and various shorter leaves in the Netherlands and back in Australia and at Caltech, he has been at NRAO since 1965. For many years he was active in the International Square Kilometre Array program. He currently works in the NRAO New Initiatives Office where he is involved in the development of new facilities for radio astronomy, and is the current Chair of the IAU Working Group on Historic Radio Astronomy.

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JOHN BOLTON AND THE DISCOVERY OF DISCRETE RADIO SOURCES

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Abstract: John Bolton was born in Sheffield in 1922 and educated at Cambridge University. After wartime service in the Royal Navy, in 1946 he joined the CSIRO's Radiophysics Laboratory in Sydney and began work in the fledgling field of radio astronomy. Radio emission from our Galaxy had been discovered and studied during the 1930s by the Americans Karl Jansky and Grote Reber. It was thought that the emission emanated from interstellar space, but the mechanism was unknown.

In June 1947, observing from Dover Heights near the entrance to Sydney Harbour, Bolton discovered that strong emission from the constellation of Cygnus came from a discrete point-like source. By the end of the year, with colleagues Gordon Stanley and Bruce Slee (a co-author of this paper), Bolton had discovered a further five of these discrete sources. However, the positions measured for them were not accurate enough to allow them to be identified optically with any known celestial objects.

In 1948 Bolton organised a three-month expedition to New Zealand where there were observing sites superior to the one at Dover Heights. The new observations gave more accurate positions and allowed Bolton to identify three of the sources: one was a supernova remnant in our Galaxy and two were unusual extragalactic objects. This paper will document this remarkable chapter in the development of twentieth century astronomy.

Keywords: John Bolton, Australian radio astronomy, discrete radio sources, optical identifications, sea interferometry, Dover Heights field station, Gordon Stanley, Bruce Slee

1 INTRODUCTION

The detection of radio waves from space in 1931 by the American physicist Karl Jansky was one of the most important discoveries of twentieth century astronomy. It opened a new 'window' in the electromagnetic spectrum through which astronomers could study the Universe. Jansky's discovery was followed up by a fellow American, the radio engineer Grote Reber, who produced maps of the intensity of radio emission across the sky. The third major breakthrough was made in 1947 by John Bolton and colleagues Gordon Stanley and Bruce Slee at the Dover Heights field station in Sydney. They were able to resolve some of the radio emission observed by Jansky and Reber into individual discrete sources. In 1949 they successfully identified three of these sources with unusual optical objects already known to astronomers. The identifications built a bridge between traditional optical astronomy and the fledgling new field of radio astronomy.

Before we examine this story in more detail, it will be useful to learn something of Bolton's background.[1] He was born in June 1922 in Sheffield, Yorkshire. Both his parents were school teachers, although his mother stopped teaching after John's birth. His parents made two unsuccessful attempts to start John at school, caused apparently by his unwillingness to accept the authority of the teacher. Fortunately there was a law in Yorkshire at this time that ruled it was not compulsory for a child to attend primary school if either parent was a teacher. John's mother taught him the basics, but otherwise Bolton was largely self-taught, reading whatever took his interest. He developed an independence of mind that seems to have

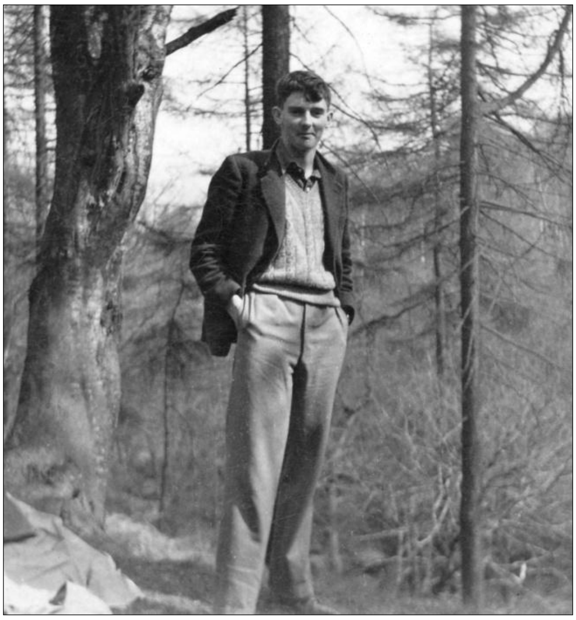


Figure 1: John Bolton at the time he entered Trinity College, Cambridge in 1940 (courtesy: Bolton family).

served him well during his career as a radio astronomer.

Bolton eventually entered primary school in grade 6 and then went on to Sheffield's leading secondary school. It was not until his final two years that he developed a special interest in physics and mathematics. He was fortunate to have his father, who was the senior mathematics teacher at another secondary school, as his tutor. In 1940 Bolton won two scholarships to study science at Trinity College, Cambridge (see Figure 1). Because of wartime conditions the normal three-year bachelor's degree was compressed into two.

Figure 2: Sydney localities mentioned in the text. Key: 1 = Collaroy, 2 = Dover Heights, 3 = Long Reef, 4 = Parramatta Observatory, 5 = Potts Hill, 6 = Radiophysics Laboratory, 7 = Georges Heights, 8 = West Head.

On graduating, Bolton joined the Royal Navy Voluntary Reserve. He spent two years carrying out research on airborne radar systems, first in Scotland and then at the Telecommunications Research Establishment in Worcester. In 1944 he was appointed radio officer on the British aircraft carrier *The Unicorn*, which saw out the remainder of the war on service in the Pacific. Bolton once remarked that his four years in the navy were far better preparation for his future career in radio astronomy than any Ph.D. program at a university (Robertson, 1984a).

At the end of the war Bolton decided not to return to England. After his discharge from the navy he applied successfully for a Research Officer position with the Radiophysics Laboratory in Sydney, a division of Australia's Council for Scientific and Industrial Research. The Radiophysics Laboratory, located in the grounds of the University of Sydney (for Sydney locations mentioned in the text see Figure 2), had been formed in 1940 to carry out secret research on radar for the Australian armed services. At the end of the war the Laboratory turned from wartime research to peacetime applications of radar and radio technology. As we see below, research in radio astronomy flourished in the Laboratory in the post-war years, largely through the activities of small groups of radio astronomers located at various field stations in or near Sydney. Observations also were carried out from the roof of the Radiophysics Laboratory, in central Sydney (see Orchiston and Slee, 2005; Robertson, 1992).

2 THE DISCOVERY OF EXTRATERRESTIAL RADIO EMISSION

To understand how Bolton's career developed during the post-war years, we need to go back to the beginning of radio astronomy some 15 years earlier (see Sullivan, 2009 for a comprehensive study on the origins of radio astronomy).[2] Many new fields of science have started as a result of serendipity, rather than design. Radio astronomy is a shining example. After graduating in physics, Karl Guthe Jansky (1905–1950; Sullivan, 1983; 1984a; 1984b) joined the Bell Telephone Laboratories in 1928 and was assigned the task of investigating sources of atmospheric static which might interfere with a new trans-Atlantic radio communication system. In 1931, at Bell's field station near Holmdel, New Jersey, Jansky constructed an aerial array mounted on four wheels with a small motor and chain drive which could rotate the array, a contraption which earned the name the 'merry-go-round' (Figure 3).

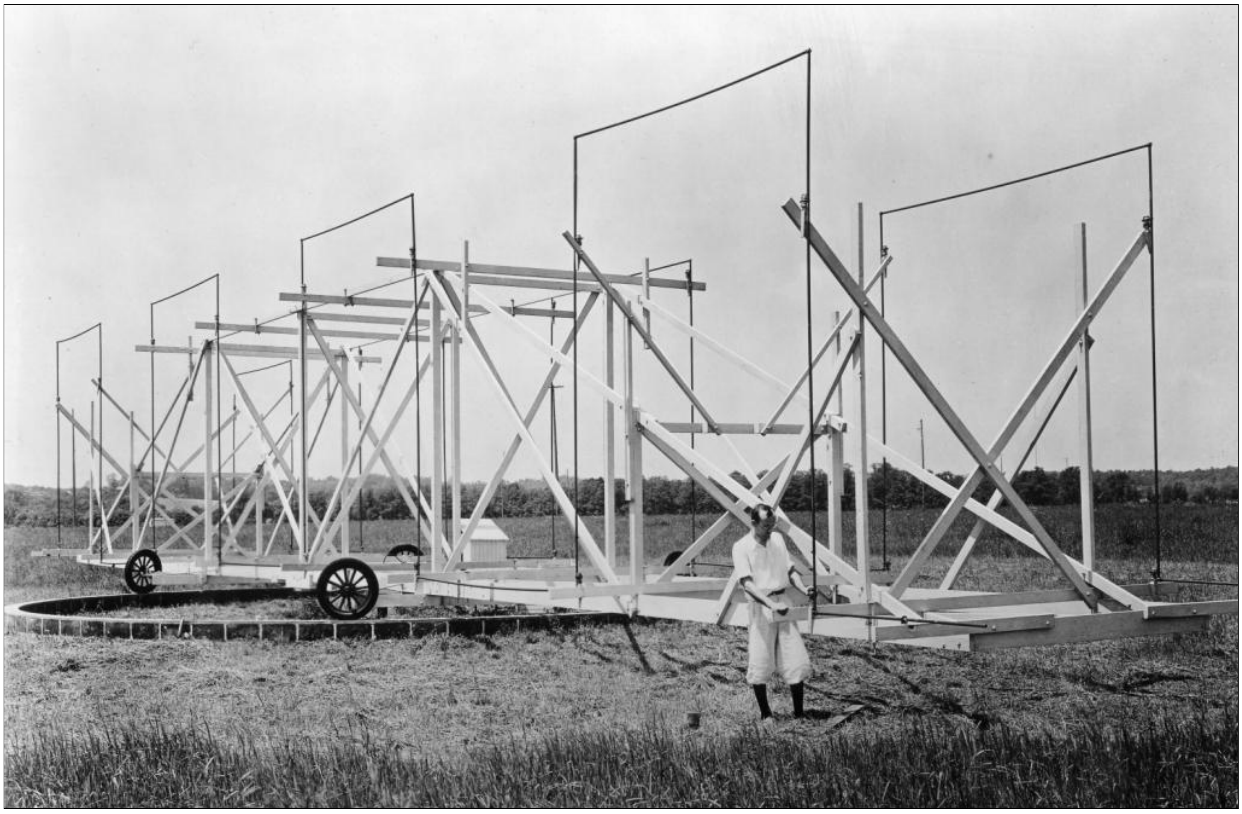


Figure 3: Karl Jansky and the 'merry-go-round' aerial used to discover extraterrestrial radio waves in 1931 (courtesy: AIP Emilio Segré Visual Archive).

Jansky was able to distinguish three distinct types of radio static. The first arose from local thunderstorms and the second was a weaker, steadier static due to the combined effect of many distant storms. The third type was composed of a very weak and steady hiss of unknown origin. Initially Jansky thought that the hiss was caused by some source of industrial interference, but then he noticed that the maximum strength of the signal came from a direction which moved around the sky each day and seemed to correspond roughly with the position of the Sun. The observations continued throughout 1932 and Jansky found that, contrary to what he first believed, the direction of the static began to drift further away from the position of the Sun. The daily period of variation of the noise was 23 hours and 56 minutes, known as the sidereal day, so Jansky concluded that the source of the noise must lie beyond the Sun, and beyond the Solar System as well. In his first two papers Jansky (1932; 1933) would cautiously state that the source of the 'cosmic static' comes from regions that are fixed with respect to the stars. Jansky continued observations for another year before publishing his final paper on the subject (Jansky, 1935). The distribution of the cosmic static across the sky was shown to approximately coincide with the distribution of stars, dust and gas visible along the plane of our Milky Way galaxy.

In 1936 Jansky's discovery was confirmed by Gennady Vasilyevich Potapenko (1894–1979) at the California Institute of Technology (Caltech) in Pasadena. Potapenko and his graduate student Donald Freeze Folland (1910–1998) built a receiver and antenna and they began observing on the roof of one of Caltech's buildings. However, Pasadena proved too radio noisy so they moved their equipment to the Mojave Desert where they succeeded in confirming Jansky's results, though their work was never published. They designed a new and much larger antenna, but were unable to find funding and the project did not go ahead (see Cohen, 1994 for details).

Although Jansky's work created some interest among astronomers, none of the US observatories followed up his discovery—primarily because no astronomer knew enough about radio engineering. The new science of radio astronomy might have fallen into limbo had it not been for the initiative of the young American engineer Grote Reber (1911–2002; Reber, 1983; 1984; cf. Kellermann, 2004; 2005). Reber read Jansky's research papers and understood their significance (Robertson, 1986). Jansky had exploited his discovery to the technical limits of his merry-go-round aerial, so Reber realised further progress would require the construction of new equipment specifically designed to observe the cosmic static. The best solution seemed to be a large parabolic reflector or 'dish' which could be accurately pointed to selected positions in the sky. Different radio frequencies could be investigated by changing the receiver placed at the focus of the dish (see Figure 4).

Reber's first attempts to detect radio emission from prominent objects such as the Sun, Moon, planets and several bright stars produced no response. He persevered and built a new receiver working at a frequency of 150 MHz. Early in 1939 he was rewarded by detecting the cosmic static along the plane of the Milky Way, thereby confirming Jansky's discovery (Reber, 1940). Reber then carried out detailed measurements of the variation in radio strength across the sky. In addition to the peak radio strength near the Galactic Centre, other subsidiary peaks were prominent in the constellations of Cygnus and Cassiopeia. While Jansky's discovery laid the first foundations for the new science of radio astronomy, Grote Reber became its first practitioner. His radio maps of the sky were not improved upon until the work of John Bolton and his group in the late 1940s.

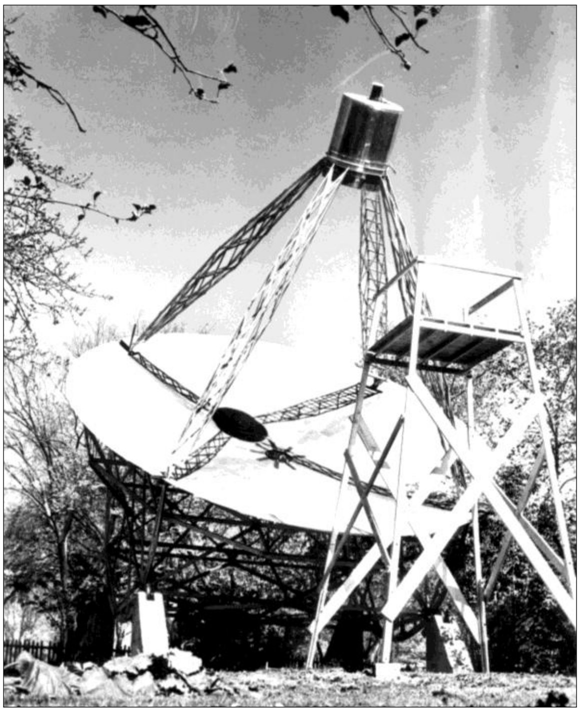


Figure 4: The radio telescope built by Grote Reber in his parents' yard in Wheaton, Illinois (courtesy: NRAO).

3 THE DOVER HEIGHTS FIELD STATION

Radio astronomy was not completely dormant during the war years. In fact, the next major development came, again through serendipity, as a direct result of wartime radar research. Late in February 1942 radar stations throughout England reported severe bursts of radio noise which had made normal operation impossible for several days. The War Office knew that the Germans had been developing methods of jamming radar and assigned James Stanley Hey (1909–2000) of the Army Operational Research Group the top priority task of investigating the problem. After an analysis of the records, Hey (1946) realised that the mysterious interference was not the result of enemy jamming, but came from a direction in the sky which seemed to coincide with the Sun. Hey checked with the Royal Greenwich Observatory and learnt that during the days of maximum interference an exceptionally active sunspot had been in transit across the solar disc. In his secret report Hey concluded that despite previous German successes in jamming British radar, this time the real culprit had been the Sun.[3] Across the Atlantic, at about the same time, George Clark Southworth (1890–1972; 1945) and a group at the Bell Telephone Laboratories—colleagues of Karl Jansky—made the same discovery, but they were working at a much higher frequency so only detected continuum emission, not solar bursts.

The existence of solar radio emission had been known in the Sydney Radiophysics Laboratory well before the end of the war, through the "... almost simultaneous arrival of three reports in the laboratory ..." (Payne-Scott, 1945) in mid-1945. One was Reber's (1944) paper in the *Astrophysical Journal*, and the other two were 'secret' wartime reports of independent radar detections by Hey in England and Elizabeth Alexander (1908–1958) in New Zealand (see Army Operational Research Group (1945) and Alexander (1945), respectively). In addition, both the Chief of the Radiophysics Laboratory, Edward George ('Taffy') Bowen (1912–1991), and senior scientist Joseph Lade Pawsey (1908–1962), had visited the Bell Telephone Laboratories and learnt of Southworth's (1945) work. Inspired largely by Alexander's New Zealand work with 200 MHz Royal New Zealand Air Force COL[4] radar antennas (see Orchiston, 2005a), in October 1945 (just two months after the end of the war) Pawsey and colleagues began their own solar observations using a Royal Australian Air Force 200 MHz COL radar antenna at Station 54 overlooking the sea at Collaroy, a northern Sydney suburb (see Orchiston et al., 2006). Success came immediately. Their observations not only confirmed the overseas reports, but then an analysis of certain features in the signals yielded a very surprising result. Even with sunspot activity at a minimum, the strength of the radio emission indicated that the Sun's corona was at temperatures as high as 10^6 degrees. Their results, anticipated on theoretical grounds by their Commonwealth Observatory colleague at Mt Stromlo, David Forbes Martyn (1906–1970; Martyn, 1946b), were summarised in the papers by Pawsey (1946) and Pawsey et al. (1946), both of which were published in *Nature*.

In their study of radio emission from sunspots Pawsey and his group introduced a technique known as sea interferometry (for an explanation of the technique see Figure 5, and Bolton and Slee, 1953). The technique is the radio analogue of Lloyd's mirror in classical optics, named after the Irish physicist Humphrey Lloyd (1800–1881). In 1834 Lloyd demonstrated that a monochromatic beam of light reflected from a glass surface, at a low angle of incidence, combines with the direct beam to produce an interference pattern, strong evidence at the time for the wave-like nature of light. The radio analogue was well known to wartime radar operators, including Bolton (Bickel, 1975). The direct radar beam received from distant aircraft combined with the beam reflected from the sea surface to produce an interference pattern. The pattern could be used to calculate the elevation of the aircraft above the sea surface, which often indicated whether the aircraft was friend or foe.[5]

John Bolton commenced work at the Radiophysics Laboratory in September 1946 and was assigned to Pawsey's solar group (Bolton, 1982). He was given the task of investigating the polarisation properties of sunspot radiation, a subject of particular interest to Martyn (1946a).[6] Bolton spent the first month designing and building an antenna in the Radiophysics workshop. The antenna consisted of two Yagi aerials, basically the same as the first television aerials. The antenna was mounted on a movable platform, so that it could track the Sun, and connected to a modified radar receiver operating at 60 MHz. Bolton installed the antenna at the Dover Heights field station near the entrance to Sydney Harbour (see Figures 6 and 7).

Bolton was assisted by another new recruit to Radiophysics, Bruce Slee (see Figure 8), who would become Bolton's first scientific collaborator. Owen Bruce Slee (b. 1924) had an interesting background leading up to his appointment. During the war he had worked as a radar mechanic at an RAAF station at Lee Point near Darwin. On several occasions late in 1945 he noticed that when the radar antenna faced west out to sea at sunset there was a sudden increase in radio noise, which he soon showed came from the Sun. Slee became yet another wartime radar operator to independently discover solar radio emission (Orchiston and Slee, 2002; Orchiston et al., 2006). After reading a newspaper article on the solar work at Radiophysics, Slee wrote to the Radiophysics Laboratory reporting his own discovery and enquiring whether there might be an opportunity to join the staff. Pawsey, now Head of the Radio Astronomy Group, was impressed and, following a meeting in Slee's home town of Adelaide, offered him a job on the spot. It was the beginning of a remarkable career. Slee started as a lowly technical assistant; studied evenings, eventually acquiring B.Sc. Honours and D.Sc. degrees; and worked his way up the ranks to become one of Australia's most distinguished radio astronomers (Orchiston, 2004; 2005b).

The attempt by Bolton and Slee to detect polarisation in the sunspot radiation was a failure. The Sun had entered a dormant period with no sunspots visible on its surface. However, Bolton had another idea. He had learnt of Jansky's discovery of cosmic noise while a student at Cambridge. He was also aware from his time as a radio officer on *The Unicorn* that pointing a radar aerial along the plane of the Milky Way would lead to a significant increase in the amount of radio interference. For most radar operators, Jansky's 'noise' was considered an operational nuisance rather than an important astronomical discovery. However, Bolton speculated that if the Sun can emit strong radiation, could there be other astronomical objects that contribute to Jansky's noise? Bolton and Slee pointed two of their Yagi aerials towards the eastern horizon to work as a sea interferometer, the same technique used earlier by Pawsey and his group to study sunspot radiation. They consulted an astronomy textbook and star atlas to guess which type of object might be a strong radio emitter. After a couple of weeks attempting to detect a number of objects as they rose above

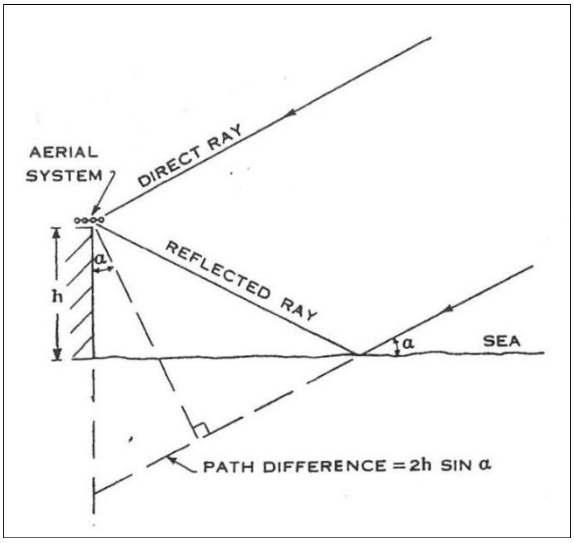


Figure 5: Radio astronomy began in Australia with the sea interferometer. The cliff-top aerial combines the direct signal with the signal reflected from the sea to create an interference pattern. These two signals produce maximum intensities when their path lengths differ by an even number of half-wavelengths 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: Fig. 1).

Figure 6: The Dover Heights field station in 1943, located 5 km south of the entrance to Sydney Harbour and overlooking the Tasman Sea to the east. The radar unit on top of the blockhouse was used for air warning during WW II. The 5 ha site, at an elevation of 79 m above sea level, was later to become one of the main CSIRO Radiophysics radio astronomy field stations. Despite its suburban location and the presence of a nearby road, the site proved suitably radio-quiet over the frequency range 40–400 MHz used for radio astronomy (courtesy: ATNF Radio Astronomy Image Archive (RAIA) B81-1).

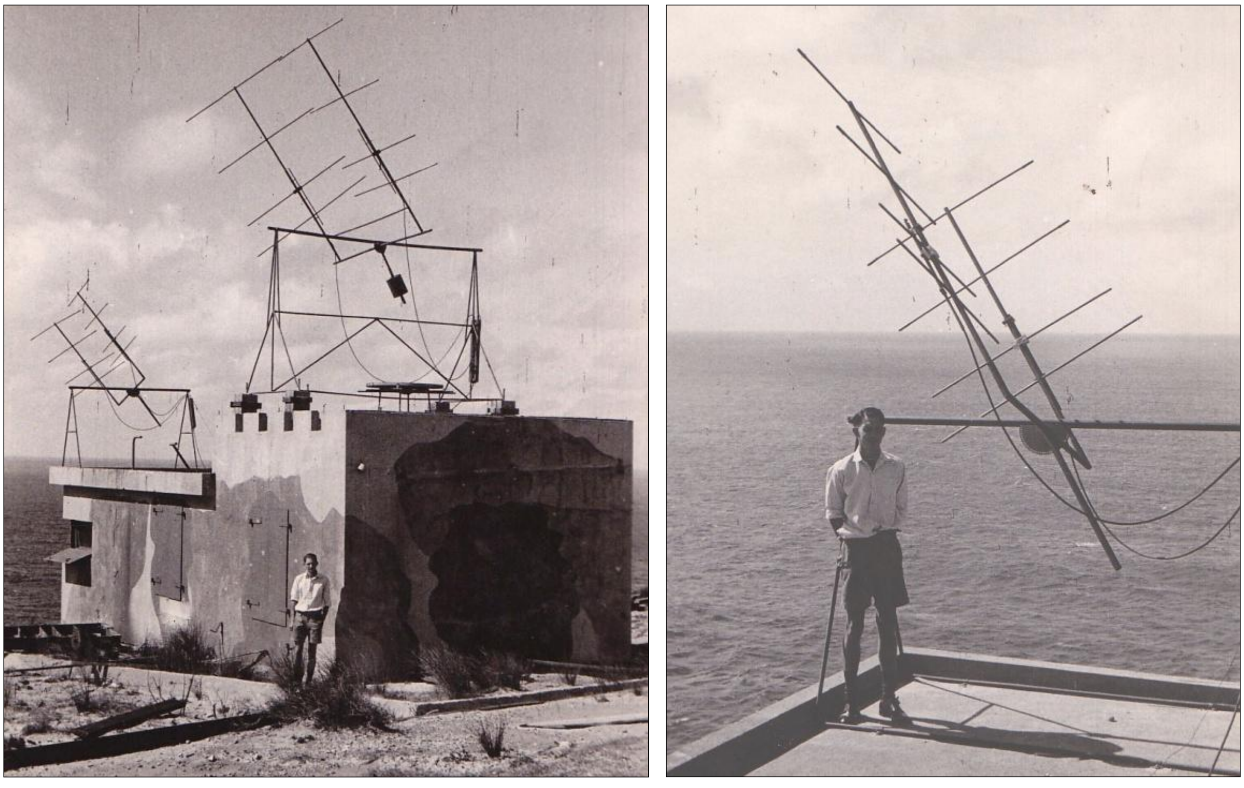


Figure 7: Bolton at the Dover Heights blockhouse in May 1947, a month before the detection of the Cygnus source. Left: Two of the twin Yagi antennas used for solar observations at 100 MHz (left) and 60 MHz. The Yagi pairs are perpendicular to each other to study the polarisation of the solar radiation. The 200 MHz antenna was on the far corner and is not visible. Right: The two elements of the 100 MHz Yagi could be positioned horizontally, pointing to the eastern horizon, to form a sea interferometer. This aerial was used for the discovery of the first eight discrete sources (courtesy: Stanley family).

the sea, the project was cut short by an unexpected visit from their boss Joe Pawsey who saw immediately that the aerials were not pointing at the Sun. Pawsey was not impressed by their insubordination and ordered the pair back to the Radiophysics Laboratory (Slee, 1994).

At the time Pawsey was planning an expedition to Brazil to observe a total eclipse of the Sun. The passage of the Moon across the solar disk would allow the location of the sunspot radiation to be measured with far greater precision than Pawsey could achieve with a sea interferometer. Pawsey reassigned Bolton to work with Gordon Stanley (1921–2001; see Figure 9) who was building equipment for the expedition. It was the start not only of a lifelong friendship, but also of a collaboration that would be the most important of both their careers. Gordon James Stanley was born in the small town of Cambridge, south-east of Auckland, New Zealand, in 1921. His father suffered from tuberculosis and so the family decided to move to the warmer and dryer climate of Sydney when Gordon was six. He left school early and joined a company that manufactured a wide range of electrical products, where he began to show an exceptional talent for understanding the operation of anything electrical. Dividing his time between work and study he earned his high school diploma and then a Diploma of Engineering from the Sydney Technical College (now the University of New South Wales). When the Pacific war broke out Stanley enlisted in the army for a period and then in 1944 he was transferred to the Radiophysics Laboratory where the authorities thought he would be of more value to the country's war effort (Kellermann et al., 2005).

As it turned out, the expense and the logistical difficulties of getting personnel and equipment halfway round the world to Brazil proved too great and the eclipse expedition was cancelled.[7] Bolton (1982: 350) later recalled:

> Towards the end of February 1947 Pawsey came into the room where Gordon and I were working and told us that the expedition to Brazil was not to take place. He then said, "If you can think of anything to do with all this equipment – you can have it." As he reached the door he turned around and, almost as an afterthought, and in typical Pawsey fashion, said, "If you can think of anything to do with Gordon – you can have him too!"

It was an opportunity too good to miss. Bolton and Stanley spent an afternoon loading up a truck with the eclipse equipment, together with tools, spares and test equipment, and next morning headed out to the blockhouse at Dover Heights. They managed to install two of the solar receivers, operating at 100 and 60 MHz (see Figure 7), when one of the largest sunspots seen for several years appeared on the Sun's limb and began its transit across the solar surface. The sunspot was inactive for almost a week until one afternoon when Bolton was about to start an observing shift. He heard the chart re-

Figure 8: Bruce Slee was John Bolton's first collaborator at Dover Heights. He trained as a radar technician and after serving at a number of radar stations in WWII, he joined the Radiophysics Laboratory in 1946 as a Technical Assistant (courtesy: Bruce Slee).

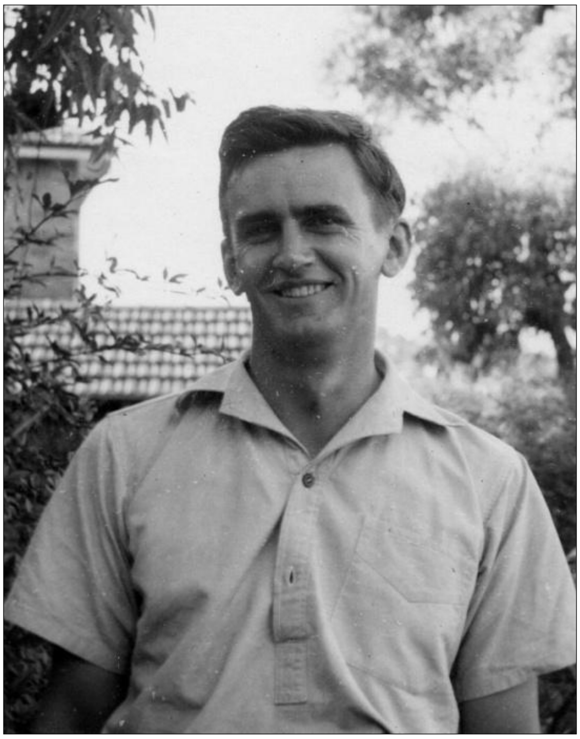


Figure 9: Gordon Stanley was John Bolton's other collaborator at Dover Heights, and they and Bruce Slee formed the team that discovered the first discrete radio sources. Stanley trained as an engineer and joined the Radiophysics Laboratory in 1944, where he specialised in receivers and electronics (courtesy: Stanley family).

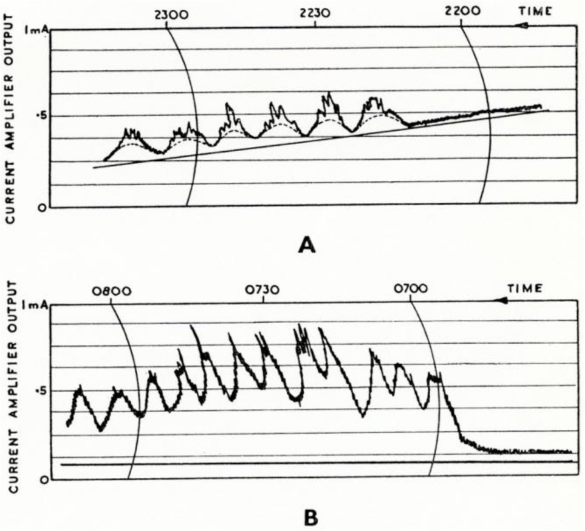


Figure 10: (A) The interference pattern for Cygnus A recorded at 100 MHz after 10 pm on the evening of 19 June 1947 at Dover Heights. The strength of the signal decreases (towards the left) as the source rises higher above the horizon. (B) For comparison, the interference pattern recorded from the quiet Sun at dawn on 24 June 1947 (after Bolton and Stanley, 1948b: 60).

corder for the 100 MHz antenna jump off scale and he moved quickly to turn the gain setting down as low as possible. After several minutes the strength of the signal began to decrease when suddenly the 60 MHz recorder also went off scale. After about 15 minutes the signal from both antennas had dropped back to normal.

Further work confirmed that the outburst was caused by a huge solar flare which generated intense radio emission first at the higher frequency of 200 MHz,[8] followed by intervals of several minutes to the lower 100 and 60 MHz frequencies. The explosive force of the flare ejected a column of ionised material out through the solar atmosphere at speeds of up to 1500 km per second. The arrival of the ionised material in Earth's atmosphere a day or so later caused auroral displays and strong magnetic storms. The following day a bright aurora could be seen in the Sydney sky, a rare event at this latitude (nearly 34° S) and demonstrating just how powerful the solar flare had been. The report on the flare event in *Nature* was Bolton's first research paper (Payne-Scott, Yabsley and Bolton, 1947).

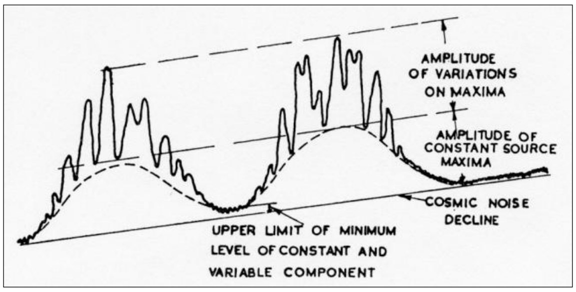


Figure 11: An enlarged section of the Cygnus record in Figure 10 showing how the maxima and minima of the constant and variable components are identified. The dashed curve results from the sinusoidal variation in path difference given by $2h \sin\alpha$ (see Figure 5). The relative heights of the maxima and minima in the dashed curve provide an upper limit on the angular size of the source (after Bolton and Stanley, 1948b: 63).

4 THE CYGNUS A 'RADIO STAR'

After the war Hey and a group at the Army Operational Research Group near London carried out a sky survey of radio emission at 100 MHz, producing isophote maps similar to those published earlier by Grote Reber (Hey, Phillips and Parsons, 1946). Hey and his group noticed that whereas radio signals from any given direction were relatively constant in strength, emission from the constellation of Cygnus exhibited peculiar fluctuations, changing in intensity during time intervals as short as one minute. In a paper reporting this discovery, Hey, Parsons and Phillips (1946) argued on physical grounds that this variable emission must come from a relatively small region of space, possibly from some unknown astronomical object. As we shall see in Section 6, this assumption turned out to be correct, but for the wrong reason.

In August 1946 the Chief of the Radiophysics Laboratory, 'Taffy' Bowen, was visiting England, and he sent Pawsey a reprint of the *Nature* letter by Hey's group and encouraged him to try to confirm the discovery. Within a few days Pawsey was able to report the detection of a variable source at both 60 and 75 MHz, with the fluctuations similar in appearance to the bursts observed in solar noise. Pawsey continued the observations hoping to find the cause of this surprising phenomenon. The initial success, however, seems to have been followed by a period of conflicting observations, during which the reality of the Cygnus fluctuations came into question. In the end Pawsey gave up observing Cygnus, not knowing what to make of Hey's claim (Sullivan, 2009: 139).

Later, in May 1947, Bolton and Stanley were at Dover Heights when the Sun again entered a phase of low activity. They decided to return to the topic which Pawsey had brought to an abrupt halt six months earlier. Pawsey had said they could use the Brazil equipment for any purpose they liked, so they would take him at his word. By day they would continue routine monitoring of the Sun, but at night they would renew the search for other radio objects in the sky. To begin with, they decided to see whether they could find Hey's anomalous source in Cygnus.

Early in June 1947 Bolton and Stanley succeeded in detecting this source on their first attempt, using the 100 MHz antenna shown in Figure 7. The signal was not as strong as the solar bursts they had been observing, but the source did produce the distinctive fringe pattern on their chart recorder (see Figures 10 and 11). They continued the observations as the source rose each night and, by the end of June, they had enough data for Bolton to give a brief talk at the Radiophysics Laboratory, with the title "Variations in cosmic noise from the constellation Cygnus". He could report that the source had been detected at 100 and 60 MHz, but not yet at 200 MHz, and he gave an approximate position for the source which differed by about 3° from the one listed by Hey. There was also a hint of a much weaker source further south.[9]

Two weeks later Bolton (1947) reported to David Martyn:

> Work on Cygnus has progressed quite well. The exact locality of the source is not known with sufficient accuracy yet. The approximate position is RA 20 hours, declination 40 deg, but errors are still of the order of 3 minutes in RA and 20 minutes in declination. A further attempt at localisation is going to be made this week. As you know, the source is rather variable and I am at present studying these factors. I hope to be able to have the general features a bit clearer before the joint colloquium at the end of July. The size of the source is certainly less than 8 minutes; again further investigations are proposed for a more accurate determination.

The most important value in the letter is the upper limit to the angular size of the source, which Bolton derived from the interference fringes, using the following formula:

$$W = (\lambda/\pi h)\,(3R)^{1/2} \qquad (1)$$

where W is the equivalent radiating strip, λ is the wavelength, h is the height of the cliff where the sea interferometer is located, and R is the ratio of the heights of the interference fringe maxima and minima above an extrapolated cosmic drift background level. Bolton's value of <8′ was an improvement by a factor of 15 on the value arrived at by Hey's group. The beamwidth of Hey's aerial was 2°, meaning that the aerial could not resolve any detail smaller than a patch of sky equal to about four times the angular width of the Moon. Hey had argued that the Cygnus source was most likely compact because of the rapid variation in its signal strength. Whereas Hey had *inferred* a small size, the Dover Heights data provided the first *proof* that Cygnus was indeed a compact star-like object. The existence of the first 'radio star', the first discrete radio source, had now been established. Years later, Bolton explained how the ratio of fringe maxima to minima provided an upper limit for the angular size of the source (Bickel, 1975):

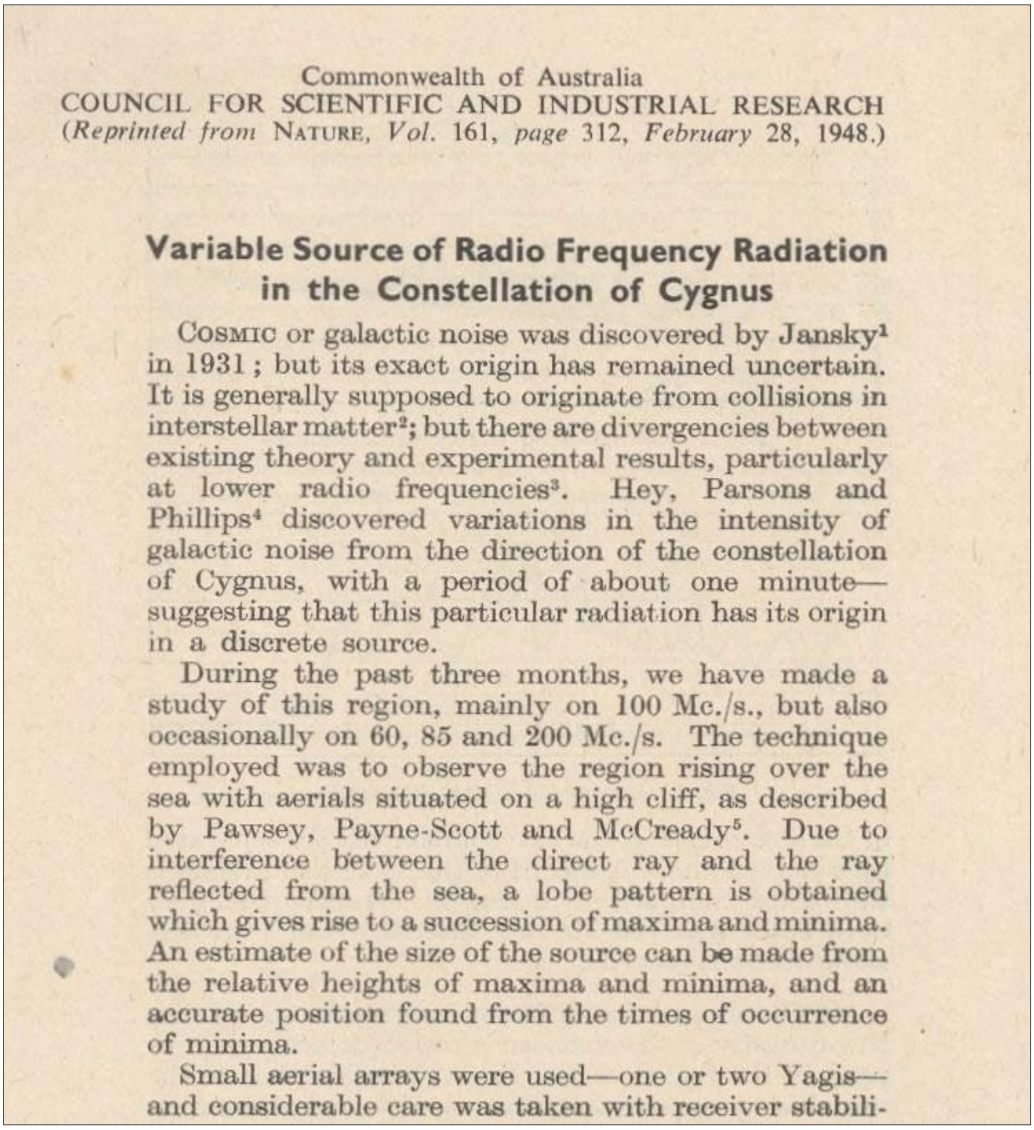
> I can give a crude analogy. If you have a picket fence and you roll a marble up and down over the pickets, the marble will describe almost exactly the form of the top of the picket fence. If you take a tennis ball, then it doesn't go up and down as far. If you take a basketball, you might as well be running it over a flat plane. There's an analogy in the sea interferometer. If the source is larger than the separation between the maxima or minima, then it won't give you a pattern. If it's intermediate, it will give you a minimum which is not a perfect minimum, a maximum which is not a perfect maximum. So we were immediately able to say, "We've got an upper limit on its diameter".

The main priority now was to measure a more precise right ascension and declination for the source, as the approximate position reported by Bolton in his talk was far too imprecise to be able to identify the source with a visible object. Both coordinates could only be measured with any accuracy by observing the source setting in the north-west and combining the data with Cygnus rising in the north-east at Dover Heights.

Early in July 1947 Bolton and Stanley towed a trailer fitted out with their 100 MHz antenna to two headlands north of Sydney. The first of the sites, known as Long Reef near the suburb of Collaroy (see Figure 2), had an elevation of only 30 metres above sea level, but it had the advantage of covering the whole hour angle range from rising to setting. Observations made over a week enabled them to measure an approximate right ascension accurate to ±1 minutes. It was difficult work and there was no option but to camp out mid-winter to guard against their equipment being stolen or vandalized.

The second site further north was an isolated promontory called West Head (see Figure 2), accessed by a dirt track in the rugged Ku-Ring-Gai Chase National Park. The site was at an elevation of 120 m above sea level (50% higher than Dover Heights) and overlooked the wide estuary of the Hawkesbury River. A nearby island and opposing cliffs blocked most of the hour angle track, but Cygnus could be observed for a couple of hours both before and after culmination. The approximate right ascension from the Long Reef site could then be used to identify the corresponding fringe minima at the second site. The elevation path of Cygnus was then reconstructed by plotting the elevations of fringe minima (corrected for refraction and Earth curvature) against sidereal time. The declination was then computed from the latitude of West Head and the duration of the semi-diurnal arc. This process was repeated on a number of nights and the derived positions were averaged to give the final position.

By September 1947, after three months of observations, Bolton and Stanley had enough data to publish. Taffy Bowen thought that the Cygnus discovery was important enough to be published in the *Proceedings of the Royal Society of London*, the most prestigious science jour-



Commonwealth of Australia
COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH
(*Reprinted from* NATURE, *Vol.* 161, *page* 312, *February* 28, 1948.)

Variable Source of Radio Frequency Radiation in the Constellation of Cygnus

COSMIC or galactic noise was discovered by Jansky[1] in 1931; but its exact origin has remained uncertain. It is generally supposed to originate from collisions in interstellar matter[2]; but there are divergencies between existing theory and experimental results, particularly at lower radio frequencies[3]. Hey, Parsons and Phillips[4] discovered variations in the intensity of galactic noise from the direction of the constellation of Cygnus, with a period of about one minute—suggesting that this particular radiation has its origin in a discrete source.

During the past three months, we have made a study of this region, mainly on 100 Mc./s., but also occasionally on 60, 85 and 200 Mc./s. The technique employed was to observe the region rising over the sea with aerials situated on a high cliff, as described by Pawsey, Payne-Scott and McCready[5]. Due to interference between the direct ray and the ray reflected from the sea, a lobe pattern is obtained which gives rise to a succession of maxima and minima. An estimate of the size of the source can be made from the relative heights of maxima and minima, and an accurate position found from the times of occurrence of minima.

Small aerial arrays were used—one or two Yagis—and considerable care was taken with receiver stabili-

Figure 12: Part of the first page of the letter by Bolton and Stanley announcing the discovery of the discrete source in Cygnus. The letter to *Nature* was submitted on 4 December 1947 and published on 28 February 1948 (after Bolton and Stanley. 1948a).

nal in the British Commonwealth. However the 'Royal', as it was known, was experiencing publication delays of over a year and there was a danger that the Cygnus discovery might be 'scooped' by another group. After some debate it was decided to make a brief announcement in *Nature* (see Figure 12), followed by a detailed paper in the new *Australian Journal of Scientific Research* (see Bolton and Stanley, 1948a; 1948b). The *AJSR* was about to be launched by CSIR Head Office in Melbourne and would be the first nationwide science journal published in Australia. The Cygnus paper appeared in the first issue of volume 1, early in 1948. A brief announcement letter in *Nature*, followed by a detailed *AJSR* paper, became the standard publishing practice for the Dover Heights group over the following years.

The *AJSR* paper reported the detection of the source at 60, 85, 100 and 200 MHz, providing the first spectrum of the source. The position given for the Cygnus source was

> Right ascension: 19 hr 58 min 47 sec ± 10 sec Declination: +41° 47′ ± 7′,

a vast improvement on Hey's position which was known to no better than 5° accuracy. Bolton and Stanley (1948b: 68) announced that the angular width of the source was less than 8′ of arc and that its radio emission had two components, one believed constant, and the other showing considerable variations with time. In the discussion of their results they noted:

> Reference to star catalogues, in particular the Henry Draper Catalogue, shows that the source is in a region of the galaxy distinguished by the absence of bright stars and objects such as nebulae, double and variable stars, *ie. the radio noise received from this region is out of all proportion to the optical radiation*. Although the experimental technique allows only an upper limit to be placed on the size of the source, this is believed to be effectively a point

> and therefore a single object. The determined position lies in a less crowded area of the Milky Way and the only obvious stellar objects close to the stated limits of accuracy are two seventh magnitude stars. There is certainly no comparable optical radiation from this region. (our italics).

Astronomers at the Commonwealth Observatory near the nation's capital, Canberra, carried out a close examination of this region and produced a photographic plate that confirmed the Draper Catalogue. There were two unremarkable stars of seventh magnitude close to the position, but no object that appeared in anyway unusual. The identity of the Cygnus source would remain a mystery for some time to come.

To conclude their paper, Bolton and Stanley (1948b: 69) speculated on a possible emission mechanism for the source. They noted that if its size was <8′, the effective temperature at 100 MHz would be greater than 4 × 10^6 K, making a thermal origin of the radiation improbable. Instead, they noted that a mechanism similar to the one proposed "... to account for the steady enhanced noise from a large active sunspot – perhaps the association of moving ionised matter and strong magnetic fields – is quite possible." This was a prescient prediction of the synchrotron emission mechanism, which was verified by theoretical work in the early 1950s (see Ginzburg and Syrovatskii, 1965).

The Cygnus results caught the attention of a number of prominent astronomers overseas. In September 1947 Joe Pawsey embarked on a year-long trip to the United States and Europe. Pawsey's first stop was to the Mt Wilson Observatory near Pasadena, home to the 100-in Hooker Telescope, the largest in the world (but soon to be overtaken by the 200-in Hale Telescope on Palomar Mountain). Pawsey (1947a) reported to Bolton and Bowen:

> I discussed the Cygnus work in some detail with the Mt Wilson people and found them intensely interested. They immediately searched out the region given in Bolton and Stanley's paper but found nothing. Further, they promised to take further relevant photographs. I consider this collaboration is very worth while and told them we would be very happy to work in with them. At present, I think this collaboration will simply involve exchange of information.

This source became of special interest to Rudolph Minkowski (1895–1976), who would later play a significant role in Bolton's career.

In November, Pawsey visited the Yerkes Observatory near Chicago and held discussions with its Director, Gerard Kuiper (1905–1973), and two visiting astronomers, Jan Oort (1900–1992) from Leiden Observatory and Bengt Strömgren (1908–1987) from Copenhagen Observatory. As Pawsey (1947b) reported to Bolton:

> These people were exceedingly interested in your work on Cygnus. In fact, we had a session which lasted nearly three hours, so you see, your work is appreciated. Out of that discussion came one suggestion which I think you should consider. One of them suggested that it is possible that the fluctuations in the source are due to the refractive effects in the ionosphere, causing fluctuations analogous to the twinkling of stars … I don't think that this explanation is correct, but I do not have enough evidence to exclude it, and I should advise you to think it over rather carefully. If you do not have observations which can be used to check this possibility, I suggest that it might be worthwhile doing a spaced receiver experiment because this seems to be a fairly direct method of testing the suggestion.

Later correspondence reveals that it was Kuiper who had argued that the ionosphere might be the cause of the fluctuations (see Pawsey, 1948b).

Early in 1948 Bolton and Stanley took up Pawsey's suggestion and carried out further observations at 100 MHz at the West Head site, about 25 km north of Dover Heights. A comparison between the signals recorded at both sites showed a good correlation between the rapid fluctuations, confirming Bolton's own view that the fluctuations were intrinsic to the source and not caused by the ionosphere. As it turned out Bolton was wrong (see below). With the West Head site almost due north of Dover and, with Cygnus relatively low on the northern horizon, the signals at each site essentially passed through the same column of the ionosphere. If the observations had been done instead with 25 km separation in an east–west direction, there probably would have been a poor correlation between the source fluctuations at each site.

5 A NEW CLASS OF ASTRONOMICAL OBJECTS

Bruce Slee rejoined the Dover Heights team in September 1947 to assist Bolton and Stanley with improvements to the receivers and antennas. The operation of equipment needed to be monitored at all times and there were routine tasks to perform such as maintaining the flow of paper to the chart recorder. Another task for the observer was to monitor the total power deflection on the recorder chart, which varied according to the galactic latitude, so that frequent adjustment of the recorder pen was often necessary. Security was another issue. Earlier when the solar flare observations were in progress the blockhouse had been left unattended at night. Even though the site was fenced off and a caretaker lived on site, on several occasions vandals had climbed onto the blockhouse roof and damaged the antennas. To guard against further damage a fringe of barbed wire was installed around the roof, and the external ladder was removed and replaced by an internal one with a steel hatch. A new steel door and steel shutters on the windows completed the vandal-proofing.

In parallel with the Cygnus observations the search continued for other possible radio sources by scanning the sky at different declinations and looking for the tell-tale interference pattern. Early in June 1947, even before the initial detection of Cygnus, Bolton and Stanley thought they had found a source in Centaurus. However, repeated attempts to confirm the detection proved a frustrating failure. It soon became apparent that —if indeed other sources did exist—the sensitivity of the antenna systems was not good enough to pick out sources from the background noise. Short time variations in the receiver noise were drowning out any signals fainter than the strong Cygnus source. Stanley made the crucial breakthrough in October when he developed a high-tension power supply that eliminated most of the noise variations in the receivers. The receiver output was stable to about one part in several thousand, so much fainter signals could now be detected. Early in November a second source was detected, in Taurus, followed early in December by a third in Coma Berenices and then a fourth in Centaurus. Taffy Bowen (1947a) wrote excitedly to Pawsey, who was in Washington, DC:

> Bolton has now discovered *three* more discrete sources of cosmic noise, two in Taurus and one near the north galactic pole. The intensities of the former are about one-fifth that of Cygnus, the latter one-fiftieth. He is quite certain of the results but not too sure of their position as yet. We are naturally very excited about this and Bolton is pushing it as hard as he can … I think, too, it would be wise not to be too specific about them in the US and UK until Bolton has had a chance of finalising his observations and getting them published. I will be sure to keep you informed of progress. (his italics).

Pawsey (1947b) assured Bolton that he was being non-committal when questioned about the existence of further sources:

> I hope your work is progressing very satisfactorily at Dover. I have heard from Bowen of the new sources which you think you have discovered, and this sounds very interesting indeed. With regard to discussions over here, I am simply saying that you suspect there are other sources, but are not sure yet of the results. It might be worthwhile at a fairly early stage, discussing the location of these new sources with the Mt Wilson people. I think they are the best crowd to collaborate with in this work, but I shall leave this for you people in the laboratory to decide.

By Christmas 1947 a fifth and a sixth source had been added to the list. It had been a vintage year for the Dover Heights group. It began in March with the lucky observation of a giant solar flare and was followed by the discovery in June that Cygnus is a point-like source. Evidence was now emerging for the existence of a whole new class of objects previously unknown to astronomers.

In March 1948 Bolton took a break from searching for new radio sources. He married Letty Leslie at Sydney's Registry Office and they spent their honeymoon on an island resort in the Whitsundays in Queensland. The couple had met in 1946 before Bolton's discharge from the navy and no doubt Letty was an important reason why John had decided not to return to England. Letty had first married Ernest Leslie in 1940 and they had two sons (who later John would formally adopt). Ernest went to England where he trained to be a navigator in the Royal Air Force. During a raid on a German submarine base his aircraft was shot down over France, killing all but one of the crew members.

In early April 1948 Bolton wrote up a further *Nature* paper on the new sources (Bolton, 1948a). Aside from Cygnus, six new sources were now known at 100 MHz and approximate positions had been found for three of them (see Table 1). All six were weaker than Cygnus, with radio intensities ranging from 0.25 down to 0.03 that of Cygnus. Initially Bolton named each source in the order it was found, followed by the year it was found; thus, source 1.46 corresponded to Cygnus, 2.47 to Taurus, etc. Later, this convention was dropped in favour of naming each source

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

Temporary Designation[A]	Position		Flux at 100 MHz (Jy)[B]	Angular Width	Type
	R.A.	Dec.			
Cygnus A (1.46)	19h 59m	+41° 47′	6000	< 8′	Variable
Taurus A (2.47)	05h 13m	+28°	1000	< 30°	Variable?
Coma Berenices A	12h 04m	+20° 30′	1500	< 15′	Constant
Hercules A (7.48)	16h 21m	+15°	200	< 1°	–
8.48	–	–	200	–	Constant
5.47	–	–	300	< 1°	Constant
Centaurus A (6.47)	–	–	1000	< 15′	Variable?

[A] A second source in Taurus (3.47) was later shown to be fictitious. Coma Berenices A (4.47) was later renamed Virgo A (see next section).

[B] The source intensities were originally given in SI units where 1 Jy ≡ 1×10^{-26} W m^{-2} Hz^{-1}.

after the constellation where it was found, followed by a letter A, B, … to indicate that it was the strongest, second strongest source, etc., in that constellation. This naming convention was quickly adopted by radio astronomers around the world and it is still partly in use today.

When writing up the *Nature* paper Bolton was advised by David Martyn at Mt Stromlo to simply present the data on the new sources and not to engage in speculation on their possible nature (Bolton, 1948b). However, Bolton felt that because the Dover group had discovered the sources he had as much right as anyone else to put forward ideas. With Bowen's blessing, half the paper was a discussion of the possible origin and distribution of galactic radiation. As Bowen (1948) informed Pawsey:

> After a few delays here and at Head Office we have finally sent off Bolton's letter to *Nature* about his new sources of cosmic noise … You will see that in addition to the experimental data he has had a fling at interpretation. We debated this a little and finally decided it couldn't do much harm in a letter to *Nature* and might do some good.

Bolton proposed that the radiation had three components, the first being the free-free transitions of charged particles in interstellar space, the mechanism favoured earlier by Reber and others [see Sullivan (2009), Section 15.2.1]. The second component was the aggregate of emissions from individual stars in regions of high star density. For the third component:

> 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. Purely electromagnetic disturbances as an origin of these have been discussed by several writers, and the following additional possibilities are envisaged: (*a*) A pre-main sequence model consisting of a large cool gas sphere, gravitational energy of contraction being radiated in the radio frequency spectrum. (*b*) A post-main sequence model – possibly a development of the planetary nebula consisting of an intensely hot central star, with its radiation in the far ultraviolet, surrounded by a shell of predominantly stripped atoms.

Both pre- and post-main sequence models may have seemed plausible at the time, but neither turned out to be correct.

6 THE EXPEDITION TO NEW ZEALAND

The overriding priority was now to measure precise positions for the new sources in the hope of identifying some of them with known optical objects. A relatively accurate position for Cygnus A had been found by observing the source at Dover Heights and West Head. However, the six new sources were all at declinations well south of Cygnus A. At West Head some of these sources would rise and set over land, rather than the Hawkesbury estuary, and so a suitable fringe pattern could not be obtained. Bolton began scouting around for a new and better site. An island near Coffs Harbour, north of Sydney, was briefly in contention, but it soon became apparent that there was nothing suitable on the eastern seaboard of Australia. Lord Howe Island and Norfolk Island in the Tasman Sea were also investigated, but the best candidate appeared to be the region close to Auckland in New Zealand where there were exceptionally high cliffs on both the east and west coasts (Orchiston, 1993; 1994; Stanley, 1994). Bowen (1947b) officially launched the expedition by writing to the Surveyor-General of New Zealand in the capital city of Wellington:

Figure 13: The ex-Army radar trailer in the grounds of the Radiophysics Laboratory. This mobile radio telescope featured four Yagi aerials, a new 100 MHz receiver, recorders, chronometers, weather recording instruments and all the tools and backup equipment needed to operate reliably at a remote location. We were not able to establish the identity of the lady in the photograph (courtesy: RAIA B1259).

> We are planning to make a special series of observations of cosmic noise from the constellation of Cygnus and find that there is no site readily available in Australia for this purpose. It appears that we are much more likely to find a suitable spot in New Zealand, possibly in the North Auckland area, and we would be very much obliged if your Department could supply maps and some information relating to this area … Such a position should be accessible by a three-ton military trailer, ie. road unnecessary if country between road and site is flat or slightly undulating with firm ground.

Bolton decided the expedition would start in June 1948 primarily because Cygnus A, the main target of the trip, would rise in the evening about 10 pm and set about 4 am, the optimum times for making accurate observations. Most of the other sources would have at least one rise or set time at night. Stanley spent April and May converting an ex-Army radar trailer into a mobile observatory (see Figure 13). Five sites on the North Island were investigated with Cape Reinga on the northern-most tip considered to be

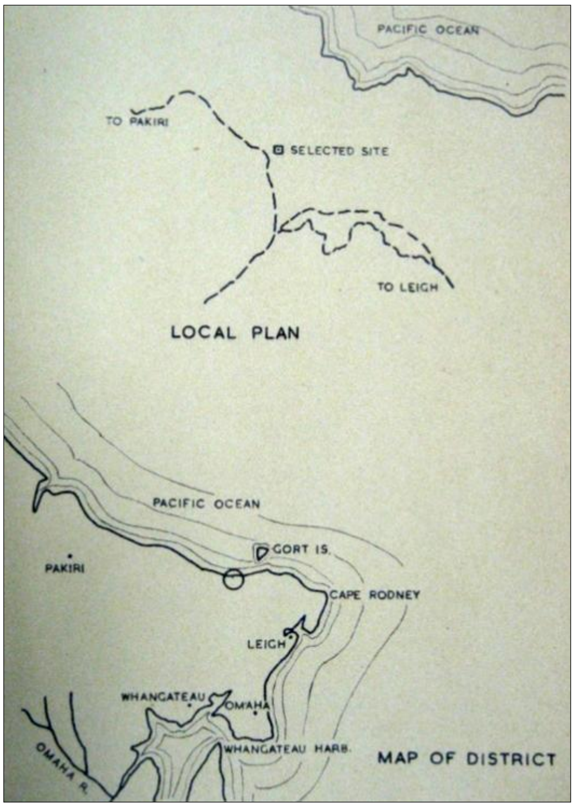


Figure 14: The observing site at Pakiri Hill north of the Leigh township showing the local plan (*above*) and a map of the district. The coastline at the site runs approximately east-west and allowed Cygnus to be observed rising in the north-east and setting in the north-west (courtesy: National Archives of Australia).

the best, but then ruled out because of poor road access and, with the nearest town 100 km away, just too isolated. Instead, two sites were chosen near the city of Auckland, one on the east coast and the other on the west coast.

For the east-coast observations a sheep farm in an area known as Pakiri Hill was chosen, just north of the small coastal town of Leigh and about 70 km north of Auckland (see Figure 14). At an elevation of 280 metres, the site was over three times the height of the Dover cliffs, which meant that the angular resolution of the sea interferometer would be over three times better. This section of the coastline ran roughly east–west which would give a view of Cygnus A rising in the north-east and setting in the north-west. The North Auckland Land and Survey Board surveyed the exact spot where the trailer would be parked. The longitude and latitude were known to an accuracy of 10 metres, while the elevation above mean sea level was measured to an accuracy of 25 cm. The site was excellent, but not perfect. An island group to the north-west cut off some of the setting, but otherwise Cygnus A could be observed throughout its six-hour transit across the northern sky.

The trailer was shipped to Auckland at the end of May, with Stanley flying over to arrange for its transport to the Pakiri Hill farm (Figure 15). Bolton arrived a week later and introduced himself to the Greenwood family who had owned the farm since the first European settlement of the district in the 1860s. Bolton (1948c) was able to report to Bowen:

> When I arrived at Leigh a week last Sunday I found the trailer on site but with no power, Stanley with a very bad cold, myself with an incipient one and a public holiday the following day. Since then I am pleased to say things have gone better … Cooperation both official and unofficial has been magnificent. The farmer on whose land we are sited has raised no objection to us using his timber, digging holes in his paddocks etc. – in fact has done everything to assist. They even brought us tea and sandwiches at five o'clock in the morning on the last two nights – for which we are very grateful. Nine hours at a stretch without Dover's comforts is just a little tough.

Figure 15: 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).

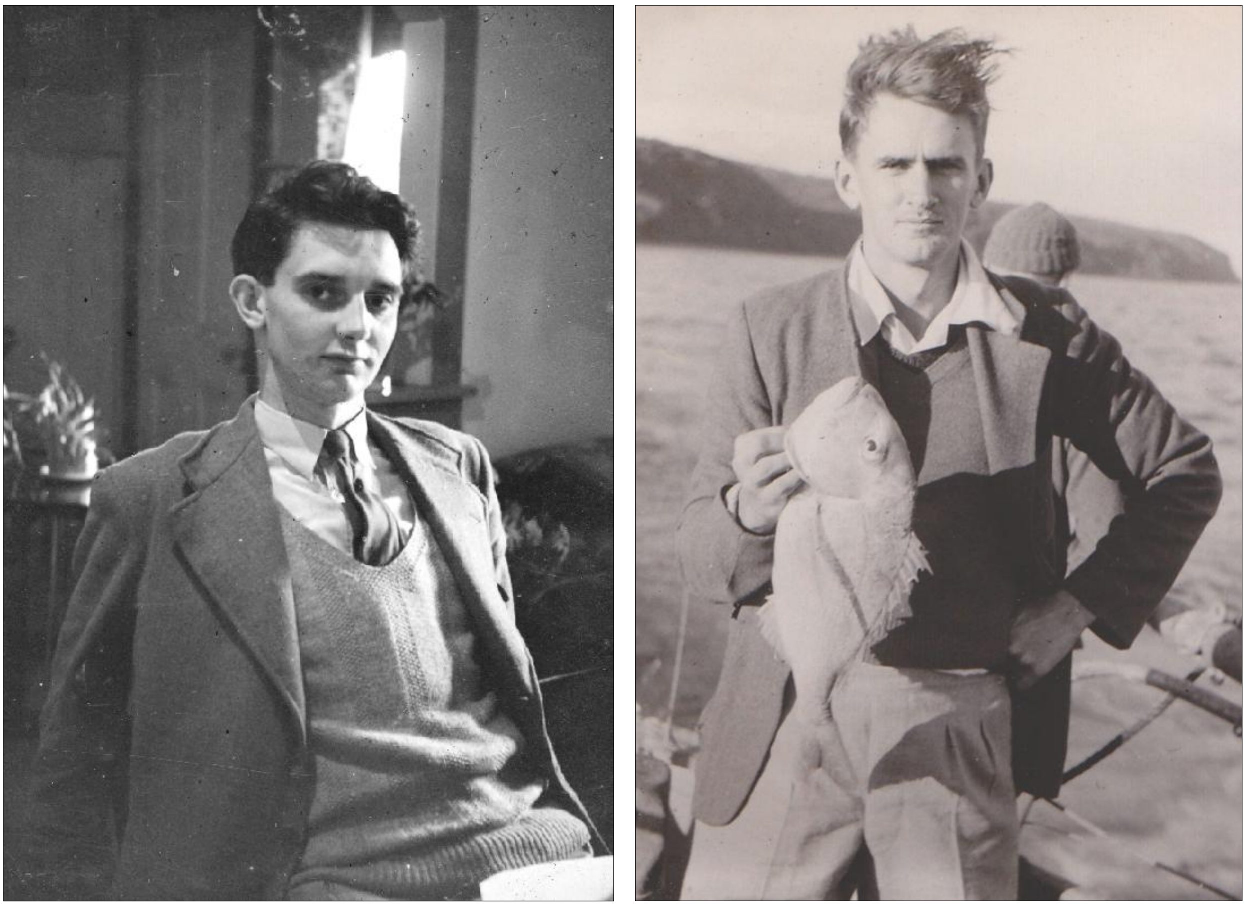
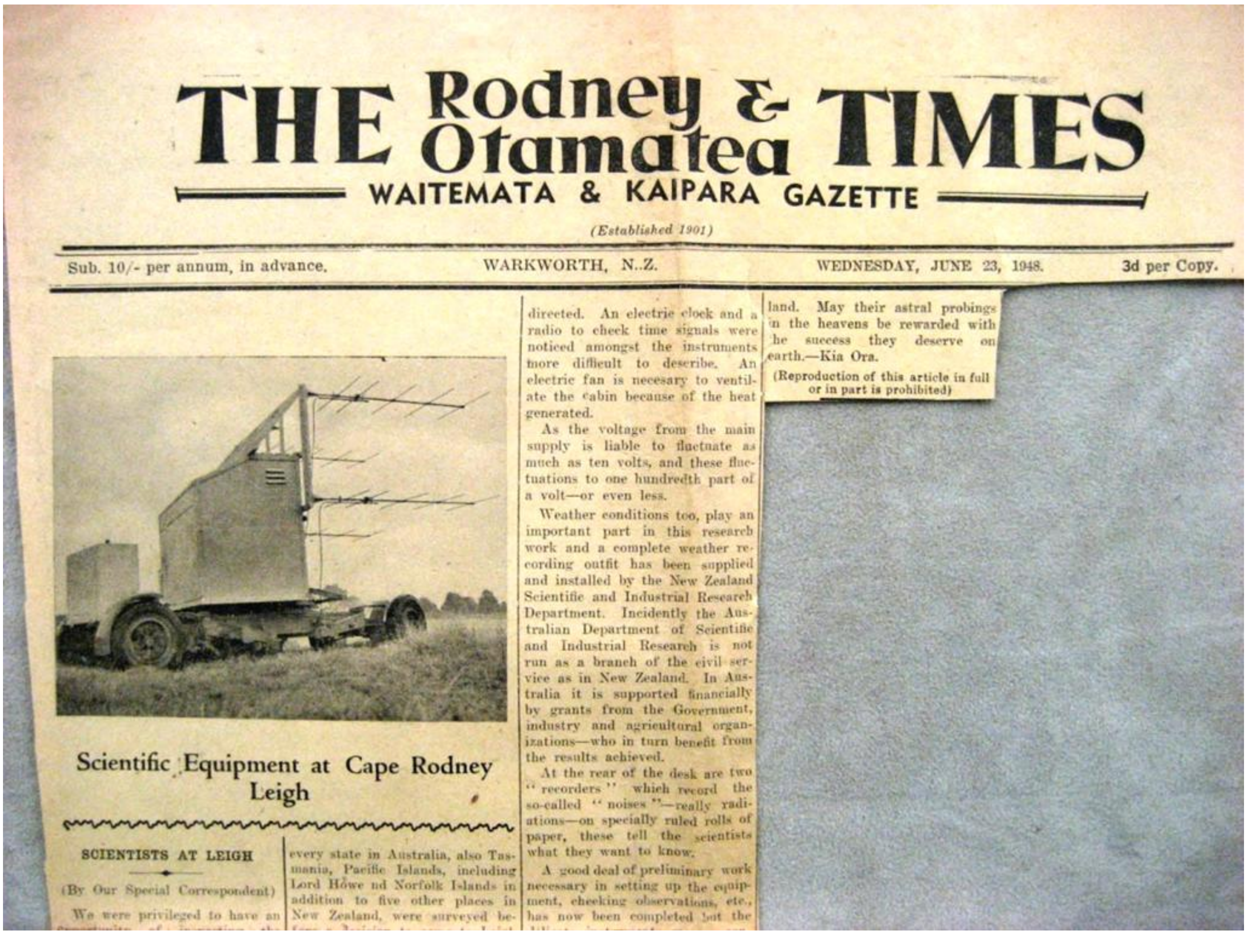


Figure 16: John Bolton (left) and Gordon Stanley stayed in the Cumberland Hotel in Leigh during their two-month observing run at Pakiri Hill. Gordon not only went fishing, but also visited relatives he had not seen since leaving New Zealand at the age of six (courtesy: Stanley family).

Although initially there were problems getting the power connected, Bolton and Stanley settled into a routine of ten observing days, followed by four days of rest and recreation (see Figure 16). Typically each observing day consisted of about 16 hours broken into two shifts. Most of each shift was spent seated at a small desk inside the trailer cabin checking that the receivers and the various instruments were operating correctly. A control panel was used to rotate the cabin mounted on the trailer and point the antenna to a different declination along the eastern horizon. The main problem was the variable power output from the 3 kW transformer installed on site which made the chart recorders run at speeds varying by up to 10%. The heat generated by the bank of instruments had to be ventilated from the cabin by an electric fan, but at least the cabin could be kept warm during the freezing winter nights. The weather at times was appalling and operations were often shutdown with the cabin lashed by storms rolling in from the Pacific Ocean.

During their sojourn at Pakiri Hill, word of the exploits of these two young scientists from Australia reached the media, and as a result they featured in the local and Auckland newspapers (e.g. see Orchiston 1994 for an account of a long and detailed article that appeared in the *New Zealand Herald* on 25 June). Much closer to home, their research made the front page of the local newspaper (Figure 17). Bolton and Stanley also were visited at Pakiri Hill by staff members, and a captivated graduate student, from the Physics Department at Auckland University College (Orchiston, 1994). After completing his M.Sc. on solar radio astronomy later that year, that graduate student, Alan Maxwell, would go to the University of Manchester for his Ph.D., and then move to the USA and build an international reputation in solar radio astronomy while at Harvard College Observatory and their Radio Astronomy Station at Fort Davis, Texas (Orchiston, 1994; Thompson, 2010).

By the end of July, Bolton and Stanley had obtained good records for Cygnus A on thirty nights and for Taurus A on five nights (see e.g. Figure 18), and a handful of records for some of the other weaker northern sources. With the work at Pakiri Hill finished, the trailer was then towed over to the west coast to start observations of the sources setting. The site chosen was a former WWII radar station a few kilometres south of Piha, a popular resort town about 30 km due west of Auckland. The site had a number of advantages, including a very stable power supply which avoided the problem



THE Rodney & Otamatea TIMES

WAITEMATA & KAIPARA GAZETTE

(*Established 1901*)

Sub. 10/- per annum, in advance. WARKWORTH, N..Z. WEDNESDAY, JUNE 23, 1948. 3d per Copy.

Scientific Equipment at Cape Rodney Leigh

SCIENTISTS AT LEIGH

(By Our Special Correspondent)

We were privileged to have an

every state in Australia, also Tasmania, Pacific Islands, including Lord Howe nd Norfolk Islands in addition to five other places in New Zealand, were surveyed be-

directed. An electric clock and a radio to check time signals were noticed amongst the instruments more difficult to describe. An electric fan is necesary to ventilate the cabin because of the heat generated.

As the voltage from the main supply is liable to fluctuate as much as ten volts, and these fluctuations to one hundredth part of a volt—or even less.

Weather conditions too, play an important part in this research work and a complete weather recording outfit has been supplied and installed by the New Zealand Scientific and Industrial Research Department. Incidently the Australian Department of Scientific and Industrial Research is not run as a branch of the civil service as in New Zealand. In Australia it is supported financially by grants from the Government, industry and agricultural organizations—who in turn benefit from the results achieved.

At the rear of the desk are two "recorders" which record the so-called "noises"—really radiations—on specially ruled rolls of paper, these tell the scientists what they want to know.

A good deal of preliminary work necessary in setting up the equipment, checking observations, etc., has now been completed but the

land. May their astral probings in the heavens be rewarded with the success they deserve on earth.—Kia Ora.

(Reproduction of this article in full or in part is prohibited)

Figure 17: The expedition featured on the front page of the local newspaper. The article appeared under the pen name 'Kia Ora', the Maori term for 'good luck' (courtesy: Bolton papers, National Library of Australia).

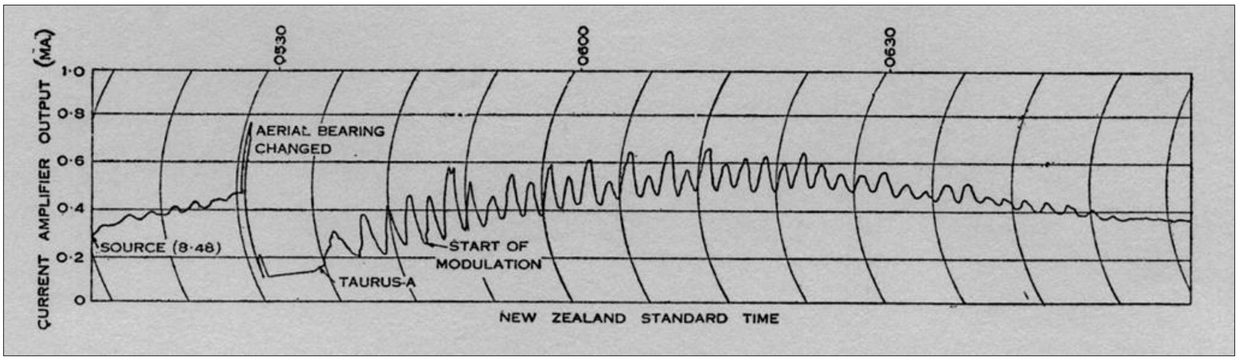


Figure 18: Record of sources (8.48) and Taurus A obtained at Pakiri Hill on 13 July 1948 at a frequency of 100 MHz. Note the modulation of the Taurus A interference pattern caused by a third source in this region. Note also the absence of the spiky structure observed for Cygnus A (see Figure 10), the result of Taurus A being an extended source (see Section 7) with angular dimensions of 4′ × 6′ (after Bolton and Stanley, 1949: 141).

faced with the chart recorders at Pakiri Hill. The level of man-made interference compared to Sydney was so low that good quality records could be obtained for some sources that set during the daytime. The weather was excellent and records were obtained over a two-week period for the four sources: Cygnus A, Taurus A, Centaurus A and Virgo A. The Virgo A source had previously been labelled Coma Berenices A (see Table 1), but the Dover Heights position turned out to be inaccurate by a massive 8°. The Piha observations meant that the source had to be moved from one constellation to another!

7 OPTICAL IDENTIFICATIONS FOR THE FIRST THREE SOURCES

Bolton returned to Sydney in mid-August 1948, while Stanley stayed on for a few days to arrange shipment of their mobile radio telescope. The expedition had been a major success on a number of levels. A further six discrete sources had been discovered, bringing the known number to 13, and there was strong evidence that there might be up to fifty more. The sources were far too faint to examine in any detail during the expedition, but could be followed up later at Dover Heights.

The fluctuations of Cygnus A also provided a further major discovery. During the expedition Bruce Slee had continued observations of Cygnus A at Dover Heights. A comparison of the Dover and New Zealand records, taken at a distance apart of 2000 km, showed no correlation between the two. As a control experiment, observations at both Dover and Piha had been made of a group of sunspots that had appeared on the Sun over a three-day period early in August. As expected, there was a strong correlation between the two sets of records. Thus, there was no longer any doubt that the Cygnus A fluctuations were not intrinsic to the source itself, but were caused by the radio signal passing through the Earth's atmosphere. Bolton's earlier belief that the fluctuations originated in the source was wrong. The suggestion by Gerard Kuiper at the Yerkes Observatory, made over a year earlier, that the Cygnus A fluctuations might be analogous to the twinkling of starlight turned out to be correct (see Section 4).

Bolton then began the long and laborious task of analysing the previous three months of observations. He decided to concentrate on calculating the celestial coordinates of the four strongest sources. Records for Cygnus A and Taurus A had been obtained at both Pakiri and Piha, but there were no records for Centaurus A and Virgo A from Pakiri as both sources rose over the land rather than the sea. For these two sources it would be necessary to rely on the Piha observations of setting in the west and of further observations at Dover Heights of rising in the east. With the two sites 2000 km apart, the records would need to be 'normalised' before the data from each site could be combined. The calculation of declination had to take into account the different latitude at each site. Similarly, the calculation of Right Ascension had to take into account the longitude of each site and also the two-hour time difference between New Zealand and Australian Eastern Standard times. Bolton also had to take note that the observations took place at different times of the year and convert solar times to sidereal times.

Bolton (1948d) prepared a series of brief internal Radiophysics reports setting out his calculations for each of the four sources. For Cygnus A, the angular size of the object was shown to be <1′, eight times smaller than the earlier measurement at Dover Heights and proving without doubt the point-like nature of the source. The new position for Cygnus A was >1° further south than the old one and showed that the previous estimate of atmospheric refraction had been significantly in error. Bolton studied the star charts with this new position, but to his great disappointment he could not see any object within the error box that seemed a likely candidate. The New Zealand expedition had been organised primarily to try to reveal the identity of the object—by choosing the time of the year when it would rise and set at night and the site at Pakiri with its view of the source low in the northern sky—but frustratingly Cygnus A continued to elude them. It would be almost three years before Cygnus A was finally identified. In 1951 F. Graham Smith at Cambridge measured a new and far more accurate position for the source (Smith, 1951). This prompted Rudolph Minkowski and Walter Baade at the Mt Wilson–Palomar Observatories to make extended observations of the position, revealing a very faint galaxy at the extraordinary distance of approximately 10^9 light-years.[10]

The disappointment of Cygnus A was soon swept away by the results for the other three sources. The position measured for Taurus A almost coincided with an ordinary star but, as Bolton (1948d) noted, also well within the error box was "... the most remarkable object in this region – NGC 1952 or the Crab nebula." Bolton's observation was a considerable understatement. The object is not only remarkable in this region of the sky, but it is one of the most remarkable in the *whole* sky. Aside from objects within the Solar System, there have probably been more research papers written about the Crab Nebula than any other astronomical object (Mitton, 1978: 175). The Crab Nebula (Figure 19) is a supernova remnant, the remains of a star that violently exploded in the year AD 1054. No account of this supernova can be found in European chronicles surviving from this time (see Stephenson and Green, 2003), but there are various Arabic, Chinese, Japanese and Korean records of it (Pankenier, 2006; Stephenson, 2004; Stephenson and Green, 2002). In particular, astrologers in the court of the Chinese emperor kept a detailed record of this spectacular event. The supernova appeared suddenly and was said to develop spikes leaving it in all directions. Its reddish-white colour remained clearly visible even in bright daylight for three weeks and for months afterwards it dominated the night sky (Mitton, 1978: 16). Bolton felt confident enough of the Taurus A identification to publish a detailed account in the Australian journal (Bolton and Stanley, 1949), which boasted the revealing title, "The position and probable identification of the galactic source Taurus A", and in it Bolton and Stanley gave a slightly revised position of RA 05h 31m 20 ± 30s and Dec. +22° 02′ ± 8′. They concluded:

> The limits in the position of the source enclose NGC 1952, otherwise known as the Crab nebula. According to Baade (7) this nebula is the remains of the supernova of AD 1054 observed by Chinese astronomers. The angular dimensions of the nebula are 4′ by 6′ and the angular rate of expansion is 0.13″ per year ... The measurements on 100 Mc/s. give an effec-

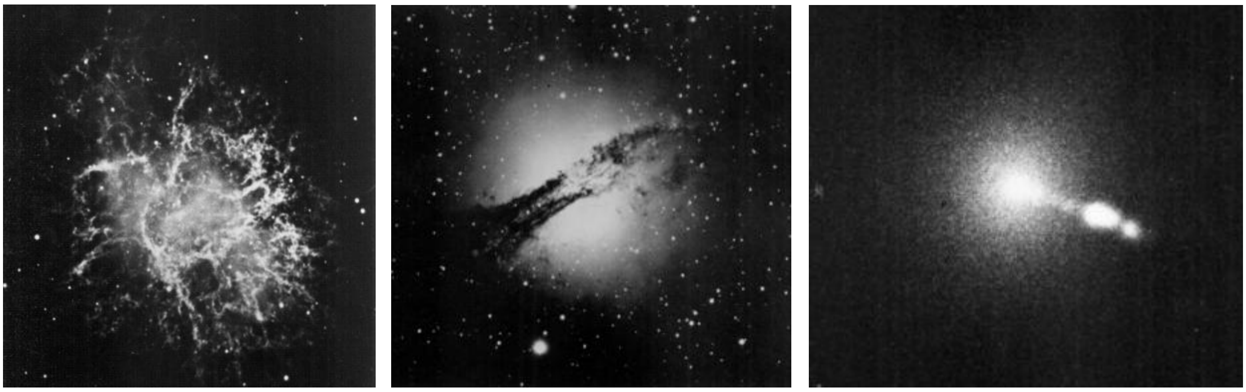


Figure 19: The first three radio sources to be identified with visible objects by the Dover Heights team. Left: Taurus A with the Crab Nebula (NGC 1952); centre: Centaurus A with NGC 5128; and right: Virgo A with M87 (NGC 4486) (courtesy: RAIA).

> tive temperature of two million degrees, assuming a source size of 5′ for Taurus A. From the present values of temperature and density in the Crab nebula it would be difficult to explain this result in terms of strictly thermal processes. However, it is not unlikely that non-thermal components would arise from differential expansion within the nebula and general expansion into interstellar matter. In view of this and the close agreement between the positions of the Crab nebula and the source Taurus A, *it is suggested that the Crab nebula is a strong source of radio-frequency radiation*. (Bolton and Stanley, 1949: 145–146; our italics).

This paper was praised by Grote Reber (1950):

> I have been greatly impressed by your series of publications upon discrete sources of galactic radio waves. The last one, in the June 1949 issue of the *Australian Journal of Scientific Research*, is a beautiful piece of work.

However, as Orchiston and Slee (2006: 46) have noted,

> It is important to stress that this initial identification was regarded by some astronomers (including radio astronomers) as tentative, and it was only when Britain's Graham Smith (1951) and RP colleague, Bernie Mills (1952a) published refined positions, and when Mills (1952b) measured the angular size of the source, that the identification was beyond doubt (see Bolton, 1955).

The two other radio sources, Virgo A and Centaurus A, provided an even bigger surprise, though initially Bolton did not realise the full significance of his identifications. Virgo A coincided with an object known as M87 (or NGC 4486). The object is distinguished by a bright blue jet of material extending from its centre, an extremely unusual feature. The other, Centaurus A (NGC 5128), turned out to be a bright and peculiar object with a dark dust band straddling its disk (see Figure 19). In his internal report Bolton (1948d) noted:

> The limits in position of the source RA 13 h 22 m 20 s ± 1 m, Declination –42° 37′ ± 8′ enclose NGC 5128. This object is classed as an extragalactic nebula. It is a seventh magnitude object with a peculiar spectrum. Baade calls it a freak and it is referred to by Shapley as a 'pathological specimen' though no details are known at present as to the exact nature of its peculiarity. It will be an interesting object to study with the Stromlo nebular spectrograph during the late summer months.

Of the four sources analysed by Bolton, Centaurus A was the only one located in the southern half of the sky. In an interesting historical twist, its optical counterpart NGC 5128 was first observed not far from Dover Heights, over 120 years earlier, by James Dunlop at the Parramatta Observatory, west of Sydney (see Robertson et al., 2010).

Bolton's identifications of the three radio sources with optical objects all turned out to be correct, though it would take several years before some astronomers were fully convinced. Each identification was to some degree a lucky guess. The error box around each radio source contained a fair number of possible candidates and there was no logical reason to rule them out. The Taurus A identification seemed the safest as a great deal was known about the Crab Nebula and it is seemed quite plausible that it could be an intense radio emitter. Bolton knew however that many of the possible candidates were relatively ordinary stars and that, if they were similar to the Sun, they could not be the source of such intense radio emission. He guessed that the optical object was more likely to be something new and unusual and here his intuition proved correct.

Although confident of the Taurus A identification, the other two sources presented a difficult dilemma. Bolton spent a week in February 1949 at Mt Stromlo talking to the Commonwealth Observatory astronomers and scouring the literature for information on NGC 5128 and M87. Although both objects were classified as extragalactic, the evidence was not strong. Individual stars had not been resolved in either object which would prove that both were indeed galaxies outside our own Galaxy. Since Centaurus A and Virgo A were among the strongest of the known

Table 2: Positions of three radio sources and their possible associated visible objects (adapted from Bolton, Stanley, and Slee, 1949: 101).

Source	Position (Epoch 1948)		Possible associated visible object	
	RA	Dec.	Object	Remarks
Taurus A	05h 31m 00s ± 30s	+22° 01′ ± 07′	NGC 1952 [A] (Messier 1)	Crab Nebula, expanding shell of an old supernova
Virgo A	12h 28m 06s ± 37s	+12° 41′ ± 10′	NGC 4486 (Messier 87)	Spherical nebula, unresolved
Centaurus A	13h 22m 20s ± 60s	–42° 37′ ± 08′	NGC 5128 [B]	Unresolved nebula crossed by a marked obscuring band

[A] Weak emission lines of H, He, forbidden lines of N, O and Si

[B] Weak emission lines, Hβ, Hγ, Hδ, and λ4686

sources, it seemed logical that both objects must be relatively close, within our Galaxy, and not at vast extragalactic distances. Bolton was concerned that an extragalactic claim for Centaurus A and Virgo A would be seen as sure evidence that he had guessed incorrectly for both and that other Galactic objects in the error boxes must be the actual sources of the strong radio emission. He also reasoned that the journal referees would probably come to the same conclusion, and in all probability the paper would be rejected for publication.

In March 1949 Bolton drafted a brief paper summarising the optical identifications of the three radio sources. The title made clear his decision: "Positions of Three Sources of Galactic Radio-frequency Radiation". Before submitting the paper he wrote to three leading experts on the Crab Nebula, Rudolph Minkowski (Mt Wilson-Palomar), Jan Oort (Leiden) and Bengt Strömgren (Copenhagen). All three were familiar with the work at Dover Heights following their discussions with Joe Pawsey during his overseas trip (see Section 4). Minkowski and his colleague Walter Baade (1893–1960) had in fact carried out the detective work that proved the Crab Nebula is the remnant of the supernova observed by the Chinese in AD 1054. In his letter to Minkowski, Bolton (1949a) gave the positions of the three sources and then noted:

> The most interesting of these is the source in Taurus whose position corresponds very closely to that of the Crab nebula. I referred to papers on this object by Baade and yourself in the *Astrophysical Journal*. The intensity of the radiation at 100 Mc/s gives an equivalent temperature of about a million degrees for an angular width of 5′. From your results on temperature and density in the Crab nebula it seems unlikely that this equivalent temperature could be due to strictly thermal processes in the nebula … I would be interested to hear your opinion on this.

Bolton received enthusiastic responses from all three astronomers. Oort wrote a five-page letter on the Crab Nebula supporting its association with Taurus A (Bolton, 1982: 352). However, he was sceptical of the identification of Virgo A with the galaxy M87 and added, diplomatically, that there are a great many objects in the Virgo cluster. Minkowski also wrote providing the latest information available on the three optical objects, including new evidence that strengthened the case that NGC 5128 and M87 were indeed external galaxies. Bolton was not persuaded, and continued to maintain that both were Galactic objects.

Early in May 1949 Bolton, with co-authors Stanley and Slee, dispatched the letter to *Nature* where it was published on 16 July (Bolton, Stanley and Slee, 1949). The heart of the paper was a brief table (see Table 2) giving the positions of the three sources and their possible associated visible objects (see Figure 19). NGC 5128 and M87 were described as 'unresolved nebula' and the case made for them to be Galactic objects:

> Neither of these objects has been resolved into stars, so there is little definite evidence to decide whether they are true extragalactic 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 in our own galaxy seems greater than a large accumulation of such objects at a great distance.

As indicated in the last sentence, Bolton believed that if the sources were extragalactic they must consist of a large number of unusual objects to account for such intense emission. It appears he did not consider the idea that the emission could come from a *single* extragalactic object. Bolton (1949b) expressed this view more colourfully in further correspondence with Minkowski: "In a letter to *Nature* (written before I consulted you) I have suggested that these objects may be within our own galaxy – on the basis that a close 'freak' is more probable than a large collection of 'freaks' at a great distance."

Bolton turned out to be spectacularly wrong. Baade and Minkowski made further observations of NGC 5128 and M87 and were able to resolve individual stars in both objects, proving almost certainly that they were external galaxies. Later, NGC 5128 was shown to be a peculiar galaxy at a distance of 15 × 10^6 light-years, while M87 turned out to be a giant elliptical galaxy at the even greater distance of 30 × 10^6 light-years (Robertson, 1992: 49). It was an extraordinary development. 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? Sullivan (2009: 324) has summed up the significance of this paper:

> The short paper 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. And what an exciting link it was, too, for this handful of intense radio stars was being associated with objects that were much fainter than any of the five thousand objects visible to the naked eye, yet still unusual enough to be included in manuals such as *Norton's Star Atlas*, the amateur astronomer's *vade mecum* that was frequently consulted by Bolton's group.

8 CONCLUSION

The short interval from June 1947, when the initial detection of Cygnus A took place, through to July 1949, when the identifications letter in *Nature* was published, was an extraordinarily productive period by the Dover Heights group. Bolton, Stanley and Slee had shown how some of the radio emission detected by Jansky, Reber and Hey was associated with discrete radio sources. The group had succeeded in measuring the positions of some of the sources with sufficient precision to identify a handful with known optical objects. And now came the most astonishing result of all—the discovery of a new class of astronomical objects with strange and intriguing properties. The youthful trio of Bolton, Stanley and Slee would all go on to carve out distinguished careers in radio astronomy, but none would produce another paper to rival the importance of their 1949 *Nature* letter. A new branch of astronomy had been founded—extragalactic radio astronomy (see Figure 20).

This new branch 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.

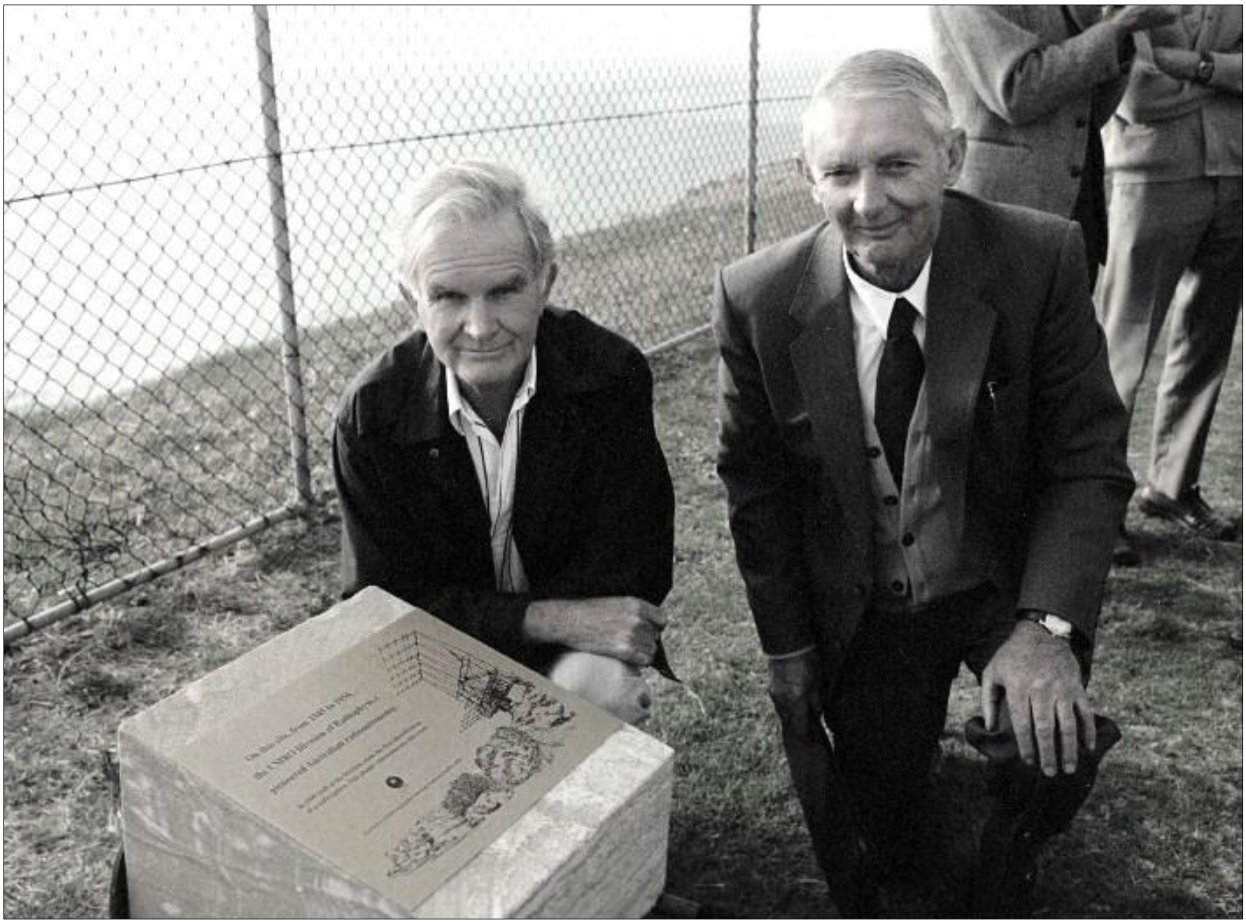


Figure 20: Bruce Slee (left) and John Bolton (right) at the unveiling of a plaque in 1989 at Rodney Reserve, the site of the Dover Heights field station. The plaque celebrated the birth of extragalactic radio astronomy forty years earlier. The field station has been converted into a rugby field with the plaque close to the sea cliff and near the halfway line (courtesy: RAIA N15506-4).

9 NOTES

1. For earlier biographical accounts of John Bolton see Goddard and Haynes (1994), Kellermann (1996), Orchiston and Kellermann (2008), Robertson (1984b) and Wild and Radhakrishnan (1995; 1996). For Bolton's own recollections of the early work on 'radio stars' see his paper "Radio astronomy at Dover Heights" (Bolton, 1982).
2. Note that we now refer to this science as 'radio astronomy' but during the 1930s, when Jansky and Reber were carrying out their pioneering work, they were investigating 'cosmic static' or 'cosmic noise'. The earliest known use of the term 'radio astronomy' was made in January 1948 in a letter by Pawsey (1948a). The new term was enthusiastically endorsed by Bowen (1948).
3. The Germans, for their part, also experienced similar problems to those encountered by Hey, and also assigned them, eventually, to solar radio emission (see Schott, 1947).
4. 'COL' stands for Chain Overseas Low-flying". These radar units were widely used during WWII and normally were coastally-located and looked out to sea in order to detect low-flying incoming aircraft.
5. The technique is also known as 'cliff interferometry' or 'sea-cliff interferometry'; however, we prefer the term 'sea interferometry', as used in the original Dover Heights publications.
6. Martyn was a former Chief of the Division of Radiophysics, and he and his Commonwealth Observatory colleague, Clabon Walter (Cla) Allen (1904–1987), were also keen to investigate solar radio emission at this time. Consequently, in early 1946 two Radiophysics staff members installed a 200 MHz radio telescope at the Observatory. This was virtually identical to the 2-element Yagi set-up that Bolton, Stanley and Slee later would use at Dover Heights (see Orchiston et al., 2006). Apart from Allen and Martyn, the Director of the Observatory, Richard van der Riet Woolley (1906–1986), was also interested in solar radio astronomy. It has been claimed, with some justification, that "The association between Mt Stromlo and Radiophysics was the first major collaboration between optical and radio astronomers anywhere in the world." (Robertson, 1992: 109). In general, it took much longer for optical astronomers in other parts of the world to accept radio astronomy as a valid area of astronomy and to collaborate with radio astronomers (see e.g. Jarrell, 2005).
7. Other nations experienced similar problems, and only the Russians ended up going to Brazil and successfully observing the 20 May 1947 eclipse (see Khaykin and Tchikhatchev, 1947).
8. The 200 MHz data were supplied by Mt Stromlo astronomers, as the 200 MHz Yagi array at Dover Heights was not operational at this time.
9. This source turned out to be Centaurus A. Bolton later made the point that if he and Stanley had detected this source first, instead of Cygnus A, they would not have cited Hey et al. in their discovery paper (Bickel, 1975). Thus, the later 'confusion' over whether Hey et al. or Bolton et al. discovered the first discrete radio source might have been avoided.
10. In fact, Bolton's Radiophysics Laboratory colleagues Bernard Yarnton Mills (1920–2011) and Adin B. Thomas, made this very optical identification two years earlier, in 1949. After observing Cygnus A from May to December 1949 with a 97 MHz swept-lobe interferometer at the Potts Hill field station (Wendt et al., 2011), Mills examined a photograph of the region that Minkowski had sent to Bolton and in the error box of their observations he noticed a faint extragalactic nebula. He felt that this could be the source of the emission and wrote to Minkowski suggesting this (Mills, 1949). However, Minkowski (1949) advised Mills against claiming the identification, so when their paper on Cygnus A finally appeared Mills and Thomas (1951) concluded that this faint galaxy was unlikely to be responsible for the emission. Smith's more precise position, obtained in 1951, confirmed that this galaxy was indeed responsible for the Cygnus A emission.

10 ACKNOWLEDGEMENTS

We are grateful to Professor Woody Sullivan for providing copies of the Bolton (1947; 1949a; 1949b) letters, and to Professor Ken Kellermann (NRAO) and Professor Richard Strom (ASTRON) for commenting on earlier drafts of this paper. One of us (PR) also is grateful to the Astrophysics Group, School of Physics, University of Melbourne for its support. The second author (WO) is grateful to the National Astronomical Observatory of Japan for providing the opportunity for him to complete the revision of this paper while at Mitaka on a Visiting Professorship.

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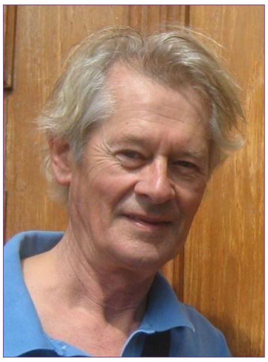

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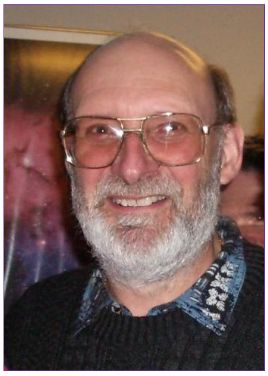

Professor Wayne Orchiston is a Senior Researcher at the National Astronomical Research Institute of Thailand, and the founder of the IAU Working Group on Historic Radio Astronomy. He has published extensively on Australian, French, Japanese and New Zealand radio astronomy and has supervised six Masters or Ph.D. theses on the history of Australian, British and U.S. radio astronomy. Currently, he, Professor Masato Ishiguro (NAOJ) and various Japanese colleagues are systematically documenting the early history of radio astronomy in Japan through a series of papers that are published in this journal.

Dr Bruce Slee is one of the pioneers of Australian radio astronomy. Since he independently detected solar radio emission during WWII he has carried out wide-ranging research, first as a member of the CSIRO's Division of Radiophysics, and then through its successor, the Australia Telescope National Facility. After working with Bolton and Stanley on the first discrete sources at Dover Heights, he moved to the Fleurs field station and researched discrete sources with Mills, using the Mills Cross. He also investigated radio emission from flare stars with the Mills and Shain Crosses, and used the Shain Cross and a number of antennas at remote sites to investigate Jovian decametirc emission. With the commissioning of the Parkes Radio Telescope he began a wide-ranging program, that focussed on discrete sources, and radio emission from various types of active stars. He also used the Culgoora Circular Array (*aka* Culgoora Radioheliograph) for non-solar research, with emphasis on pulsars, source surveys and clusters of galaxies, and continued some of these projects using the Australia Telescope Compact Array. He also has used a range of overseas radio telescopes for his research; has participated in VLBI experiments; and has collaborated on multi-wavelength observations of active stars. Over the past two decades, he also has been writing papers on the history of Australian radio astronomy, and he has supervised a number of graduate students who were researching history of radio astronomy theses. At 90 years of age he continues to conduct research as an honorary associate of CSIRO's Division of Astronomy and Space Sciences.

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THE ABORIGINAL AUSTRALIAN COSMIC LANDSCAPE. PART 1: THE ETHNOBOTANY OF THE SKYWORLD.

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Abstract: In Aboriginal Australia, the corpus of cosmological beliefs was united by the centrality of the Skyworld, which was considered to be the upper part of a total landscape that possessed topography linked with that of Earth and the Underworld. Early historical accounts of classical Australian hunter-gatherer beliefs described the heavens as inhabited by human and spiritual ancestors who interacted with the same species of plants and animals as they had below. This paper is the first of two that describes Indigenous perceptions of the Skyworld flora and draws out major ethnobotanical themes from the corpus of ethnoastronomical records garnered from a diverse range of Australian Aboriginal cultures. It investigates how Indigenous perceptions of the flora are interwoven with Aboriginal traditions concerning the heavens, and provides examples of how the study of ethnoastronomy can provide insights into the Indigenous use and perception of plants.

Keywords: ethnoastronomy, cultural astronomy, ethnobotany, aesthetics, Aboriginal Australians

1 INTRODUCTION

How people conceive and experience physical space and time is culturally determined. Iwaniszewski (2014: 3–4) remarked

> While modern societies tend to depict these categories as type [*sic*] of independent entities, real things, or universal and objective categories, for most premodern and non-Western societies time and space remained embedded in their activities and events.

In the Australian ethnographic literature, reference to the ‘Skyworld’ refers to an Aboriginal concept of the heavens as having an existence as a country, upon which exist ancestors who are seen as celestial bodies. Existing overviews of the astronomical traditions of Aboriginal Australia have highlighted the main elements of the Skyworld, such as its physical structure, the influence of its occupants over earthly events and the existence of genealogical relationships between celestial bodies. While there is considerable variation within the associated mythologies, the Skyworld was experienced through a shared aesthetic system. Australian hunter-gatherers experienced time as the passage of cycles (Clarke, 2009b; Davis, 1989; 1997; Morphy, 1999). They were keen observers of change within their environment, with the onset of seasons signaled by such things as the movement of celestial bodies, weather shifts and the flowering of calendar plants.

1.1 Data Sources

In Australia there is a wealth of recorded ethnobotanical information concerning Indigenous relationships with plants, although there are major biases (Clarke, 2003b; 2007a; 2008a; 2012; 2014a). The ethnobotanical work has largely been focused on physical plant uses, and in particular with documenting species used as raw materials for food, medicine and artefact-making. Ethnobotanists have generally ignored the cultural roles of plants, such as those involved in the psychic realm. There has also been an imperative to record the plant uses from the classical hunter-gatherer period, to the detriment of studying aspects of the changing relationships that Indigenous people have had with the flora since British colonisation. The spatial coverage of Aboriginal plant use records across Australia is such that there are detailed records available for much of the tropical and arid zones, but major gaps for most of the temperate zone. European colonists arriving in Australia from the late eighteenth century were unfamiliar with most Australian plant species, which has led to a shortage of data for regions, such as south-eastern Australia, where settlement first began.

In comparison to ethnobotany, the field of ethnoastronomy is much smaller in Australia, although similar in the diversity of its data recorders and research practitioners. For the purposes of the current work, the focus on the heavens requires a deeper explanation of the data sources.

The published summaries of the ethnographic records for Aboriginal Australia that are relevant to ethnoastronomy have highlighted deficiencies, particularly in southern temperate regions where British colonization commenced and has been most intense (Clarke, 1997; 2008b; 2009a; 2014b; Fredrick, 2008; Hamacher, 2012; Haynes, 1992; 2009; Isaacs, 1980; Johnson, 1998; 2005; Norris, 2007; Norris and Hamacher, 2009; 2014; Tindale, 2005). For the Indigenous star lore of many areas we must chiefly rely upon anecdotal accounts from those settlers and colonial officials who had ethnological interests, such as Peter Beveridge (1829–1885), James

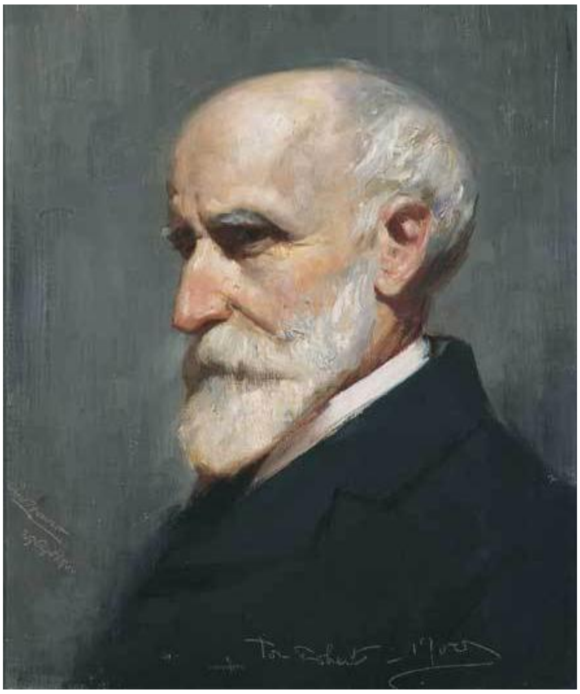

Figure 1: An oil painting of A.W. Howitt by Tom Roberts in 1900 (courtesy: Monash University Collection).

Dawson (1806–1900), John Philip Gell (1816–1898), the Reverend Peter MacPherson (1826–1886), George Augustus Robinson (1791–1866), William Edward Stanbridge (1816–1894), Watkin Tench (1758–1833) and Charles White (1845–1922). As eighteenth and nineteenth century scholars, they were able to compile information from Aboriginal people who were the survivors of the first wave of European settlement. In this period, missionaries, such as William Ridley (1819–1878) and Christian Gottlieb Teichelmann (1807–1888), were more thorough with their recordings of Indigenous culture, although they were working before academic anthropology had begun in Australia.

Information collected by colonists on Indigenous astronomical lore was often distorted and truncated. In the absence of anthropological training, early scholars often tried to package the information received from Aboriginal sources as scientific observation. When this could not adequately be done, they blamed the reliability of their informants. For example, a late nineteenth century newspaper correspondent stated "When retailing this [astronomical] lore to a whitefellow, these astrosophists are frequently guilty of gross exaggeration." (E.K.V., 1884). Some corruption of the base data has been more deliberate, with many examples of the willingness of European authors to use the idiom of Aboriginal myth for their popular writing, which has added different elements and altered the emphasis of the original narrative (Clarke, 1999a: 60–63).

A generation of scholars who had developed close relationships to Aboriginal communities emerged from the late nineteenth century. Such a person significant to the study of ethnoastronomy was Alfred William Howitt (1830–1908; Figure 1; Stanner, 1972), who was born in Nottingham, England, and in 1852 emigrated to Australia, settling in Melbourne (for Australian localities mentioned in this paper see Figure 2). He was briefly the manager of a sheep station and a prospector, prior to becoming an explorer. In later life, Howitt became a natural scientist and an authority on the Aboriginal people of south-eastern Australia. Another significant recorder of Aboriginal cosmology was Robert Hamilton Mathews (1841–1918; McBryde, 1974), who was born at Narellan, near Sydney, in New South Wales. During his working life as a surveyor he travelled widely. Without the contributions of Mathews and Howitt, the total ethnographic record of south-eastern Australia would be much poorer.

During the twentieth century, researchers from backgrounds spread across several disciplines recorded Aboriginal ethnoastronomical data. Anthropologists with records pertaining to Australian ethnoastronomy included Daisy May Bates (1859–1951), Ronald Murray Berndt (1916–1990), Catherine Helen Berndt (1918–1994), Daniel Sutherland Davidson (1900–1952), Adolphus Peter Elkin (1891–1979), Ethel Hassell (1857–1933), Helmut Petri (1907–1986), Father Ernest Alfred Worms (1891–1963) and the present author (b. 1961). Missionaries of this period based in the Northern Territory, such as Wilbur Selwyn Chaseling (1910–1989) and Carl Friedrich Theodor Strehlow (1871–1922), were able to work alongside anthropologists. Examples of modern linguists who recorded Aboriginal Skyworld beliefs are Amee Glass, Dorothy Hackett, John Henderson (b. 1957), Luise A. Hercus (b. 1926), John C. McEntee, Michael Sims and Dorothy Tunbridge. Scholars with interests in museum collections, such as Robert W. Ellis, Charles Pearcy Mountford (1890–1976), Walter Edmund Roth (1861–1933), Theodor George Henry Strehlow (1908–1978), Peter Sutton (b. 1946) and Norman Barnett Tindale (1900–1993), have used Aboriginal astronomical data as a means of interpreting Aboriginal material culture and art. An astronomer's perspective of Indigenous Australian beliefs concerning the Skyworld has been provided by Duane W. Hamacher, Roslynn D. Haynes, Trevor M. Leaman, Brian Gilmore Maegraith (1907–1989) and Ray P. Norris, while Keith C. McKeon (1892–1952) was a naturalist with an interest in Aboriginal relationships to the environment.

Even with researchers who are properly trained in astronomy, recording problems occur when using a Western European model of the heavens to elicit an Aboriginal version of the night sky. Bates, in her account of the astronomy of

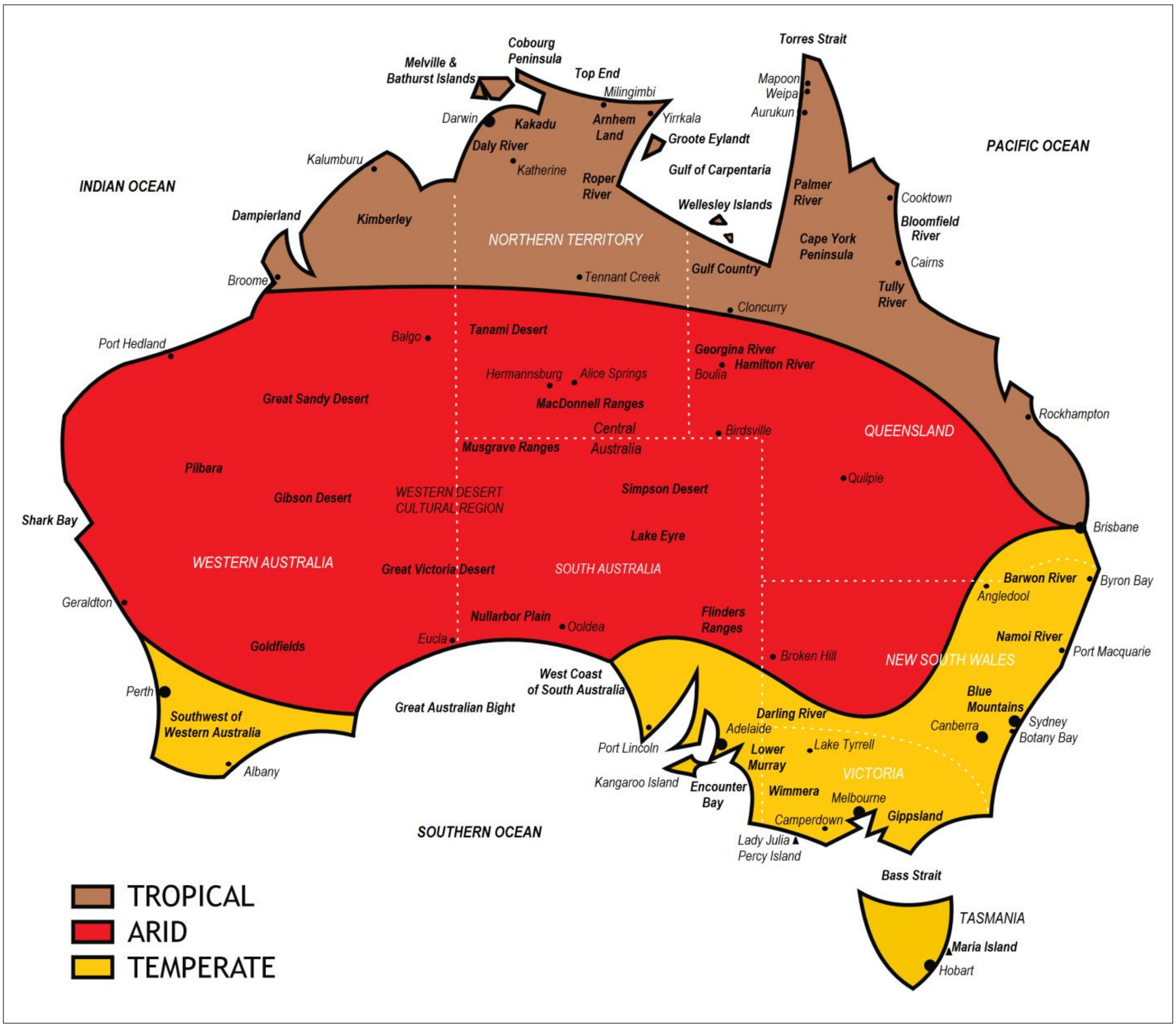

Figure 2: Australian localities or regions mentioned in the text.

the Bibbulmun people in the south-west of Western Australia, warned that:

> There is no aboriginal generic term for "Zodiac," other than the dialectic equivalents for "road" or "track," and as all native and animal tracks are winding ones throughout Australia, the aboriginal zodiac winds here and there amongst the myriads of heavenly bodies. (Bates, 1924: 170).

Maegraith (1932: 19) summarized the methodlogical issues for the study of Indigenous astronomy:

> To mark out the configuration of the constellations is by no means easy even to an educated observer … the aborigine has complicated his star groupings by the introduction of marriage classification and relationship, and by tribal divisions.

Apart from translation difficulties, the way Aboriginal people perceived space in the classical period of their culture was fundamentally different from that of modern Western Europeans (Sutton, 1988; 1998).

2 THE CULTURAL LANDSCAPE

For contemporary geographers, the cultural landscape is a concept that encompasses both the physical and cultural aspects of the human construction and perception of space (Baker, 1999: 20–23; Clarke, 1994: 50). The heavens are part of the space that people experience. In Aboriginal Australia, interpretations of the sky must be understood in terms of the cosmological traditions that explain the making of the world. Fundamental to Aboriginal religious beliefs is the concept that there was a Creation period when totemic spiritual ancestors performed heroic deeds, moulded and imparted spiritual power to the land, and formulated customs for their descendants to follow (Berndt and Berndt, 1999: 137–138, 229–230; Clarke, 2003a: Chapter 2; Hiatt, 1975; Sutton, 1988). These ancestors often took the form of animals and birds, but many also were plants, atmospheric and cosmological phenomenon or even human diseases. The paths the ancestors made across the land during the Creation became ancestral tracks, or song lines, which connect mythological sites where according to Aboriginal tradition certain events had taken place. When the Creation period drew to a close, it was Aboriginal belief that many of these spiritual ancestors travelled up into the heavens, and for this reason anthropologists have referred to them as 'Sky-heroes' (e.g. Elkin, 1964: 252–254).

Aboriginal people in the classical period believed that they lived in the centre of a finite world. This is described by Ethel Clifton, who in 1871 at the age of 21 married Albert Hassell and moved to a sheep station named Jarramungup, a four-day ride from Albany. For the next few years of her life Ethel Hassell (Figure 3) sympathetically recorded details of the culture of the local Wiilman people. In 1910 she brought this study together in a manuscript titled *My Dusky Friends* which she deposited in the Mitchell Library, Sydney, but it was only in 1975 that this was published as a book (Hassell, 1975). In 1930 and 1931, shortly before her death in 1933, Ethel Hassell wrote to the American anthropologist D.S. Davidson about her studies, and in a paper that he subsequently published (Hassell and Davidson, 1936) they remarked on beliefs concerning the "... rotundity of the Earth ..." that were held by the Wiilman people of the south-west of Western Australia. They also noted:

Figure 3: A photograph of Ethel Hassell (booknet-booooks4all.blogspot.com/2010_03_01_archive.html).

> The earth was considered round like a ball. The natives argued that everything was round. Wherever one stood and looked things seemed to be thus. If a baby was put down he would not run straight like a fence but around in circles. If sheep got lost they ran around and around. Kangaroos did not run straight but around and around like sheep. When a white man got lost he walked around in circles. Where the sky touches the earth it is round. Trees are round, and bushes are round. It was just natural for everything to be round, hence why not the earth? (Hassell and Davidson, 1936: 687).[1]

The world they lived within was comprised of a curved but relatively level Earth, with a Skyworld above and an Underworld below.

In many parts of Australia, the sky was perceived as a solid vault that sat on top of what was termed "... a flat limited surface." (Howitt, 1904: 433). For instance, Howitt recorded in the Wimmera district of western Victoria that:

> A Wotjobaluk legend runs that at first the sky rested on the earth and prevented the sun from moving, until the magpie (*goruk*) propped it up with a long stick, so that the sun could move, and since then "she" moves round the earth. (Howitt, 1904: 427).

The theme of the sky being held up by wooden poles or living trees is present in other south-eastern Australian accounts (e.g. Clarke, 2003a: 194; Howitt, 1904: 427; Massola, 1968: 105–106; Morgan, 1852 [1980: 64–65, 191]; Worms and Petri, 1998: 129). In Central Australia the German-born Lutheran missionary-anthropologist Carl F.T. Strehlow (Figure 4; Veit, 1990), who was based at the Hermannsburg Mission from 1894 until 1922, found it was Arrernte tradition that the heavens rested on top of 'stone legs' (Strehlow, 1907; cited Goldenweiser, 1922: 212]). Aboriginal logic held that the sky region began at the height of a tall tree or at most a hill (see Clarke, 2015).

In Aboriginal Australia, the levels within the total cultural landscape were named entities. For instance, Sims made a detailed cosmological study of the Tiwi people of Melville and Bathurst Islands in the Northern Territory and he described how they divide their Universe into four levels: the Underworld (*Yilaru*), the Earth (*Kaluwartu*) upon which the living reside, the Upperworld (*Tuniruna*), and above that the Skyworld (*Juwuku*) (Sims, 1978: 165–167). The Tiwi Underworld was seen as a valley where nothing grows, so there is no food, only water from a stream. There are two high stony ridges here, and in the valley between them the Sun, as the carrier of fire, travels with a bark torch during the night. For the Tiwi, the Creation ancestors originally emerged from the ground on Earth to give their country meaning and form. The Upperworld is similar to Earth with respect to land and the seasons, and for part of each year was the home of spiritual ancestors who controlled the weather. At certain times, these ancestors would move into the Skyworld, which is the abode of other ancestors who are seen as the stars, Moon and Sun.

The Diyari people of eastern Central Australia viewed their cosmos as having two zones above Earth. It was recorded that:

> Beyond the sky is another country, which may be called sky-land. This belief is indicated in one of the Dieri [Diyari] legends, which tells how Arawotya, "who lives in the sky," let down a long hair cord, and by it pulled up to himself the Mura-mura [Creation ancestor] Ankuritcha and all those who were with him. (Howitt, 1904: 432–433).

The Diyari and neighbouring groups also conceived the existence of an Underworld, where the Sun ancestor had first emerged (Hercus, 1987; Howitt, 1904: 427–428). Other accounts in Aboriginal Australia do not distinguish between the layers of the sky. For instance, Howitt recorded that the Wurunjerri (Woiworung) people around the northern side of Melbourne in Victoria believed that they:

> … had a sky country, which they called *Tharangalk-bek*, the gum-tree country. It was described to me as a land where there were trees. The tribal legends also tell of it as the place to which Bunjil [supreme male ancestor] ascended with all his people in a whirlwind. (Howitt, 1904: 433).

Here, the land was named after *tharangalk* trees, which are manna gums (*Eucalyptus viminalis*) that were a source of edible manna and sugar lerp (extract produced by leaf insects).[2]

The gulf between terrestrial space and the sky was more easily crossed at the time of events taking place in the Creation period. For instance, in Diyari tradition from the north-east of South Australia:

> The legend of the Yuri-ulu [two Mura-mura youths] tells how, after the holding of the *Wilyaru* ceremony they went on their wanderings, and finally beyond the mountains passed through what may be briefly termed a "hard darkness" into another country, whence looking back, they recognised what they had passed through as the edge of the sky. (Howitt, 1904: 426).

Through magical means, shorter routes from Earth to the Skyworld were also available. Aboriginal groups along the Darling River in western New South Wales believed that the

> … Pleiades were a lot of young women who went out on a plain searching for yams and a whirlwind came along and carried them up into the sky, depositing them where they are now seen. (Mathews, 1904: 283).

The historical accounts of Aboriginal traditions sometimes blur the distinction between the Skyworld and the Underworld. Aboriginal groups living along the coast of southern South Australia believed that in order for the spirits of the deceased to reach the Skyworld, they had to follow the path of their Creation ancestors by first entering the Underworld or 'Land to the West' by diving into the sea (Clarke, 1997: 127). For instance, Berndt et al. (1993: 226) record at the close of the Creation period in the Lower Murray of South Australia, the supreme male ancestor *Ngurunderi* travelled to the western end of Kangaroo Island, where he said to his kinfolk:

> Here you must dive when death occurs, when the spirits leaves your body. When you die, all of you will dive into the sea, following my example; then you will go up walking as I did, cleansed; you will follow me into the sky! (see also Clarke, 1995).

This pathway follows the same course perceived for the Sun: going to the western horizon to enter the Underworld, then travelling below to exit on the eastern horizon of Earth, where the vault of the heavens was close enough to step into the Skyworld.

Figure 4: Carl Strehlow, Pastor of Hermannsburg Mission, circa 1895 (courtesy: State Library of South Australia, B 42410).

It was considered a serious matter if for any reason the separateness of the Earth, Skyworld and Underworld regions was compromised. For the Wiilman of the south-west of Western Australia, the University of Pennsylvania anthropologist D.S. Davidson (McCarthy, 1981) drew on previously-unpublished material from the 1880s recorded by Ethel Hassell regarding the sighting of *jannock* spirits as water spouts, which were:

> … viewed with the greatest terror, for the meeting of the sea and the sky, except on the edge of the world, was regarded as a most unholy union which could bring nothing but misfortune to the unlucky witnesses. If a native saw the sea rising and the clouds lowering to meet it, he at once informed the tribe and they broke camp immediately to move as far inland as their boundaries would permit. They allowed a long time to elapse before they returned to that spot. (Hassell and Davidson, 1936: 702).

Figure 5: A portrait of Watkin Tench circa 1800 (courtesy: Mitchell Library, State Library of New South Wales).

In 1788, the British marine officer Captain Watkin Tench (Figure 5), who arrived in Sydney with the First Fleet in 1788 and returned to England in 1792, wrote of the Aborigines at Botany Bay:

> The native of New South Wales believes that particular aspects and appearances of the heavenly bodies predict good or evil consequences to himself and his friends … Should he see the leading fixed stars (many of which he can call by name) obscured by vapours, he sometimes disregards the omen, and sometimes draws from it the most dreary conclusions. (Tench, 1788–1792: 249).

Figure 6: C.P. Mountford in 1947 (courtesy: National Archives of Australia, A1200/1).

Aboriginal people routinely looked for omens in the heavens (Clarke, 1997: 138–139; 2009a: 52–53; Hamacher and Norris, 2010a; 2010b; 2011; Johnson, 1998: 86–89).

In the eyes of Aboriginal observers, the first Europeans to arrive in their country were their own deceased kin in spirit form, having returned from the Skyworld (Clarke, 1999b: 154–155; 2007b: 143–144). At the time of British colonisation, it was widely believed by south-eastern Australian Aboriginal people that the eastern prop that held up the vault of the Skyworld had decayed, perhaps due to British expansion occurring in the region (Clarke, 2009a: 52; Willey, 1985: 55). They reasoned that unless formal gifts of possum skins and stone hatchet heads were sent to the old man who ritually looked after it, then people on the terrestrial plain would be crushed by the falling vault of the heavens. It was also believed that spirits of the deceased (i.e. Europeans) would cause havoc for the living, having returned from the Skyworld.

2.1 The Skyworld

According to Aboriginal tradition, the Skyworld was similarly organised to that of Earth, to the extent that the celestial bodies as ancestors were subject to the same laws as people and animals. For example, on the Adelaide Plains of South Australia, the *Mankamankarranna* stars (Pleiades cluster) were seen as girls who gathered roots and other vegetables around them in the sky (Clarke, 1990: 6; 1997: 136).[3] The connection between spirit ancestors and the sky is indicated in Western Desert culture with the word *pirntirripiriny*, which is an adjective for ‘immortal’ and literally means ‘like the stars’ in the Ngaanyatjarra and Ngaatjatjarra languages (Glass and Hackett, 2003: 324). In north-east Arnhem Land, Yolngu people believed that the *Junkgowa* ancestors made a man and two women as founders of a ‘horde’ (clan) to live in the heavens. The Reverend W.S. Chaseling from the Methodist Overseas Mission, who was the founding missionary at Yirrkala Mission in Arnhem Land in 1935, recorded that:

> This horde-family of the heavens lives as naturally as do the Yulengor [Yolngu]. By day the women forage for swamp rush-corms [spike rush or water chestnut, *Eleocharis dulcis*], water-lilies [*Nymphaea* species], and cycad [*Cycas* species] nuts, and at night sing and dance by the fire. (Chaseling, 1957: 149).

In a recorded Yolngu song concerning the *Mandjigai* (Sandfly clan) of the Wonguri language group, the deceased spirits in the Skyworld sat 'like mist' in the shade of paperbark (*Melaleuca* species) trees, living on bread prepared from cycad (*Cycas media*) nuts (Berndt and Berndt, 1999: 374). Similarly, the South Australian mechanic turned anthropologist/filmaker C.P. Mountford (Figure 6; Jones, 2000), who made a succession of expeditions to Northern Australia during the 1940s and 1950s, has reported that according to a western Arnhem Land Aboriginal tradition there is a family of Skyworld inhabitants called *Garakma* who roam across the heavens foraging for water-lily (*Nymphaea* species) bulbs in the Milky Way and gathering fruit from a tree in the Coal Sack (Mountford, 1956: 487).

The cultural construction of space in classical Aboriginal Australia drew upon the body of knowledge concerning the perceived existence of spirits, both of the creative ancestors and deceased humans. It was an Aboriginal belief that the human soul fragments after death, leaving a 'ghost' spirit that may linger on Earth, while the ancestral component merges with the spirit ancestor, often via a sacred place, and then ascends to an existence within the Skyworld (Clarke, 1999b: 160–161; 2007b: 148–149). White (1904) claimed that:

> In parts of Queensland and South Australia the natives believed the "Milky Way" to be a sort of celestial place for disembodied spirits. They said it was the smoke proceeding from celestial grass which had been set on fire by their departed women, the signal being intended to guide the ghosts of the deceased to the eternal camp fires of the tribe.

A similar tradition existed in western Victoria. British-born W.E. Stanbridge (Figure 7; Hamacher and Frew, 2010) arrived in Australia in 1841, and in the early 1850s he purchased land near Daylesford north-west of Melbourne and further north-west at Lake Tyrrell, where he studied the culture of the local Indigenous people. In 1857 he reported that *Warring* ('Galaxy') was "The smoke of the fires of the Nurrum-bunguttias ['old spirits'] ..." (Stanbridge, 1857: 138). Spirit ancestors could be simultaneously seen as a feature of the landscape, such as a tree or a hill, and a celestial body like a star. For example, the Perth anthropologists, Professor Ronald Berndt and his wife Dr Catherine Berndt (Figure 8) from the University of Western Australia stated that for the southern desert peoples living in the vicinity of Ooldea in western South Australia:

> Most of the totemic ancestral beings are represented in the sky by stars and planets. Although they leave their material bodies on earth metamorphosed into stone, their spirits are the stars, etc. There seems to be some division of their spirits between their earthly metamorphosed bodies and the stars. In the sky they are said to be alive, and the movements of the stars, planets, constellations and the Milky Way are said to be part of their eternal wanderings. The women have some knowledge of the stars, but it properly belongs to the secret life of the men. (Berndt and Berndt, 1943: 62).

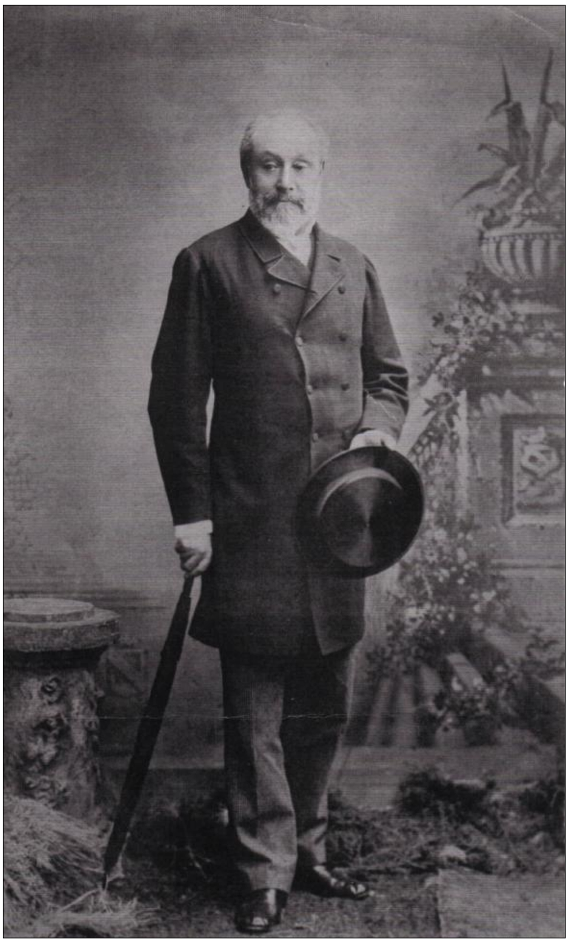

Figure 7: W.E. Stanbridge ca. 1880 (courtesy of Keva Lloyd).

Ancestors could also be seen in different forms, depending on whether it was day or night. For instance, Worms and Petri (1998: 158) remarked that it was tradition held by the Karadjari people of south-west Kimberley, that "*Bulanj* ['creative rain-serpent'] is the rainbow of the daytime sky and the river of the Milky Way in the night sky."[4]

Figure 8: Ronald and Catherine Berndt (es-es.facebook.com /R.M. Berndt).

Connections between human spirits and the Skyworld were broad, and involved both ends of a person's life. In Aboriginal Australia, it was widely believed that the ancestors produced the spirit children (Tonkinson, 1978). For instance, on the Adelaide Plains it was tradition that the souls of the unborn, newly arrived from the 'Land to the West', would hover among grass-trees (*Xanthorrhoea* species), and there wait for the hour of their conception (J.P. Gell, 1842 [cited Clarke, 2014a: 52]). Similarly, Yaraldi-speaking woman, Pinki Mack, stated that in the Lower Murray prior to birth "... children are said to be little, flying about in the air, dropped out of a bag and they could be caught." (A. Harvey, 1939 [cited Clarke 1999: 127]). The Berndts recorded that among the Yaraldi, the "Spirits of unborn babies inhabited a region located behind the vault of the sky (Waiyuruwar)." (Berndt et al., 1993: 133). During the early 1990s, an elderly Lower Murray Aboriginal man told the present author that the Ngarrindjeri term for 'stars' and 'semen' was "... all the same, *peli*'."

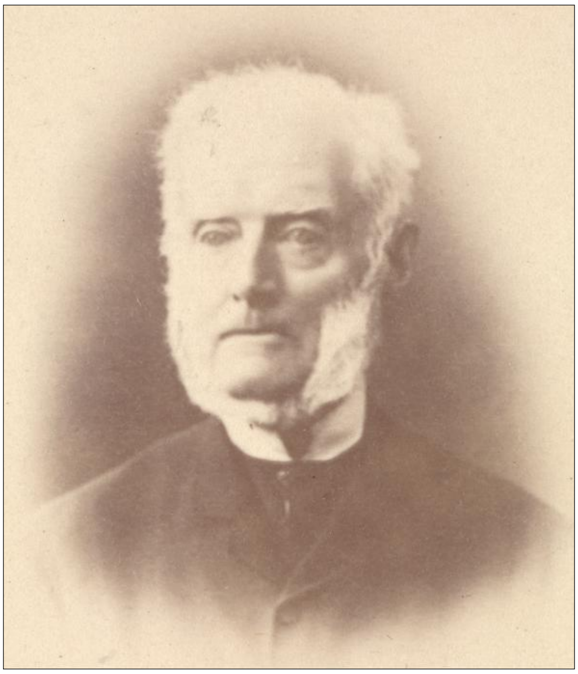

Figure 9: A photograph of James Dawson in 1892 by Johnstone, O'Shannessy & Co. (courtesy: State Library of Victoria, H2998/84).

In Aboriginal Australia, the Skyworld was a destination for the spirits of deceased people. For instance, Tench at Botany Bay in New South Wales claimed in 1788 that among the Aboriginal people here "When asked where their deceased friends are they always point to the skies." (Tench, 1788–1792 [1996: 252]). It was an Aboriginal belief that the spirits of the recently deceased followed the same or similar routes their spirit ancestors had taken through the Aboriginal landscape. In south-west Victoria, Scottish-born James Dawson (Figure 9; Corris, 1972), who from 1844 spent most the remainder of his life farming in the Camperdown area of Victoria studying the local Indigeous people and championing their cause, recorded:

> On the sea coast, opposite Deen Maar [Lady Julia Percy Island] … there is a haunted cave called Tarn wirring, 'road of the spirits', which, the natives say, forms a passage between the mainland and the island. When anyone dies in the neighbourhood, the body is wrapped in grass and buried; and if, afterwards, grass is found at the mouth of the cave, it is proof that a good spirit, called Puit puit chepetch, has removed the body and everything belonging to it through the cave to the island, and has conveyed its spirit to the clouds; and if a meteor is seen about the same time, it is believed to be fire taken up with it. Should fresh grass be found near the cave, when no recent burial has taken place, it indicates that some one has been murdered, and no person will venture near it till the grass decays or is removed. (Dawson, 1881: 51–52).

Spirits of deceased people were perceived as passing through the Underworld before making their ascent into the Skyworld.

The Skyworld country was humanised, as the ancestors had partitioned it into distinct areas by assigning celestial 'countries' to specific cultural groups. Adelaide-born Brian G. Maegraith (Figure 10; Radford, 2012) carried out anthropological research during university vacations while studying to be a doctor, before leaving Australia in 1931 and pursuing post-graduate studies at Oxford. He described Aboriginal astronomical traditions in an area of Central Australia where Western Arrernte people interacted with the Luritja of the Western Desert, and stated that:

> … the division into Aranda [Arrernte] and Luritja, depending upon the relation of the stars to the east or the west of the Milky Way, has been adhered to strictly; e.g., the stars Alpha and Beta Crucis, lying to the west of the galaxy, are classed as Luritja, whereas the stars Alpha and Beta Trianguli, which lie to the east, are classified as Aranda. (Maegraith, 1932: 21).[5]

Maegraith noted that there were many Aboriginal 'camps' seen in the night sky, with their identity dependent upon whether they were in the east or the west. In Mountford's account of the Pitjantjatjara culture of the Western Desert, the Skyworld was split up into two groups—the summer sky (Orion, Pleiades and Eridanus) and the winter sky (Scorpio, Argo and Centaurus) (Mountford, 1976: 450). In Western Desert kinship terms, the summer sky was considered to be *nganatarrka* (*nananduraka*), meaning the generation of one's self, grandparents and grandchildren.[6] The winter sky was *tjanamiltjan* (*tanamildjan*) and therefore of the parents' and children's generation level. Due to difficulties in translation, it is likely that the Indigenous words for 'heaven' that were recorded in the dictionaries of the colonial period variously concern several parts of the landscape rather than just one.

Some recorded accounts of the total landscape as it was during the Creation period are Utopian, depicting a golden age when food and water was easily procurable everywhere (e.g., Strehlow, 1947: 35–38). It was believed that afterwards this idyllic existence was generally restricted to the Skyworld, where deceased spirits who had left Earth continued their foraging activities in a land of plenty (e.g. Howitt, 1904: 434; cf. Strehlow, 1907 [cited in Goldenweiser, 1922: 211–212]). In central New South Wales, it was Aboriginal tradition that for the deceased there was plenty of fruit and grass seed in 'women's heaven', while activities such as hunting kangaroos in the celestial grasslands and fire-making were reserved for 'men's heaven' (McKeown, 1938: 8; Parker, 1905). In the historic period, such Indigenous beliefs would have resonated with the missionaries teachings of the Christian afterlife and possibly have appropriated from them.

Living people were generally barred from the sky, although there were some exceptions to the rule. Howitt recorded that the *kunki* or 'medicine-men' of the Diyari people of Lake Eyre in Central Australia:

> … can fly up to the sky by means of a hair cord, and see a beautiful country full of trees and birds. It is said that they drink the water of the sky-land, from which they obtain the power to take the life of those they doom. (Howitt, 1904: 359).

According to University of Sydney's Professor of Anthropology A.P. Elkin (Figure 11; Wise, 1996) healers ('medicine-men') reportedly learnt new songs and gained special knowledge of ritual from spirits in the heavens (Elkin, 1977: 22, 33, 53, 75–77, 79, 81, 87, 90, 124, 127). Their crossing into the Skyworld was achieved by various means, such as by climbing to the top of a large spirit tree or walking to the peak of a certain high hill (Clarke, 1997: 127–128; 2015; Howitt, 1904: 432–438). In many cases, such travel was part of the initiation for 'healers'.

The identities of celestial bodies varied across Australia, although the corpus of cosmological traditions was united by some common elements (Clarke, 2009a: 53–54). In general, the Moon and Sun ancestors were of primary importance, due to their dominating influence over the night and day skies respectively. Often the Moon was male and subordinate to the Sun, which had a female gender. While there are many structural similarities in Aboriginal beliefs concerning the Milky Way, Orion, Pleiades and Magellanic Clouds, there is considerable variation in accounts of the Southern Cross. In Aboriginal Australia it was believed that after the Creation period, ancestors in the Skyworld retained some influence over life on Earth, particularly in relation to the seasons and weather production (Clarke, 2009b: 82–88; 2015).

Figure 10: Queen Elizabeth II meeting Professor Brian Maegraith in 1954 (www.lstmliverpool.ac.uk/about-lstm/history-of-lstm/lstm-archives/maegraith-archive/).

2.2 The Underworld

The Underworld was an essential structural component of the Aboriginal cultural landscape. After

Figure 11: A.P. Elkin (courtesy: State Library of New South Wales, Government Printing Office 2-06647).

the ancestral Sun being had travelled through the Skyworld to the western horizon, it was generally believed to return by distant routes to the east (Clarke 2009a: 45). Some Aboriginal peoples considered the path back as being along the southern or northern edges of their country, while others thought it was underneath, via an underground passage through the Underworld. According to Howitt (1904: 428), the Wotjobaluk people of the Wimmera in western Victoria:

> … say that the sun was a woman who, when she went to dig for yams, left her little son in the west. Wandering round the edge of the earth, she came back over the other side.

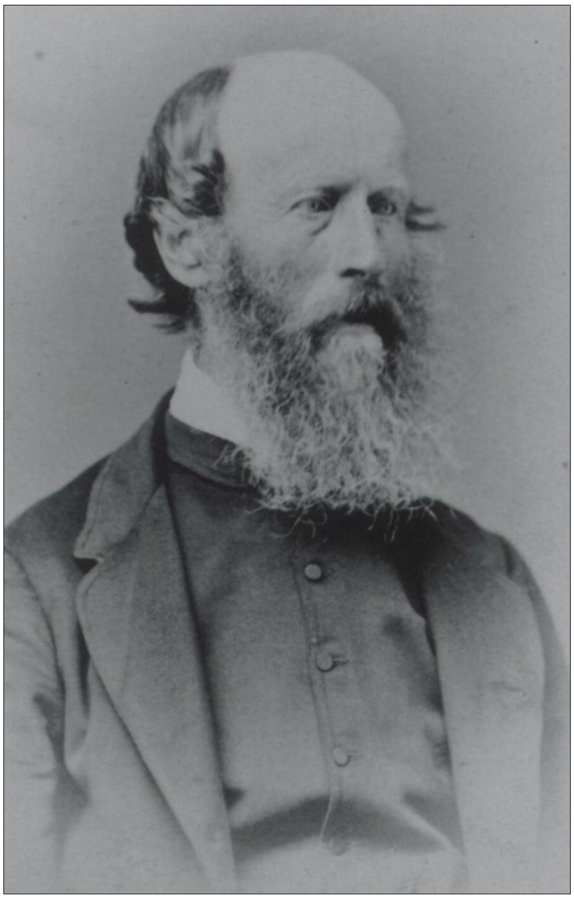

Figure 12: C.G. Teichelmann (courtesy: Leipzig Mission).

The neighbouring Kulin people, however, believed that when the Sun disappeared in the west, she entered a cave at a place called *Ngamat*, which had the appearance of a hole in the ground like that left behind by a large tree burned in a bush fire (Howitt, 1904: 432). Caves feature in many Aboriginal traditions that concern the Sun and other ancestral beings (i.e. Clark, 2007; Howitt, 1904: 427–428; Smyth, 1878 (1): 456).

The existence of the Underworld is also important in traditions concerning the Moon ancestor. Mountford (1958: 174) recorded a belief among the Tiwi people at Melville and Bathurst Islands that:

> At one time the moon-man used to return to the east by a road just under the southern horizon. But a nest of hornets [wasps], which lived along that road, stung him so badly that he changed his path and now returns to his home by a northern route … Most informants, however, said that the moon returned to the east through the same underground world as the sun-woman.

With an Aboriginal model of 'curved' space, it is possible that all of the lower geographic spaces outside the periphery of Earth were treated as the same. The Underworld was sometimes recorded as the 'Land to the West' (Clarke, 1991: 64–66; 1997: 127).

3 FLORA AND THE AESTHETICS OF THE SKYWORLD

The flora was ever present in the Aboriginal accounts of where their spirits resided, with plants being perceived as part of the visible structure of the Skyworld. For instance, in southwest Victoria the crepuscular rays in the west after sunset were called "... rushes of the sun ..." (Dawson, 1881: 101). According to the German-born Lutheran missionary/anthropologist C.G. Teichelmann (Figure 12), who arrived in Adelaide in 1838 and established the first school for Indigenous people in South Australia on the banks of the River Torrens, the local Adelaide people in southern South Australia considered the Milky Way to be a large river, along the banks of which common reeds (*Phragmites australis*) were growing (Teichelmann, 1841: 8; cf. Clarke, 1990: 5; 1997: 134). A similar recording came from the Barwon River, near its junction with the Namoi River in central New South Wales, where the Weilwan people believed

> The Milky Way they call Warrambool, that is a strip of land abounding in fine trees and shrubs, with a stream of water running though it – home or promenade of the blessed dead ...

while the Southern Cross was called *Nguu* and represented a 'tea-tree' (W. Ridley, in Smyth, 1878(2): 286).[7] In the Gamilaraay group of languages in northern central New South Wales, the Southern Cross was called *Yarraan* and was seen as a large river red gum tree (*Eucalyptus camaldulensis*) like those that grow along the inland creek systems (Ash et al., 2003: 152; McKeown, 1938: 18).[8]

In Aboriginal Australia, terrestrial and celestial spaces possessed similar geographies. In some cases particular topographic features were seen as continuous. For instance, London-born G.A. Robinson (Figure 13; Robinson ..., 1967) who arrived in Hobart, Tasmania, in 1824 and spent the next 15 years studying the Island's Indigenous people, reported that in Tasmania it was perceived that established foot tracks through the woodland continued beyond the clan boundaries into the Skyworld, where they could be seen as a 'white streak' in the Milky Way going "... all along down to the sea." (Robinson, 1829–1834, cited by Plomley, 1966: 368). The floras of the Skyworld and Earth were also perceived as closely linked. In the Gulf Country of south-west Queensland, White (1904) observed that

> The natives of the Hamilton and Georgina Rivers called the star Venus mumungooma, or big-eye, and believed that it was a fertile country covered with bappa, or grass, the seeds of which were converted into flour, and that it was inhabited by blacks. There was no water in the star, however, but there were ropes hanging from its surface by means of which the earth could be visited from time to time and thirst assuaged.

The south-west of Queensland was part of a larger region where the grinding of grass seeds was a major subsistence strategy, particularly during droughts (Clarke, 2003a: 146–148). Aesthetically, the 'ropes' hanging from Venus in this account are equivalent to the 'strings' of the Morning Star (Venus) in the mythology of north-east Arnhem Land, both of which symbolically represent rays of light along which spirits can travel.[9]

Aboriginal orientation in terrestrial space was based upon the observed movements above of celestial bodies, particularly the Sun and the Moon, and the prevailing directions of the seasonal weather (Clarke, 2009a: 47–48). It is common in Aboriginal languages for the terms for 'west' to refer to the "... direction to which the Sun travels ...", while the 'east' is often associated with 'dawn' or 'Moon', and in some instances the word for 'south' is linked to 'cold' (Nash, 1992: 293–295; Tindale, 1974: 44–49). In Central Australia, desert dwellers used a variety of techniques to orientate themselves, including wind temperature and star position (Lewis, 1976: 274–276). Terrestrial places were also associated in myth with heavenly bodies. For instance, a place near Tanunda, which is north-east of Adelaide, was called *Kabminye*, which was said to mean 'Morning star' (Venus) (Cockburn, 1908 [1984: 111]).

The material culture of Aboriginal Australia has been shaped by a commonly-held sense of aesthetics, which can also be seen to influence what was perceived in the sky.[10] The orientation of stars was more relevant than the brightness of the individual elements (Clarke, 2009a: 46–47; Haynes, 1992: 128; MacPherson, 1881: 74). In Aboriginal Australia, colour is of fundamental importance when determining the significance of specific celestial bodies. For example, the traditions of the Arrernte people in Central Australia gave prominence to stars that are reddish or whitish, while largely ignoring those that are predominately yellow or blue (Haynes, 1992: 128; Haynes et al., 1996: 8; Maegraith, 1932: 25). In an Aboriginal perspective, celestial bodies that are not bright red or shiny white objects in the night sky are more likely to be seen as part of the background than as elements with individual identities. Aboriginal people in south-west Victoria perceived the 'smaller stars' as 'star earth' (Dawson, 1881: 99).

Celestial features other than stars and planets were important too. Wiradjuri people in central New South Wales perceived the dusky haze of the Great Nebula as the smoke from the ancestors' fires upon which mussels from the great Skyworld river (the Milky Way) were being cooked (McKeown, 1938: 18).[11] Irregular phenomena in the skies were mostly attributed to the unpredictable actions of ancestors present in the Skyworld. London-born and Oxford-educated Walter E. Roth (Figure 14; Reynolds, 1988), a doctor who practised in north-west Queensland from 1894 and then became the first 'Northern Protector of Aboriginals' in 1898 based in Cooktown, reported that the Aboriginal residents of Mapoon in northern Queensland considered that a comet observed during May 1901 had been caused by two elderly women ancestors lighting a fire (Roth, 1903: 8).


Figure 13: G.A. Robinson (courtesy: en.wikipedia.org).

Aboriginal observers did not generally recog-

Figure 14: Walter E. Roth (courtesy: en.wikipedia.org).

nise shapes formed by connecting individual stars, although strings of stars representing clusters of ancestors were perceived as making tracks across the night sky. For instance, a nineteenth century newspaper correspondent outlining Aboriginal celestial lore remarked that

> Stars that are in a line either horizontally or perpendicularly are generally honoured with a legend, in some cases extending over two or three of our constellations … For the most part groups forming curves or angles are apparently ignored. (E.K.V., 1884).

Meanwhile, Maegraith (1932: 19) stated that in Central Australia,

> ... the aborigine has not generally adopted the idea of tracing out a figure amongst the stars, a single star usually representing a whole animal or its track.

By way of example, he explained how he had obtained an account of the arrangement of stars (Gamma Crucis, Delta Crucis, Gamma Centauri and Delta Centauri) that comprised *Iritjinga*, the Eaglehawk ancestor, and:

> On being asked which stars represented the wings, head, legs, etc., of the bird, the aborigine's response was always to the effect that the group of stars as a whole represented the hawk, no star separately indicating any particular part of the bird's anatomy. (Maegraith, 1932: 20).

In the adjacent southern regions of South Australia and Western Australia, Irish-born self-taught anthropologist Daisy M. Bates (Figure 15; De Vries, 2008; Reece, 2007) who lived in small settlements in Western Australia and South Australia from 1899 and tirelessly studied Indigenous culture for the next 40 years, noted that the planets Jupiter and Venus were seen by desert Aboriginal people as 'heads', not bodies, who were "... always following one another along the 'dream road' which they themselves had made." (Bates, 1936). In summary, Maegraith (1932: 26) claimed that "In general, the figured constellation is rare in aboriginal astronomy, a single star representing a whole animal or its tracks." These observations are at odds with some more recent Aboriginal sky maps, which are not part of the classical tradition (e.g. Cairns and Yidumduma Harney, 2004).

The flora is prominently mentioned in myth narratives that concern the colours of the Skyworld. In the Darling River area, it was believed that

> … the planet Jupiter was a great Kilpun-gurra [a moiety] man of the olden days, called Wurnda-wurnda-yarroa, who lived on roasted yams, and got his reddish colour by being so much about the fire cooking his food. (Mathews, 1904: 283).

Given the colour description it is possible that surveyor and self-taught anthropologist R.H. Mathews (Figure 16) had confused Jupiter with a bright red star. In Central Australia, the Anmatyerre-speaking people considered a bright star or planet (such as Mars) as *lherrm-penh*, meaning "... something that had been burnt in the flames." (Green, 2010: 395). In an account of the mythology of Logan River in Brisbane it was said that little girls were taken to the Skyworld "... where they for ever shine in colours like the flowers they were wearing." (Hanlon, 1934).

The notion of red being a powerful colour for Aboriginal people is supported by a late eighteen-

Figure 15: Daisy Bates (en.wikipedia.org).

th century account from the central eastern Australian coast, where Haynes (2009: 11) noted that:

> … meteors are associated with fire and linked to the waratah plant, *Telopea speciosissima*, a member of the Protea family, which is resistant to fire and whose brilliant red flowers seemed to the Aborigines like sparks from a fire, as each petal is shaped like a miniature meteor. This was why, in the early years of white settlement, some Aborigines brought waratahs to the European blacksmiths: they identified the sparks from the anvil with meteors and hence with the waratahs.

According to Peck, it was an Aboriginal belief in the Blue Mountains area of eastern New South Wales that waratah foliage had the power to repel heat (see Figure 17). Concerning the local Aboriginal people, it was stated:

> In the earliest days of white occupancy of Australia they brought these [waratah] stems to blacksmiths and told them that they could never be injured by fire from the anvils, which they took to be supernatural fire such as that seen in the heavens when there is a meteor travelling there, if they used them, and to please the natives the blacksmiths did use them and paid in those showy trifles that the natives valued, for them. (Peck, 1933 [2014: 129]).

The waratah had cultural significance for hunter-gatherers, shown on one occasion when Sydney Aboriginal people placed a waratah flower alongside the body of an Aboriginal man being buried (Collins, 1798–1802(2): 66). Foragers also obtained nectar by sucking its tubular flowers (Maiden, 1889: 62). It was perceived that the power from the heavens could be lodged in other plants. An anonymous writer in a newspaper claimed that an Aboriginal myth, probably from the Australian east coast, "... states that the gum in the hearts of wattle trees [*Acacia* species] is made by shooting stars lodging there and breaking into bits." (Anonymous, 1904a). The pale honey-like gum of certain wattles was a major food source, as well as a wider variety being used medicinally and as hafting cement for artefacts (Clarke, 2007a: 18, 22, 101, 120; 2012:134–135; see Figure 18).

In the Underworld the presence of wood, and therefore trees, is inferred in many descriptions concerning the illumination of the Sun, which has this ancestor gathering fuel during the night for burning the next day during its journey across the sky (Macdougall, 1912). Aboriginal groups living across the inland river systems of south-eastern Australia credited their supreme male ancestor, *Baiame*, with creating a fire which was seen as the Sun (Beveridge, 1883: 60–61; Haynes, 1992: 130). Here, the warmth of the day linked to the strength of his fire and how much fuel was left to burn.

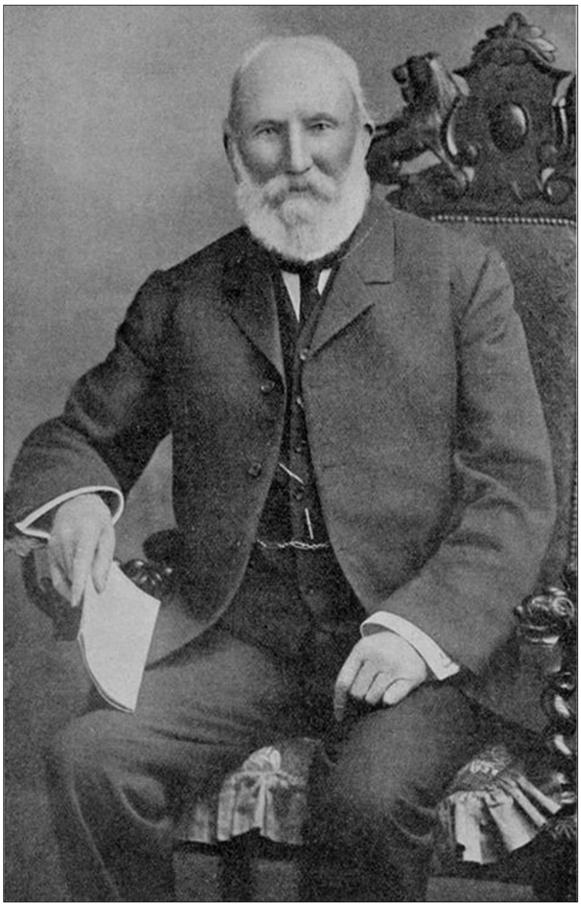

Figure 16: R.H. Mathews (after Mathews, 1909).

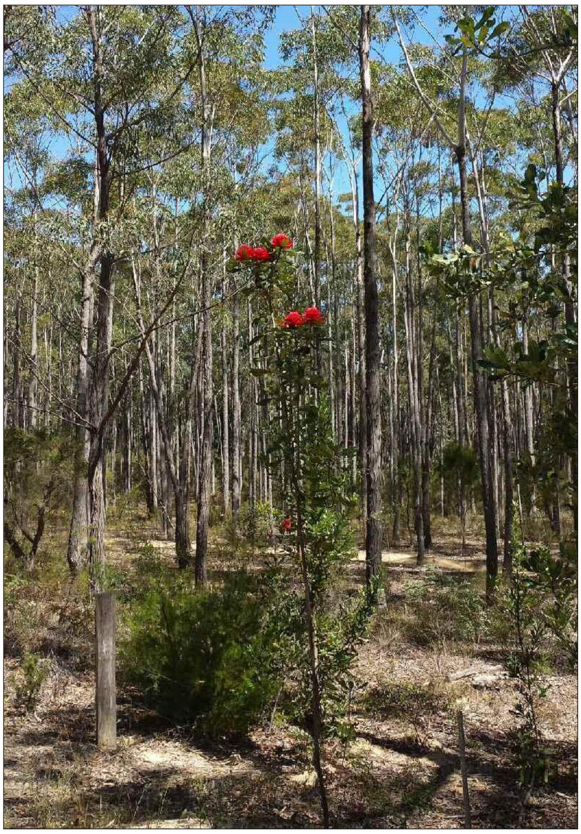

Figure 17: Waratah (*Telopea speciosissima*) in eucalypt woodland, the flowers of which were symbolically 'meteors' and the foliage thought to repel heat (courtesy: M.R. Clarke private collection, McPherson State Forest, New South Wales, 2014).

Figure 18: Golden wattle gum (*Acacia pycnantha*), possibly seen by some Aboriginal groups as the remains of 'shooting stars' (P.A. Clarke private collection, Mount Bold, South Australia, 1985).

Mrs Catherine (Katie) Langloh Parker (1856–1940; Muir, 1990) was born at Encounter Bay, South Australia, and after marrying at age 18 she moved to her husband's property near Angledool, New South Wales, where for the next two decades she studied the culture of the local Indigenous people. For a popular readership Parker (1896 [1953]) presented stylised accounts of the mythology possessed by the Ualarai people of central northern New South Wales.[12] A myth involving the male ancestor *Baiame* concluded with the formation near *Warrambool* (Milky Way) of *Yaraan-doo*, the "... place of the white gum-tree ..." (river red gum) which Europeans see as the Southern Cross (McKeown, 1938: 18; Parker, 1896 [1953: 9–10]; 1905 [2013: 123]).[13] Parker explained:

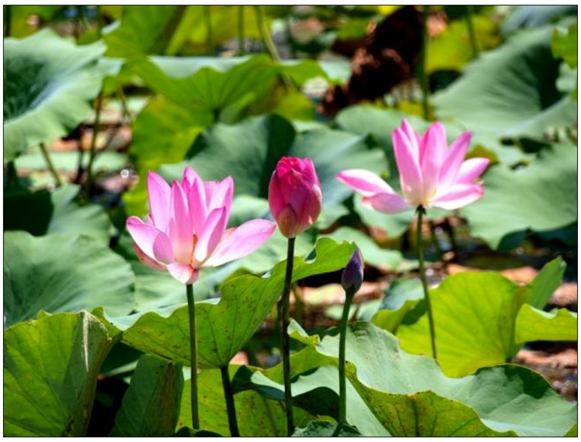

Figure 19: Lotus ('red lily', *Nelumbo nucifera*) flower, which in Arnhem Land represents the 'evening star' sitting on top of a stem that is symbolic of its path. P.A. Clarke private collection, Kakadu, Northern Territory, 2010

> The Southern Cross was the first Minggah, or spirit tree a huge Yaraan, which was the medium for the translation of the first man who died on earth to the sky. The white cockatoos which used to roost in this tree when they saw it moving skywards followed it, and are following it still as Mouyi, the pointers. The other Yaraan trees [river red gums] wailed for the sadness that death brought into the world, weeping tears of blood. The red gum [kino] which crystallises down their trunks is the tears. (Parker, 1905 [2013: 123]).[14]

A man had been extracted from Earth with the tree and placed in the night sky, along with two *Mouyi* (*Mooyi*, Sulphur-crested Cockatoo ancestors) who, as the Pointers, had unsuccessfully tried regaining their roosting place.

The theme of rebirth is expressed with plants. At Tully River in northern Queensland, it was tradition that *Carcurrah* the Moon ancestor was pushed back into the sky by the growing grass, after he had become dizzy and fallen to Earth (Henry, 1967: 34, 38). In north-east Arnhem Land, Venus as the 'evening star' is perceived as a spirit in the form of a lotus (*Nelumbo nucifera*) flower sitting on top of a stem that represents its path (Berndt and Berndt, 1999: 374–375; see Figure 19). Here, in a song, this ancestor was said to be

> Shining on to the fore-heads of all those headmen. On to the heads of all those Sandfly [clan] people. It sinks into the place of the white gum trees, at Milingimbi.

The lotus is important in many cultures across south-east Asia and beyond, as a powerful symbol of rebirth and purity (Clarke, 2014a: 146–149). In Top End varieties of Aboriginal English, the lotus is called 'red lily', and grows widely in billabongs (Clarke, 2014a: 148–149). Here, it was an important seasonal food source, as much of the plant is edible.

The cosmological traditions of Aboriginal Australia contain many references to objects made from plants. For instance, the Ngulugwongga people at Daly River in the Top End of the Northern Territory believed that the Milky Way was comprised of a grass plaited rope made by a woman who was trying to escape from her husband with her two daughters. According to the Berndts:

> The mother tossed the rope up into the sky. The elder sister climbed first, the younger sister was in the middle, and the mother came last. They climbed up the rope into the sky. There they sat down under their banyan [*Ficus*

> *virens*] tree, with their food, and they coiled the rope to form the extent of the Milky Way. (Berndt and Berndt, 1989: 345).

Other Aboriginal artefacts incorporating plant materials are also seen in the night sky. In north east Arnhem Land, a Crow ancestor placed a basket made from paperbark (*Melaleuca* species) into the celestial river (Milky Way), in which it is seen as a dark patch (Warner, 1937: 533). Arrernte-speaking people in Central Australia see a collection of stars (near the Pleiades, possibly the Hyades) as a 'yam stick', both of which are called *atneme* (Henderson and Dobson, 1994: 310). The neighbouring Anmatyerr-speaking people further north-east, had a similar belief, calling the constellation and the digging tool *anem* (Green, 2010: 88). In the Anmatyerr language the word, *uralep*, means both 'firestick' and 'a group of stars' (Green, 2010: 533). Inland from the Great Australian Bight, the Milky Way was perceived as a large sacred board, a symbolically-decorated sheet of bark (Ker Wilson, 1977: 1–28). Aboriginal people in western Victoria had a tradition that the Pointers were hunters that killed the Emu in the sky, seen as the Coal Sack, with their spears stuck in a tree, represented by the Southern Cross (MacPherson, 1881: 72; Massola, 1968: 106–108; Stanbridge, 1857: 139).

4 CONCLUDING REMARKS

In Aboriginal cosmology, the perceived Skyworld was a distorted reflection of the terrestrial landscape, with many shared species of plants living in both places. While human visitors to the Skyworld were able to bring back to Earth 'new' rituals and songs they had learnt above, there is no evidence suggesting that different types of plants existed in the sky. Aboriginal people perceived the Skyworld flora to be essentially the same as that found in their own country on Earth, although perhaps with favoured and useful species existing in greater abundance for the benefit of the spirits of deceased hunter-gatherers. In contrast, in most Aboriginal traditions the Underworld through which the Sun and Moon passed appears to have been a country without plants, apart from piles of dry wood used by the Sun to maintain a fire. The ethnobotanical investigation of Skyworld floras can be insightful when determining which plant species have special cultural significance, with species of seasonal importance to hunter-gatherers on Earth being seen as prominent in the heavens.

5 NOTES

1. Hassell and Davidson (1936) use the term 'Wiilman', while the form favoured by Tindale (1974: 260) is 'Wheelman'.
2. Clarke (1986: 6–7; 2007a: 22, 35, 56) described the Aboriginal use of lerp.
3. Spelling variations of *Mankamankarranna* include *Mankankarrana* and *Mangkamangkarranna*.
4. Worms and Petri (1998) use the term 'Karadjari', while the form favoured by Tindale (1974: 244) is 'Garadjeri'.
5. Maegraith (1932) uses the term 'Arunta' when referring to the Arrernte people (Sutton, 1995: 149–153).
6. Generational kinship terms are described by Glass and Hackett (2003: 216, 420).
7. Ridley (1875) uses the term 'Weilwan', while the form favoured by Tindale (1974: 200) is 'Wailwun'.
8. In the literature, spelling variations of *yarraan* include *yaaran* and *yaraan-doo*.
9. Refer to Morphy (1998: 226–230) for a description of the Barnumirr (Morning Star) ceremony.
10. For descriptions of Australian Aboriginal decorative traditions refer to Morphy (1998) and Sutton (1988).
11. McKeown (1938) uses the term 'Wiradjurie', while the form favoured by Tindale (1974: 201) is 'Wiradjuri'.
12. Parker uses the term 'Ualarai', while the form favoured by Tindale (1974: 199) is 'Euahlayi'.
13. Refer to Ash et al. (2003: 152) for word derivations of *yaraan*, *yarraan*. McKeown (1938) refers to *Baiame* as *Byamee*.
14. See Elkin (1977: 91) for an explanation of *minggah*.

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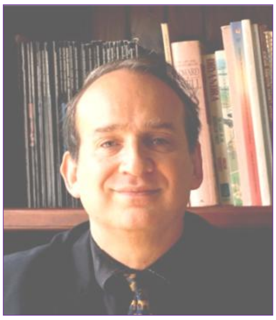

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DECLINATIONS IN THE *ALMAGEST*: ACCURACY, EPOCH, AND OBSERVERS

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Abstract: *Almagest* declinations attributed to Timocharis, Aristyllos, Hipparchus, and Ptolemy are investigated through comparisons of the reported declinations with the declinations computed from modern positions translated to the earlier epochs. Consistent results indicate an observational accuracy of ≈ 0.1° and epochs of: Timocharis, c. 298 BC; Aristyllos, c. 256 BC, and Hipparchus, c. 128 BC. The ≈ 42-year difference between Aristyllos and Timocharis is confirmed to be statistically significant. The declinations attributed to Ptolemy were likely two distinct groups—observations taken c. AD 57 and observations taken c. AD 128. The later observations could have been taken by Ptolemy himself.

Keywords: The *Almagest*, Aristyllos, Hipparchus, Ptolemy, Timocharis, stellar declinations

1 INTRODUCTION

The declinations of stars in the *Almagest* are given in Book VII, Chapter 3. In some translations (e.g., Taliaferro, 1952) they are given in the text following the practice of earlier Greek language versions (Heiberg, 1903; Ptolemy, 1538), whereas our principal source (Toomer, 1998) lists the declinations in a table. There are three values for each of 18 stars for a total of 54 observations. The observers are listed as Timocharis, Aristyllos, Hipparchus, and in Ptolemy's words (Toomer, 1998), "As found by us." We refer to the latter as Ptolemy(?) because of uncertainty in his participation. See Section 4 for discussion. These declinations were given without their right ascensions. Declinations are relatively easy to observe. An observer with knowledge of the observing site's latitude can determine a star's declination by measuring its altitude at meridian crossing. Right ascension measurements are more difficult and involve determining a star's angular distance from the right ascension zero point or from a star of presumed known right ascension (e.g., van de Kamp, 1967: Chapter 2, Section 2). The actual observers (besides possible problems with Ptolemy) are somewhat in doubt. We discuss this in Sections 2, 3, 4 and 5.

We note that the declinations that are the subject of this paper are only those recorded in the *Almagest* (Book VII, Chapter 3) and are not augmented from other sources. Specifically, Manitius (1894) gave some 44 declinations from Hipparchus in his *Commentary on Aratos.* These are not close to the *Almagest* declinations in accuracy (Maeyama, 1984) and we do not consider them here. Also note that the declinations under discussion in this paper are distinct from Ptolemy's extensive star catalogue in which the positions are recorded in ecliptic latitude and longitude (Toomer, 1998: 341–399).

Ancient astronomical data can assist modern astronomy by providing specific information such as the date and circumstances of an eclipse (Eddy, 1987) or by providing insight into the origins of modern astronomy. Understanding the *Almagest* declinations is significant because they are an important facet of the beginnings of modern astronomy, via astrometry. Evans (1998: 259) notes that the observations by Timocharis are the oldest observations of position in Greek astronomy and that he "… may be considered the founder of careful and systematic observations among the Greeks." These observations were recorded, survived through history, and were accurate (as we will demonstrate). They were seriously used by Tycho Brahe (e.g., Brahe; 1648; Moesgaard, 1989) and Edmond Halley (e.g., Halley, 1717; cf. Brandt, 2010) many centuries later. Of course, there were other ancient astronomers actively observing the sky, particularly in Babylonia and China. They had lists or catalogues of star positions, but these did not have accurate star positions as their primary goal or did not survive. Babylonian astronomers determined the positions of approximately 31 stars in the zodiacal belt, the so-called Normal Stars, for use in their astronomical diaries as reference points for keeping track of the movements of the Moon and planets (Sachs, 1974; Sachs and Hunger, 1988). This list is probably the first catalogue of star positions. In discussing them, Sachs (1952) would write, that the "… catalogue of Normal Stars … Despite its grossness in rounding-off to integer degrees and its other inaccuracies of as much as 1° or 2°, is nonetheless a real catalogue …" China had a tradition of observing celestial phenomena and keeping records. These have been used, for example, to help determine the past motion of Halley's Comet as far back as 240 BC (Yeomans and Kiang, 1981). Some stellar positions were determined circa 300 BC and they were used to make a map of the heavens (Ronan, 1996; Thurston, 1994). Unfortunately, the original positions were lost. The *Almagest* declinations are special and we know of no other comparable stellar positions from this period in antiquity.

In this paper, we describe, review, and update several earlier approaches for evaluation and draw conclusions from the results. All involve a comparison of the recorded position to a modern calculated position that allows for precession and proper motion. These include the earlier work of Pannekoek (1955), Maeyama (1984), and Rawlins (unpublished manuscript, 1982a). Our preliminary reports were given in Brandt, Zimmer, and Jones (2011; 2013) and in Zimmer, Brandt, and Jones (2013). We also report on a new approach to the data (Section 3). All approaches are consistent with a remarkable accuracy of ≈ 0.1°.

Using translated modern positions to determine the epochs of historical observations has appeared in a recent paper (Barron et al., 2008). Their method yields epochs of images by running proper motions backward in time to produce the configuration that best matches the image. Thus, they fit an entire image rather than individual stars as done by the methods applied to the *Almagest* declinations.

2 THE DATA AND LISTED OBSERVERS

The *Almagest* declinations are listed in Table 1 following Toomer (1998) together with modern names and designations.

Table 1: Declinations in the *Almagest*[1]

Star		Declination(°)			
Almagest Description	Designation	Timocharis	Aristyllos	Hipparchus	Ptolemy(?)
The bright star in Aquila	Altair-α Aql	+5 $^{4}/_{5}$	—	+5 $^{4}/_{5}$	+5 $^{5}/_{6}$
The middle of the Pleiades	Alcyone-η Tau[2,4]	+14 ½	—	+15 $^{1}/_{6}$	+16 ¼
The bright star in the Hyades	Aldebaran-α Tau	+8 ¼	—	+9 ¾	+11
The brightest star in Auriga, called Capella	Capella-α Aur[4]	—	+40	+40 $^{2}/_{5}$	+41 $^{1}/_{6}$
The star in the advance shoulder of Orion	Bellatrix-γ Ori[4]	+1 $^{1}/_{5}$	—	+1 $^{4}/_{5}$	+2 ½
The star in the rear shoulder of Orion	Betelgeuse-α Ori	+3 $^{5}/_{6}$	—	+4 $^{1}/_{3}$	+5 ¼
The bright star in the mouth of Canis Major	Sirius-α CMa	–16 $^{1}/_{3}$	—	–16	–15 ¾
The more advanced of the [two] bright stars in the heads of Gemini	Pollux-β Gem	—	+33	+33 $^{1}/_{6}$	+33 $^{2}/_{5}$
The rearmost [of the bright stars in the heads of Gemini]	Castor-α Gem	—	+30	+30	+30 $^{1}/_{6}$
The star in the heart of Leo	Regulus-α Leo	+21 $^{1}/_{3}$	—	+20 $^{2}/_{3}$	+19 $^{5}/_{6}$
The star called Spica	Spica-α Vir[4]	+1 $^{2}/_{5}$	—	+ $^{3}/_{5}$	– ½
Of the three stars in the tail of Ursa Major -the one at the top	Alcaid-η UMa[4]	—	+61 ½	+60 ¾	+59 $^{2}/_{3}$
-the second from the end, in the middle of the tail	Mizar-ζ UMa	—	+67 ¼	+66 ½	+65
-the third from the end, about where the tail joins [the body]	Alioth-ε UMa	—	+68 ½	+67 $^{19}/_{30}$[3]	+66 ¼
Arcturus	Arcturus-α Boo[4]	+31 ½	—	+31	+29 $^{5}/_{6}$
Of the bright stars in the claws of Scorpius [i.e., in Libra] -the one in the tip of the southern claw	Zubenelgenubi-α Lib	–5	—	–5 $^{3}/_{5}$	–7 $^{1}/_{6}$
-the one in the tip of the northern claw	Zubeneschamali-β Lib	+1 $^{1}/_{5}$	—	+ $^{2}/_{5}$	–1
The bright star in the chest of Scorpius, called Antares	Antares-α Sco	–18 $^{1}/_{3}$	—	–19	–20 ¼

Notes:

1 This Table follows Toomer (1998), with additions.

2 The star η Tau is used as a surrogate for the middle of the Pleiades.

3 Toomer (1998) gives +67 $^{3}/_{5}$° in his table, but lists in a footnote a value of +67 $^{2}/_{3}$°, which he notes "… may be correct". We have adopted the mean or +67$^{19}/_{30}$°.

4 Denotes the six stars selected by Ptolemy for his precession discussion.

Declinations for these stars at a given epoch are readily calculated from modern observations allowing for precession and proper motion. We use position and proper motion values from *Hipparco*s (the European Space Agency's astrometry mission) (Perryman et al., 1997) and precession/geodesy based on NOVAS 3.0 (Kaplan et al., 2009). These modern data should be an improvement on input data used by Maeyama and Rawlins.

We can compute plots of residuals, the *O* (observed) – *C* (computed) declinations, versus epoch (given here by calendar year) for each observer. These are given in Figures 1, 2, 3, and 4. These plots are the basic data for analysis. They can be approached in different ways, but these plots plus some historical information are all that we have.

Uncertainty over the actual observers of the declinations starts with the *Almagest* itself. In an introductory paragraph to the declinations (Toomer, 1998: 330), they are described "… as recorded by the school of Timocharis, as recorded by Hipparchus, and also as determined in the same fashion by ourselves." Thus, the text implies that the declinations attributed to Timocharis might be part of a group effort. While the observations by Timocharis and Aristyllos are noted separately in the Almagest Table, Toomer lists their observations in the same column. To add to the general uncertainty, the translation by Taliaferro (1952) does not say "… school of Timocharis." For matters involving the Greek text and translation, we have consulted Dr Lorenzo Garcia, Classics Program, Department of Foreign Languages and Literature, University of New Mexico. The accurate translation

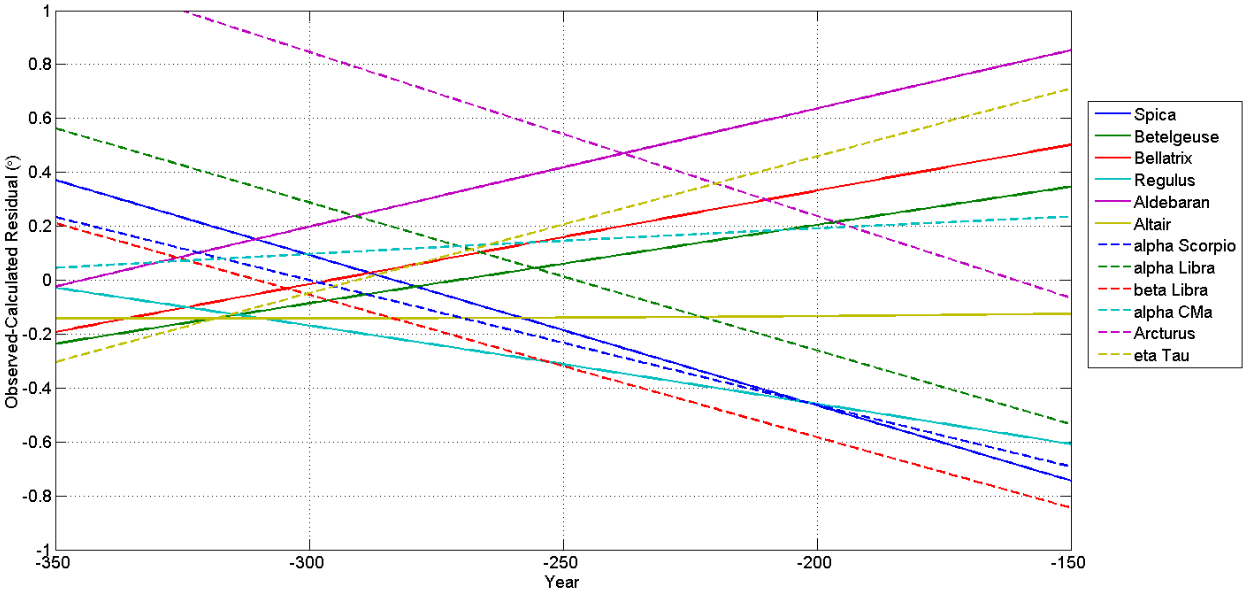

Figure 1: Residuals (Observed minus calculated, *O* – *C*, declinations) for Timocharis as a function of year.

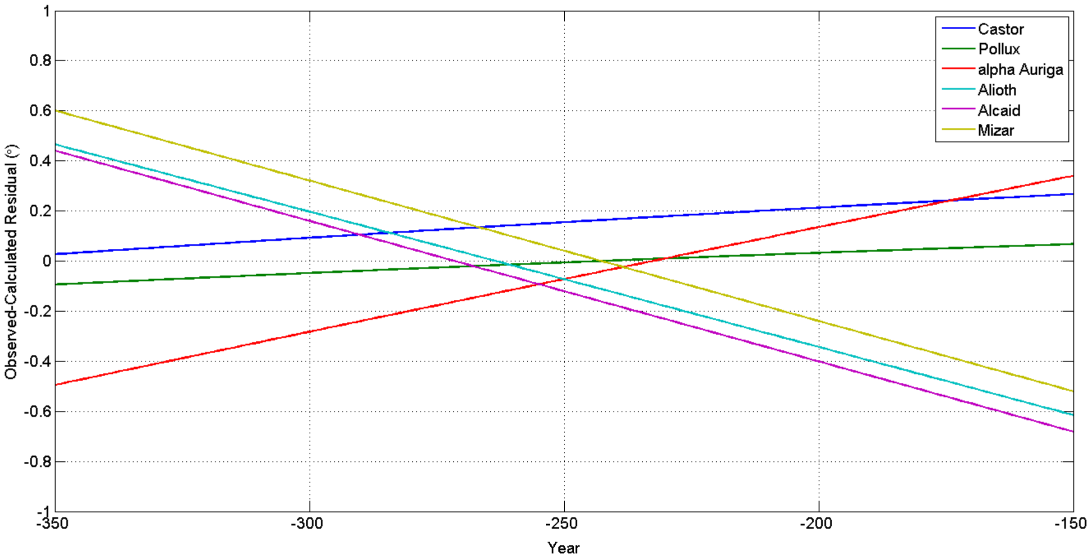

Figure 2: Residuals for Aristyllos as a function of year.

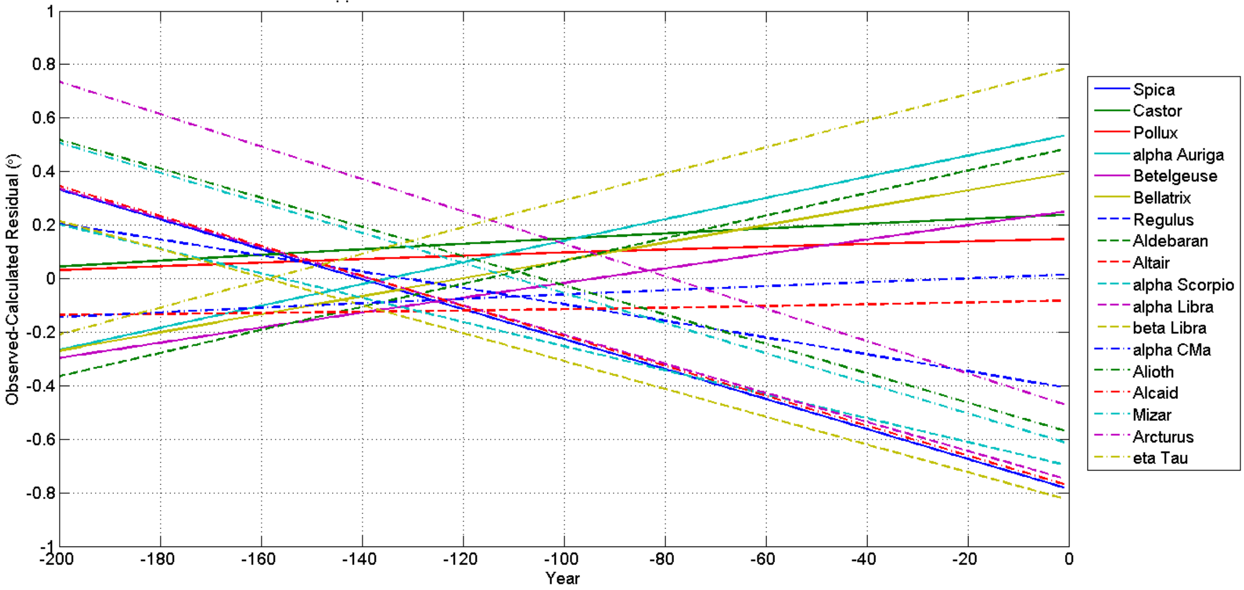

Figure 3: Residuals for Hipparchus as a function of year.

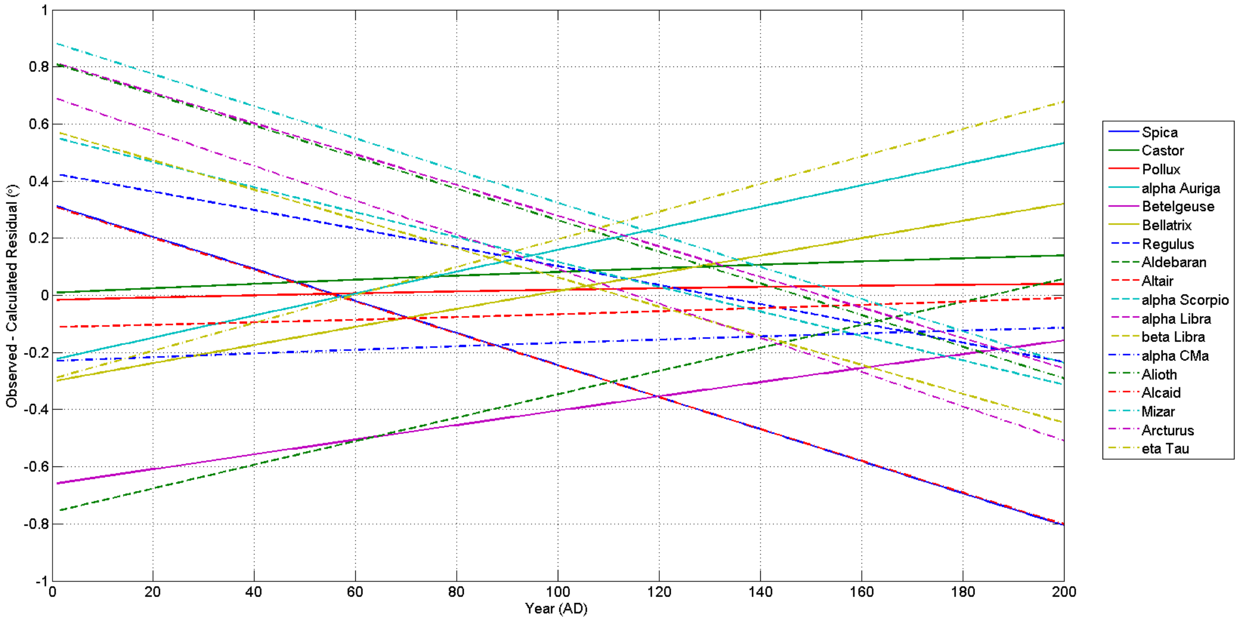

Figure 4: Residuals for Ptolemy(?) as a function of year.

is "… school of Timocharis." In this paper, we consider that the observers are as listed, but that others may have been involved. A special case is Ptolemy(?) as discussed in Section 4.

Historical information for the listed observers is as follows. Timocharis (Sarton, 1959: 53) is known from citations to his work by Ptolemy. He worked at Alexandria during the 290s and 280s BC, possibly in association with the Museum of Alexandria. The *Almagest* declinations mention Timocharis and Aristyllos together. Aristyllos may have been a student of Timocharis. Until recently, Timocharis and Aristyllos were thought to have worked during the same time period. Since the early 1980s, it has been clear that Aristyllos' declinations date approximately 30–45 years later than Timocharis' declinations. See Sections 3 and 5 for discussion.

Hipparchus (Sarton, 1959: 284−285) has specific references from Ptolemy in the time period 161–127 BC. He worked on the island of Rhodes. His lifespan can be estimated as c. 190 BC to c. 120 BC.

Ptolemy's lifespan has been estimated (Pedersen, 1974; Toomer, 1998) to be c. AD 100 to c. AD 175. The *Almagest* was written around AD 150 or perhaps a little later.

3 APPROACHES TO THE DATA

The earliest declinations were often not regarded as accurate. This idea goes back to Ptolemy himself. He notes that Hipparchus

> … had found very few observations of fixed stars before his own time, in fact practically none besides those recorded by Aristyllos and Timocharis, and even these were neither free

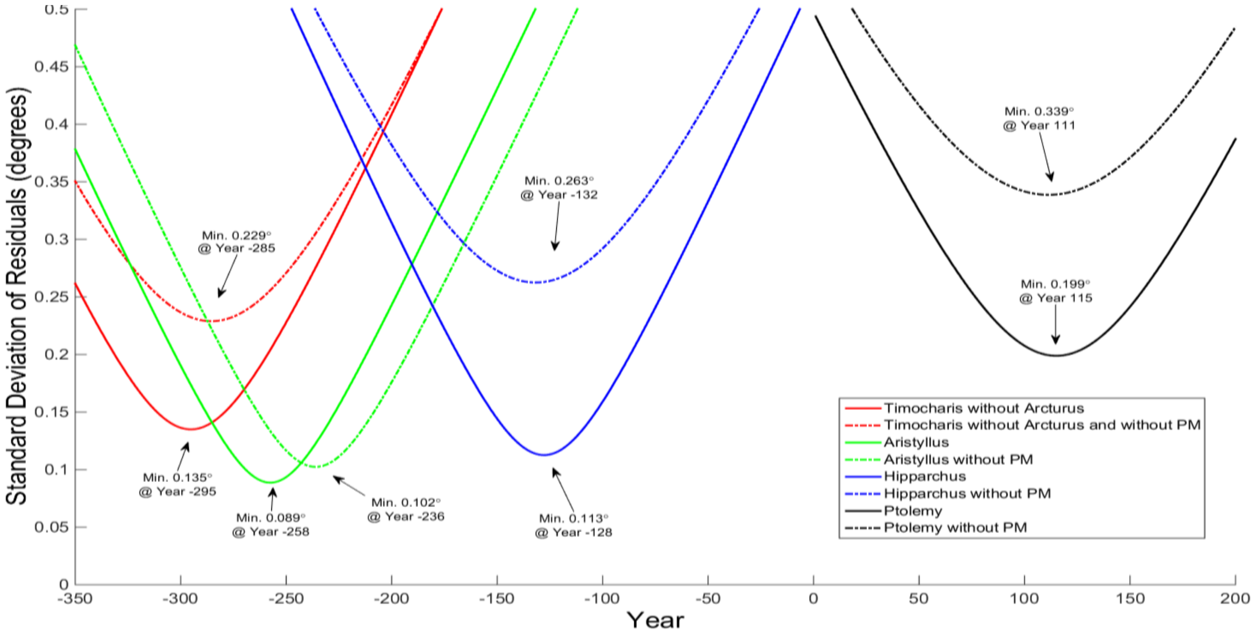

Figure 5: Standard deviation of residuals for Maeyama's method with and without proper motion.

> from uncertainty nor carefully worked out … Toomer, 1998: 321).

Ptolemy also writes (Toomer, 1998: 329) that "… the observations of the school of Timocharis are not trustworthy, having been made very crudely." This viewpoint has been repeated in modern times. Examples are the attribution of uncertainty or lack of accuracy to Aristyllos' observations (Taran, 1970) and to both Aristyllos' and Timocharis' observations by Neugebauer (1975: 287). Note that there was no known basis for this judgment since Pannekoek's (1955) paper (see just below) and we find (see Section 6) that these observations are accurate.

Pannekoek (1955) examined the accuracy by assuming the epoch and calculating the *C* position using simple precession formulae. Pannekoek took the relevant epochs to be 289 BC for Timocharis and Aristyllos, 129 BC for Hipparchus, and AD 137 for Ptolemy(?). He found mean errors of 0.15° for Timocharis (this value comes from dropping the observation for Arcturus; see Section 5); 0.12° for Hipparchus; and 0.22° for Ptolemy(?). Timocharis and Aristyllos were analyzed together using a single epoch, which we now know is incorrect. In addition, proper motion was not included. Pannekoek (1955) was apparently the first modern astronomer to show that the ancient declinations were accurate.

Maeyama (1984) used data from the Boss (1910) catalogue to calculate *C*. Then, he determined the RMS error in the residuals, *O* – *C* values, as a function of epoch. Finding the minimum in RMS error presumably fixes the epoch and thus the RMS error.

Maeyama (ibid.) analyses Timocharis and Aristyllos separately and finds epochs of 290 BC and 260 BC, respectively. See the additional discussion below and the statistical discussion in Section 5.

Proper motion is not mentioned anywhere in Maeyama's paper, yet it must have been included. His results are close to ours and a separate analysis with proper motion *not* included shows substantial differences as shown in Figure 5.

Results for RMS error and epoch from Maeyama (1984) are: Timocharis: 0.13°, 290 BC; Aristyllos: 0.087°, 260 BC; Hipparchus: 0.124°, 130 BC; and Ptolemy(?): 0.18°, AD 120. Note that Arcturus was dropped from the analysis for Timocharis by Maeyama and that the results for Ptolemy(?) are the raw or initial value. For example, Maeyama adjusts Ptolemy's(?) epoch to AD 130 by dropping three stars from the analysis. Maeyama notes that his historical sources indicate observational activity in the years AD 137/138. Also see the discussion in Maeyama, his Section 5.4.

We have repeated the analysis using Maeyama's method and the results are shown in Figure 5. Our accuracies (RMS) and epochs are: Timocharis: 0.135°, 295 BC; Aristyllos: 0.089°, 258 BC; Hipparchus: 0.113°, 128 BC; and Ptolemy(?): 0.199°, AD 115. We have also dropped Timocharis' observation of Arcturus from the analysis. See Section 5 for the statistical justification. Again, see below for additional discussion of the results for Ptolemy(?). Our analysis gives results close to those found by Maeyama (1984).

Dennis Rawlins produced a manuscript titled "Aristyllos' Date with Vindication and New Light on Ptolemy and the Roots of his Precession:

Table 2: Summary results.

	Accuracy (°)			Epoch			
Observer	Maeyama[1]	Rawlins[2]	*O* – *C* = 0[3]	Maeyama[1]	Rawlins[2]	*O* – *C* = 0[3]	Medians from Section 5
Timocharis[4]	0.135	0.135	0.135	295 BC	296 ± 11.0 BC	298 ± 13.2 BC	298 BC
Aristyllos	0.089	0.089	0.089	258 BC	256 ± 11.1 BC	259 ± 11.8 BC	253 BC
Hipparcus	0.113	0.113	0.113	128 BC	128 ± 7.3 BC	128 ± 8.4 BC	----
Ptolemy(?)[5]	0.199	0.199	0.199	AD 115	AD 115 ± 12.9	AD 117 ± 17.4	----
Ptolemy(E)[6]	0.023	---	---	AD 57	----	----	AD 56
Ptolemy(L)[6]	0.095	---	---	AD 128	----	----	AD 130

Notes:
1 Results from our updated calculation using Maeyama’s method; see Section 3.
2 Results from our updated calculation using Rawlins’s method: see Section 3.
3 Results from our approach as described in Section 3.
4 Timocharis’s declination for Arcturus dropped from the analysis for all cases; see Sections 3 and 5.
5 All results for Ptolemy(?) are based on the entire sample.
6 The division of Ptolemy(?) into an early (E) and a late (L) subset is described in Section 4.

Studies of Hellenistic Star Declinations” in the early 1980s. It was circulated, but not published. Maeyama (1984) noted its existence. Rawlins has kindly supplied a copy of this manuscript, which we denote as Rawlins (1982a).

In addition to epoch and accuracy, Rawlins was also interested in checking for possible errors in the latitudes of the observers. He wrote an equation based on the analytical expression for precession. This equation with minor changes in notation is:

$$O - C = x + t(p\sin\varepsilon)\cos\alpha = x + (E - E_o)P\cos\alpha \tag{1}$$

Here *O* – *C* = the observed minus computed declination (Section 2); *x* = the error in the observer’s latitude; $t = E - E_o$ = the difference in epoch from the assumed value; *p* = the annual precession; $P = p \sin \varepsilon$; *ε* = the obliquity of the ecliptic; and, *α* = the right ascension. The relevant quantity is *P*, and we have used 0.3338 arcmin/year, the same value that is used by Rawlins.

A least squares solution for a bivariate linear regression curve applied to the ensemble of stars for each observer yields the epoch and the error in the observer’s latitude. With the epoch determined, the accuracy immediately follows. Rawlins explicitly includes refraction. Rawlins’ results are: Timocharis: 0.15°, 296 BC; Aristyllos: 0.10°, 257 BC; Hipparchus: 0.12°, 132 BC; Ptolemy(?): Not available; see below. We note that Rawlins (1982b) quoted the separation between the epochs for Timocharis and Aristyllos in a discussion of Hellenistic astronomy.

Our repeat analysis using Rawlins’ method yields: Timocharis: 296 BC ± 11.0; Aristyllos: 256 BC ± 11.1; Hipparchus: 128 BC ± 7.3; Ptolemy(?): AD 115 ± 12.9. The epochs found by both analyses are quite similar. Rawlins did not present results for the entire sample of 18 stars possible for Ptolemy. Our accuracies are given in Table 2 and come from the RMS residual curves in Figure 5. They are the same as the accuracies for Maeyama’s method because the epochs are nearly the same and thus, close to the minima in the Figure 5 curves. Sirius was not used in the average for Ptolemy(?).

We return to the subject of the accuracies and epochs for Ptolemy’s observations in Section 4. Rawlins (1994) has presented a later table of his results for epochs and observers’ latitude. For Timocharis, Aristyllos, and Hipparchus, the epochs and latitudes are close to our values. For Ptolemy(?), Rawlins considers the observer to be Anonymous, and he gives an epoch of AD 131.

We can infer that the ancient observers knew their latitudes accurately. Our assumed latitude of 31.2° for Timocharis, Aristyllos, and Ptolemy(?) is appropriate for observations taken near Alexandria and the latitude of 36.2° assumed for Hipparchus is appropriate for observations taken from the island of Rhodes. The assumed latitudes enter the calculations directly through the refraction correction. For the epochs given in the previous paragraph, the accuracy of the observer’s latitudes is: Timocharis, 0.012° (excluding Arcturus); Aristyllos, 0.003°; Hipparchus, 0.004°; and Ptolemy(?), 0.009°.

3.1 The Resulting Epochs

The trajectories for individual stars (e.g., Figures 1–4) cross the x-axis (or *O* – *C* = 0) and these crossings can be used to estimate the epoch and the spread in epochs. The crossing epochs are shown in Figure 6. The full *O* – *C* program was not run outside the epoch ranges shown in Figures 1–4. Crossing times outside these epochs were determined from linear, quadratic, and quartic extrapolations. The dates from the different extrapolations are essentially the same except for Ptolemy(?)’s observation of Sirius. The linear extrapolation yields AD 389 while the quadratic and quartic extrapolations yield no zero crossing and a closest approach near AD 650. This is marked by the circle on Figure 6.

Our results for averages obtained using weighting by absolute value of the slope are as follows: Timocharis: 297.5 ± 13.2 BC; Aristyllos:

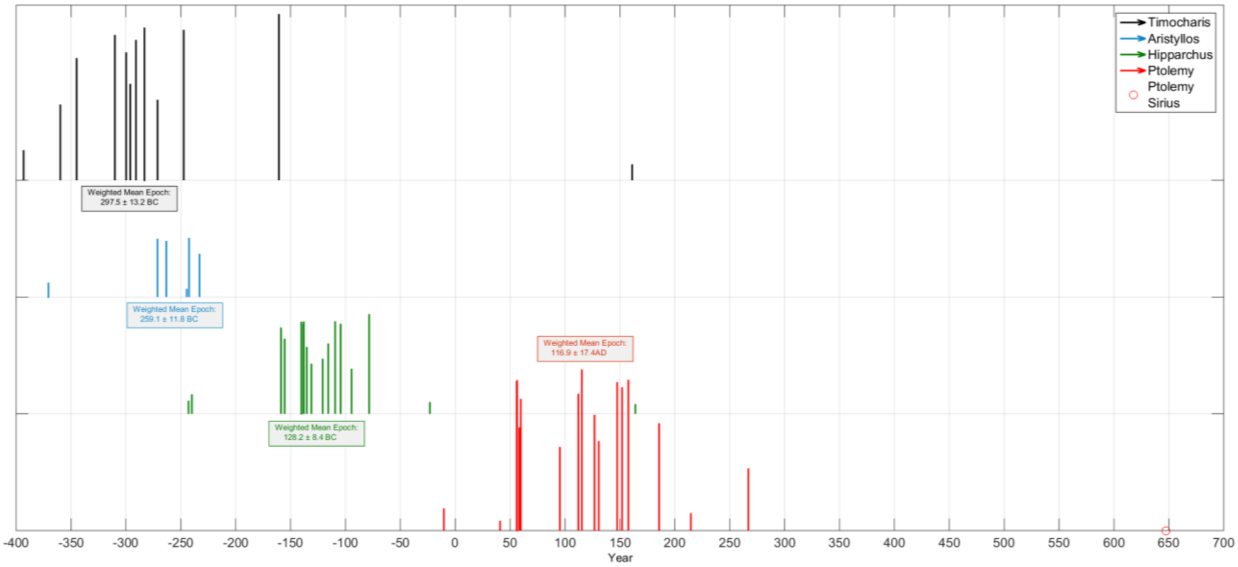

Figure 6: Dates of (O – C) = 0 for the different observers. The lengths of the bars are proportional to the absolute value of the slope.

259.1 ± 11.8 BC; Hipparchus: 128.2 ± 8.4 BC; and Ptolemy(?): AD 116.9 ± 17.4.

Inspection of Figure 6 shows that these dates are plausible. Figure 6 also shows grouping that will be discussed in Section 5.

4 PTOLEMY(?)

If we accept the probable dates for Ptolemy's life time of c. AD 100 to c. AD 175 and the likely date for the Almagest of c. AD 150 or perhaps a little later, we have a problem. The formal solutions for epoch in the range AD 115 to 120 are much too early for the observer to have been Ptolemy himself. Maeyama and Rawlins approach the situation by dropping observations from the analysis. Maeyama ultimately settles on AD 130. Although Maeyama (1984: 281) states that "… the names of different astronomers will only serve as a means to divide the available observations into different groups …" from the discussion later in the paper he (apparently) still considers that Ptolemy is the observer. Rawlins discusses values of AD 141 (based on 12 of 18 stars; dropping Ptolemy's six 'precession' stars, noted in Table 1) and AD 153 (based on 11 of 18 stars; in addition, dropping Betelgeuse) and considers the observer to be unknown, but not Ptolemy. Also recall that Rawlins (1994) gives an epoch of AD 131 for "Anonymous".

The computed measurement accuracies found for Ptolemy(?) in Section 3 are distinctly inferior to those found for Hipparchus; in addition, the spread in O – C = 0 dates found in Section 3 is much larger for Ptolemy(?) than for Hipparchus. Inspection of the O – C vs. epoch plots for Hipparchus (Figure 3) and for Ptolemy(?) (Figure 4) shows a much tighter grouping for Hipparchus than for Ptolemy(?). Specifically, the clustering near 130 BC is clear for Hipparchus, but no single clustering is plausible for Ptolemy(?). There are, however, two plausible clustering around AD 65 and AD 125, as clearly shown in Figure 6. Inspection of this figure suggested splitting the sample into zero crossings before and after AD 100 and that three observations were 'unhelpful'. These are Betelgeuse, Aldebaran and Sirius. They have zero crossings later than AD 200 and small slopes.

The results for two distinct samples are instructive. The formal solutions (Maeyama's approach) date the earlier sample to AD 57 (Figure 7) and the later sample to AD 128 (Figure 8). In addition, the computed accuracy for each is much improved. The summary results are shown in Figure 9. The summary includes the three observations that we deem unhelpful.

The statistical issues involved in considering the Ptolemy(?) observations as two distinct groups are described in Section 5. A cluster analysis is presented and we show that it is reasonable to divide these observations into two groups.

Our analysis leads to the conclusion that these *Almagest* declinations are reasonably attributed to two periods, an early (E) one around AD 57 (possibly associated with the Museum of Alexandria) and a late (L) one around AD 128. The fact that this latter date falls within the dates for Ptolemy being an active observer, AD 124–141, is unlikely to be a coincidence. Hence, the later observations could have been taken by Ptolemy himself.

We are not the first authors to suggest problems or worse for the declinations attributed to Ptolemy. Unfortunately, we find ourselves in the long-running dust-up concerning the legitimacy of Ptolemy's observations. This situation

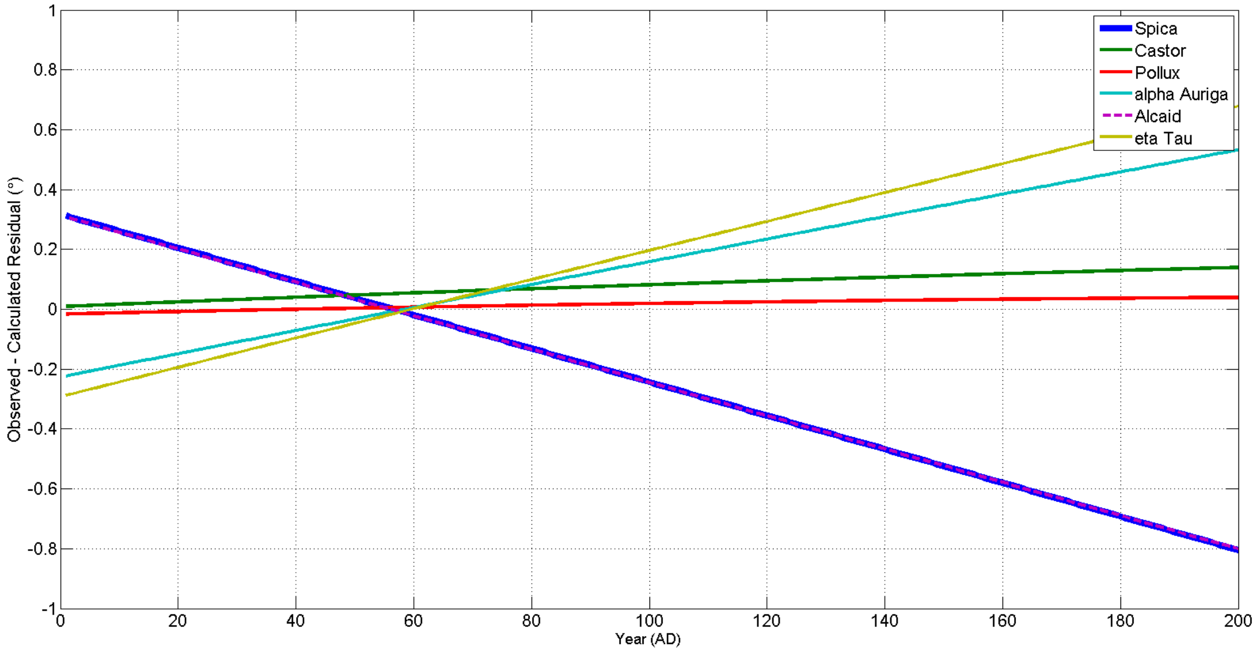

Figure 7: Residuals for Ptolemy's early group (E) as a function of year.

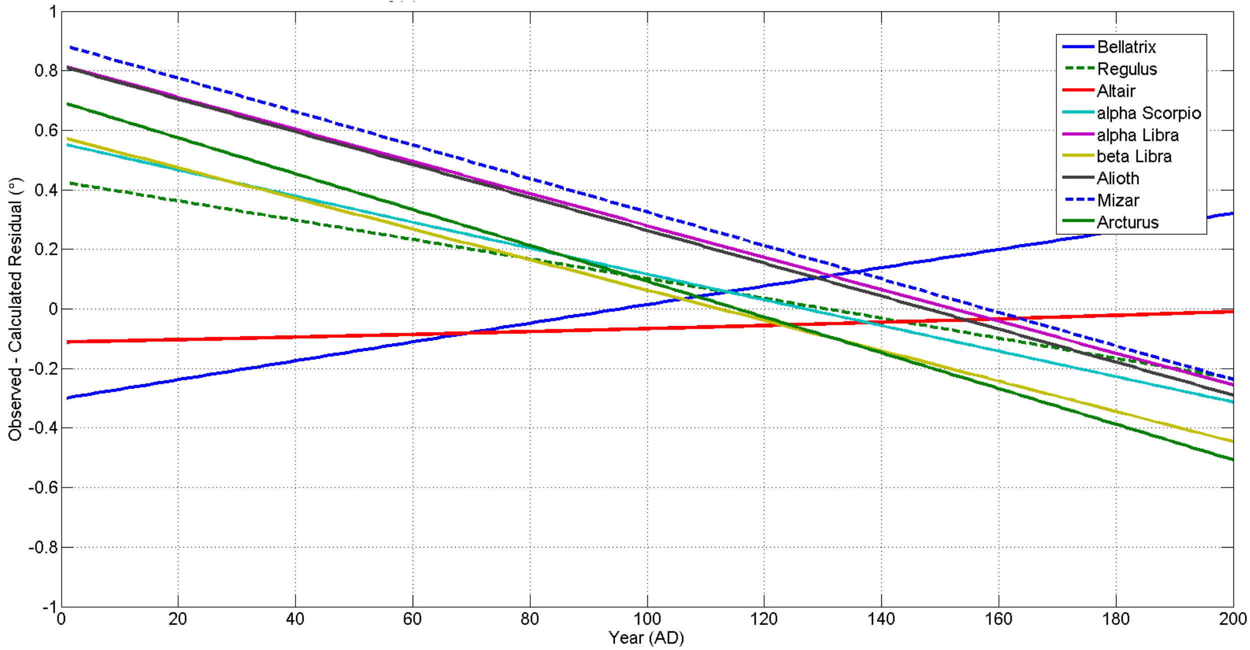

Figure 8: Residuals for Ptolemy's late group (L) as a function of year.

goes back at least to Delambre (1817; 1819) and was more recently reignited by R.R. Newton (1977). In our context, just after the declinations are given in the *Almagest* (Book VII, Chapter 3), Ptolemy selects just six stars (of the 18 available) to determine a value for precession. He finds 1° per 100 years, whereas the correct value is 1° per 72 years. Ptolemy offers additional evidence for his value elsewhere in the *Almagest* (e.g., Toomer, 1998: 338) and it is reasonable to believe that the six stars were selected because they yielded the desired result (see Duke, 2006 for additional discussion and references).

The situation has been nicely summarized by Evans (1998: 262):

> Few developments in science have so exercised the historians of science as Ptolemy's measurement of the precession rate. At stake is Ptolemy's reputation as an astronomer; at issue are his honesty and reliability as an observer.

Evans (1998) follows this quote with a short history of the issue of Ptolemy's reputation, primarily in the context of his Star Catalogue containing more than one thousand stars. We return to this subject after examining the statistical issues raised in our investigation. In the meantime, we note that Ptolemy does not literally claim to have observed all of these declinations by himself. The declinations are listed thusly: "As found by us …" (Toomer, 1998) or as "… we find." (Talia-

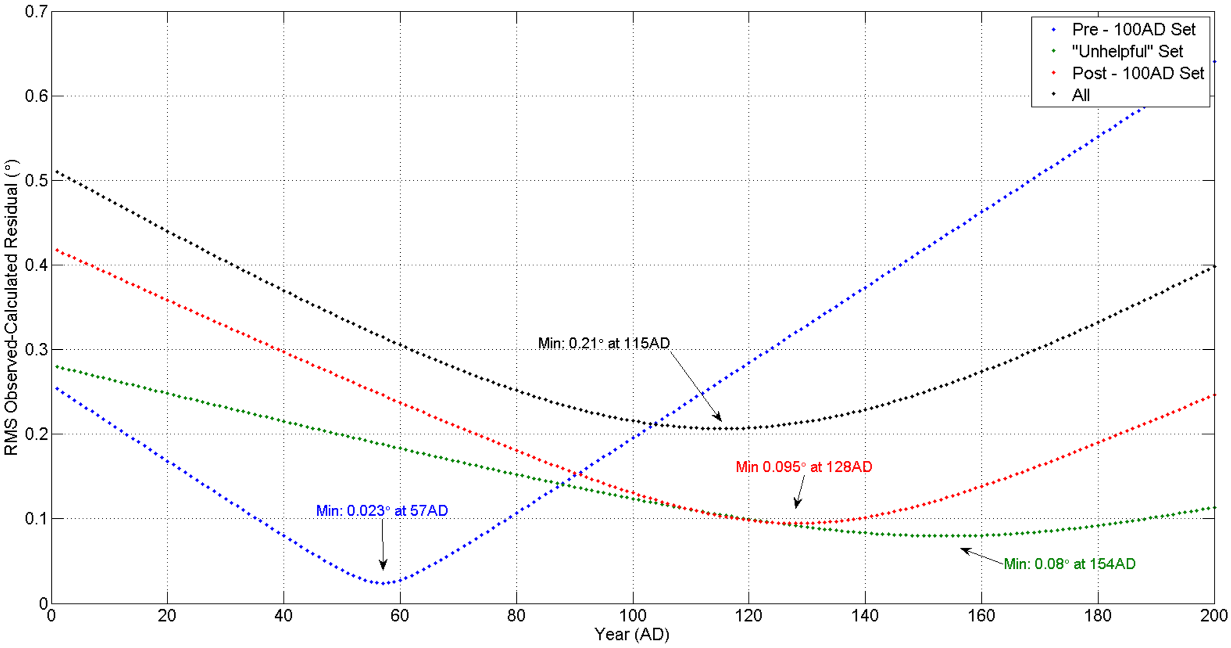

Figure 9: Standard deviation of residuals for the Ptolemy observations as a function of year showing the early (E) and late (L) groups.

ferro, 1952). But, we know from our consultation with Dr Garcia that the 'royal we' may be involved here. Finally, our groupings have no simple connection to Ptolemy's selected six stars. Of these, three fall in our early or AD 57 group, two fall into the later or AD 128 group, and one falls into our unhelpful group.

5 STATISTICAL ISSUES

In this Section, we examine several issues that are statistical in nature. First, our general approach is not to discard observations unless the decision is based on solid evidence. Timocharis' observation of Arcturus as reported is highly likely to be in error and has been discarded. The value is the same in all versions of the *Almagest* available to us. In addition, previous investigations (Maeyama, 1984; Pannekoek, 1955; Rawlins, 1982a) have also noted this. Our values show this point to be in error by 5.5σ for Timocharis' 11 observations or 7.7σ if the 17 observations of Timocharis and Aristyllos are taken as a group.

Are the dates for the observations by Timocharis and Aristyllos distinctly different? Until the early 1980s, as noted above, they were taken to be the same. Currently, the dates are considered to be different (Maeyama, 1984; Rawlins, 1982a; 1982b; 1994). Does a statistical analysis support this view?

Because the sample sizes were very small and the estimates of dates quite variable, we decided to investigate the crossing times using the Wilcoxon rank-sum test (rather than the more familiar two-sample *t* test) to determine whether the locations of the sample dates for Arystyllos and Timocharis differed significantly. The dates were rank ordered from lowest (earliest) to highest (latest) and the mean ranks were tested for differences. Two observations by Timocharis have been discarded, Arcturus, as noted above, and Altair. The later had an estimated crossing date of AD 518 and the slope was very small. If Timocharis and Aristyllos observed at approximately the same date, the mean ranking of the dates should be approximately the same in the two groups. The belief that Aristyllos observed later than Timocharis implies that Aristyllos' observations should have systematically higher rankings. For Aristyllos, five of the six observations had rankings that were ≥10 (only the value for Castor was small, rank = 2), while eight of the ten rankings for Timocharis were <10. The Wilcoxon statistic for the test was 69.00 with a Z approximation (Lehmann, 1975) yielding a probability of 0.0288. In other words, if the dates for the two observers were the same, a statistic this high or higher would be obtained by chance less than 3% of the time, suggesting that Aristyllos is quite likely to have observed at a later date than Timocharis. The best estimates for those dates from the approach taken here are probably the sample medians because the individual dates are highly variable. For Timocharis, the median date for the ten observations was 298 BC. For Aristyllos, the median date for six observations was 253 BC. These dates show a 45-year difference and the individual dates are remarkably close to the values obtained in Section 3 and given in Table 2.

Examining the difference between the two possible groups for Ptolemy(?) presents a rather

Table 3: Agglomeration schedule for Ptolemy's 14 stars.

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	1	15	.215	0	0	4
2	4	18	1.506	0	0	4
3	12	17	8.934	0	0	8
4	1	4	9.111	1	2	9
5	7	10	10.176	0	0	8
6	11	14	20.621	0	0	7
7	11	16	62.687	6	0	11
8	7	12	222.174	5	3	10
9	1	3	305.629	4	0	13
10	6	7	647.512	0	8	12
11	8	11	1079.407	0	7	12
12	6	8	1973.603	10	11	13
13	1	6	6675.667	9	12	0

different problem. Because the initial division date was chosen arbitrarily, it is inappropriate to do this kind of division and then test whether the division produces two meaningful samples based on the same criterion. We can use a hierarchical cluster analysis to examine the possibility of natural groupings.

Cluster analysis is a descriptive statistical procedure that is used to examine similarities among objects based on a distance parameter (Seber, 1984). Each star initially is in a cluster by itself. The two stars with the closest estimated dates or distances are combined first, creating a cluster with two objects in it. From the two initial clusters, now forming a single cluster, a heterogeneity coefficient is generated for the data set. Note that the initial value of the heterogeneity coefficient is zero when each star is in its own cluster. Then, the inter-cluster distances are recomputed and the two closest clusters are combined. This may be two other objects or the newly-formed cluster being combined with one other star. At each step, a new heterogeneity coefficient is calculated and the intercluster distances are calculated as well. This process continues until only a single cluster remains. Examining the heterogeneity coefficients, which increase as stars or clusters are added at each step, helps to determine natural groupings. The results can be presented in an *agglomeration schedule* to see the progression of the heterogeneity coefficients and to suggest natural orderings. Before proceeding to our results, we note that four stars were dropped from the final analysis. The crossing dates for these stars were determined using linear extrapolation (see Section 3) and seemed clearly problematic from the viewpoint of this analysis: Castor (21 BC), Altair (AD 226), Betelgeuse (AD 261), and Sirius (AD 389). These stars were included in an initial analysis, but their heterogeneity coefficients were so extreme compared to the rest of the observations that dropping them was appropriate. An analysis with similar dates for the first three stars and c. AD 650 for Sirius would have the same result.

Table 3 is an agglomeration schedule for the 14 stars. The heterogeneity coefficient increases from 0 to 0.215 after the first step and reaches a value of 6675.667 on the final step. The progression is reasonably smooth with only the last step showing an extremely large jump. This suggests that the remaining 14 stars might be properly divided into two clusters.

These results can be shown with a graphical representation called a *dendrogram*, Figure 10. The vertical lines show the stars combined into a cluster and the horizontal distance is a distance measure proportional to the heterogeneity coefficient. The dendrogram shows the same result as Table 3. The heterogeneities increase in a smooth manner, but the last step shows an increase from 8 to 25. This clearly suggests that two groupings of stars could be considered appropriate rather than a single grouping. In turn, this suggests that the observations reported by Ptolemy(?) fall into two natural groupings and that they were taken at different times. The medians of these two groups, excluding observations with dates below 0 and above AD 200, are AD 56 and AD 130 respectively.

These dates are compatible with our results from Section 4. We note that the groups determined here and in Section 4 are slightly different. An observation that appears to be associated with a group as selected in Section 4 may have a very small slope and fall outside the criteria for the cluster group analysis. Also, the two groups determined by the cluster analysis are not simply related to Ptolemy's selected six stars. Four of them fall into the early group and two into the late group.

6 CONCLUSIONS

Table 2 summarizes our results for our various approaches to the data. Specific values for epoch, accuracy and mean error are remarkably consistent for Timocharis, Aristyllos and Hipparchus. These observers clearly knew what they were doing. Historical information for them is not extensive, but nevertheless is consistent with

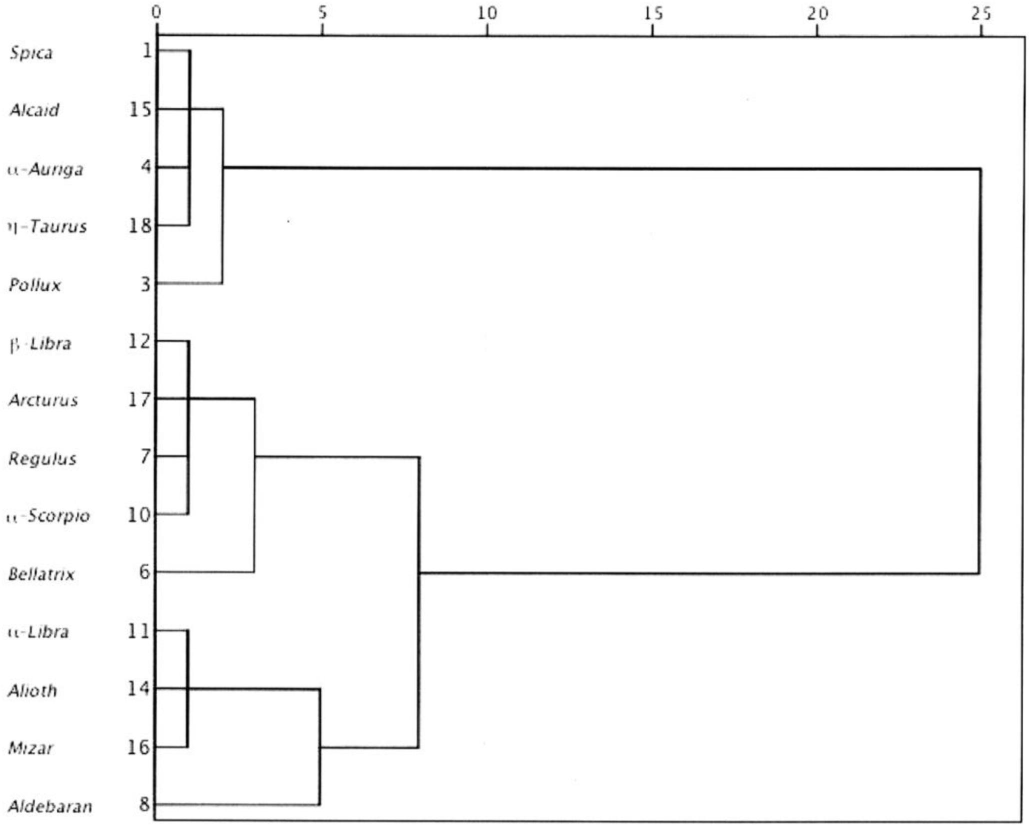

Figure 10: Graphic illustration of the cluster analysis for Ptolemy via a dendrogram using centroid linkage. See the text for discussion.

the derived epochs.

The straightforward results for Ptolemy(?) are another matter. The derived epoch for the entire ensemble of observations in the range AD 115–120 is incompatible with the historical evidence indicating a lifespan for Ptolemy of approximately AD 100–175. He would have been much too young. In addition, the accuracy of almost 0.2° is much worse than the earlier observers. Did the observational techniques deteriorate, or is there another explanation? Inspection of the residuals vs. epoch plot for Ptolemy(?) (Figure 4) and comparison with the plot for Hipparchus (Figure 3) shows that the trajectories for Ptolemy(?) are not clustered around the derived epoch (as they are for Hipparchus), but show possible clusterings at other epochs, specifically near AD 65 and AD 125. This point is also clearly shown in Figure 6. In addition, the spread in dates for Ptolemy(?) (Section 3) is much larger than for the other observers.

We have approached this question in two ways. In Section 4, we analyzed groups based on inspection of the trajectory diagram for Ptolemy(?), Figure 4, plus the zero crossing dates, Figure 6, and find support for observations taken circa AD 57 and AD 128. We have also divided the Ptolemy(?) observations into two samples (Section 5) based on a cluster analysis. The clusterings are qualitatively sound and the median dates for the two groups are AD 56 and AD 130. Thus, the observations were almost surely taken by observers ≈ 70 years apart. The early observer cannot be Ptolemy himself, but he certainly could have been the later observer. Support for this view comes from the determination by Neugebauer (1975) based on Ptolemy's dated observations in the *Almagest* that his active observing period spanned AD 124–141. The observations for Ptolemy(?) translated as "… we find …" (Taliaferro 1952) or "As found by us…" (Toomer 1998) does not necessarily imply a group effort. Again, we have consulted Dr Lorenzo Garcia on Greek usage. Use of the 'royal we' is customary throughout Classical and Hellenistic Greek. Thus, we have no idea from the text itself if others were involved in obtaining the observations circa AD 128. The 'we' concept may be appropriate for the observations circa AD 57. A likely source for the observations is the Museum of Alexandria.

Thus, we find that all of the declinations given in the *Almagest* are remarkably accurate with an RMS error ≈ 0.1° or about 6 arc min. Subsequent history shows how impressive they are. The accuracy would not be significantly improved until Tycho Brahe's work in the 16th century AD and his accuracy of approximately 1 to 1½ arc min (North, 2008: 327; Rawlins, 1993; Wesley, 1978).

The accuracy of the *Almagest* declinations implies considerable depth of astronomical understanding and sophistication in instrument-making technology, at least including metallurgy and the ability to make accurate fiducial markings. Support for such a technology in ancient Greece certainly exists (Evans, 1998: 80–83). Cicero (106–43BC) has described a mechanical device due to Archimedes (c. 287–212 BC), an orrery that showed the motions of the Sun, Moon, and five planets. Archimedes also wrote a book, now lost, on astronomical mechanisms. Cicero also noted an apparently similar orrery made by Posidonius (c. 135–51 BC). A splendid example is the Antikythera Mechanism (Charette, 2006; Evans et al., 2010; Freeth et al., 2006; 2008; Marchant, 2006; 2010; Wright 2007), a complex, multi-geared astronomical calculator recovered in 1901 in fragments from a Roman shipwreck. The device was probably made in the time period 150 BC to 100 BC. This extraordinary device surely was the result of a mature technological tradition. The instruments used to take the *Almagest* declinations are almost certainly part of this ancient Greek tradition.

7 ACKNOWLEDGEMENTS

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HARVEY BUTCHER: A PASSION FOR ASTRONOMICAL INSTRUMENTATION

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Abstract: This paper covers some aspects of the scientific life of Harvey Butcher who was the Director of the Research School for Astronomy and Astrophysics at the Australian National University in Canberra from September 2007 to January 2013. He has made significant contributions to research on the evolution of galaxies, nucleosynthesis, and on the design and implementation of advanced astronomical instrumentation including LOFAR (Low Frequency Array Radio telescope). He is well known for his discovery of the Butcher-Oemler effect. Before coming to Australia he was the Director of the Netherlands Foundation for Research in Astronomy from September 1991 to January 2007. In 2005 he was awarded a Knighthood in the Order of the Netherlands Lion for contributions to interdisciplinary science, innovation and public outreach. This paper is based on an interview conducted by the author with Harvey Butcher for the National Project on Significant Australian Astronomers sponsored by the National Library of Australia. Except otherwise stated, all quotations used in this paper are from the Butcher interview which has been deposited in the Oral History Archives of the National Library.

Keywords: Harvey Butcher, the Butcher-Oemler effect, LOFAR, Square Kilometre Array (SKA), Giant Magellan Telescope (GMT), space research

1 INTRODUCTION

Born in Salem, Massachusetts in 1947, Harvey Raymond Butcher (see Figure 1) came from a middle class family. His father was a surgeon. As a young boy his interest in astronomy was fired by reading an article on high-resolution spectra in cool stars which appeared in the *Scientific American*. This was in his high school years. He had not realised that if you make a spectrum of the Sun or the stars, you see many spectral lines, and that they tell you about the physics and the composition of the distant stars. He thought that this was amazing. He was very keen to become a professional astronomer, but his father was less impressed. "He did not encourage me to be an astronomer by any means," Butcher recalled. "He was supportive, as a father should be, but very sceptical." Nevertheless, Butcher went to the California Institute of Technology to study astronomy. Although he found the place intellectually exciting and stimulating, he also found it stressful.

He then arranged a part-time job at Mount Wilson Observatory (Figure 2), where he met a number of well-known astronomers who came to observe. His role was to help with the development of infrared photometry in one of the first surveys of the sky at infrared wavelengths (the Neugebauer-Leighton Two Micron Sky Survey). He also spent a lot of time with Allan Sandage (1926–2010; Figure 3; Lynden-Bell, and Schweizer, 2012), who was very encouraging, and very helpful. It was Sandage (described by Francis Bello in the June 1954 issue of *Fortune* magazine as the astronomer who was helping to define the age and structure of the Universe), who first suggested to Butcher that he should go 'down under' to undertake his Ph.D. studies at Mount Stromlo Observatory in Australia. Sandage was a good friend of Olin Eggen (1919–1998; Figure 4; Trimble et al., 2001), then Director of Mount Stromlo Observatory. In fact, Eggen had teamed with Sandage and Lynden-Bell and written the famous 'ELS paper' on the formation of our Galaxy which gave them a citation count of 1499, a very high figure for the 1960s. The time he spent at Mount Wilson was also the beginning of Butcher's deep interest in the designing and construction of new astronomical instrumentation to probe the secrets of the Universe. It was to remain his passion throughout his career.

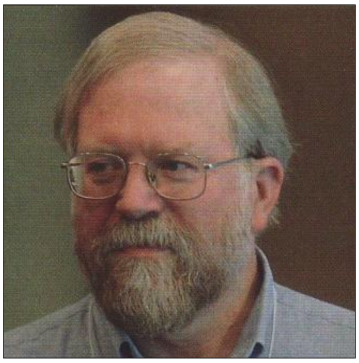
Figure 1: Harvey Butcher (courtesy: University of Virginia).

Butcher graduated from Caltech in 1969. He then took up Sandage's suggestion and went down to Mount Stromlo Observatory in February 1970 to do his Ph.D. What amazed him was that at Mount Stromlo there were no lecture courses, and students were treated almost as staff members for access to telescopes and other facilities. He had been completely fed up with sitting in lecture courses and taking exams. The idea of having four years to do nothing but

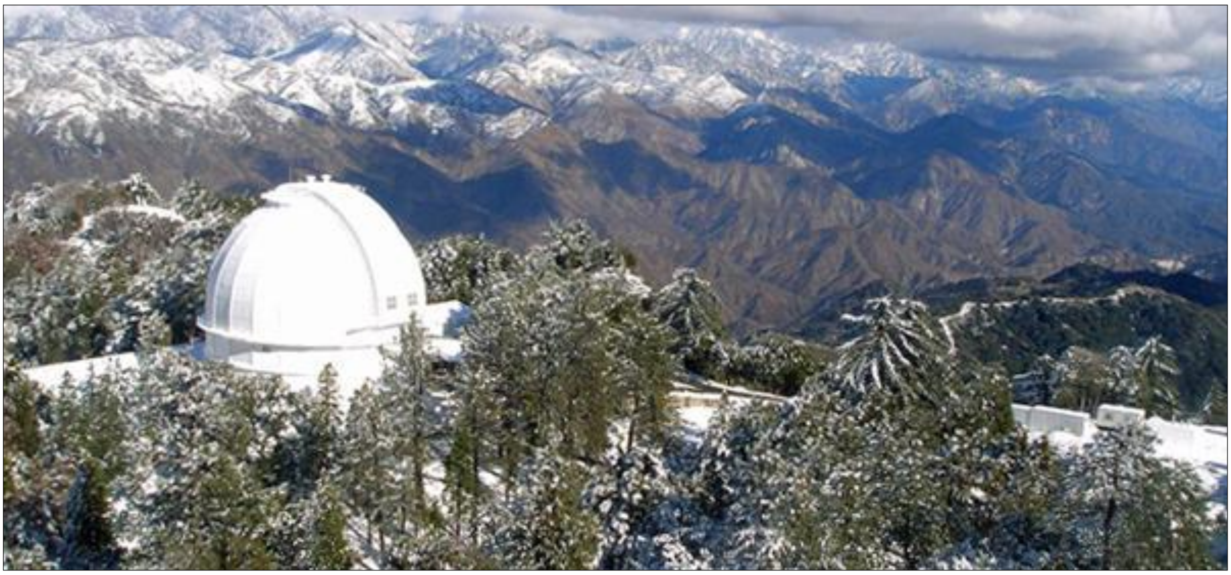

Figure 2: Mt Wilson Observatory (www.pa.ucla.edu/).

Figure 3: Allan Sandage (en.wikipedia.org).

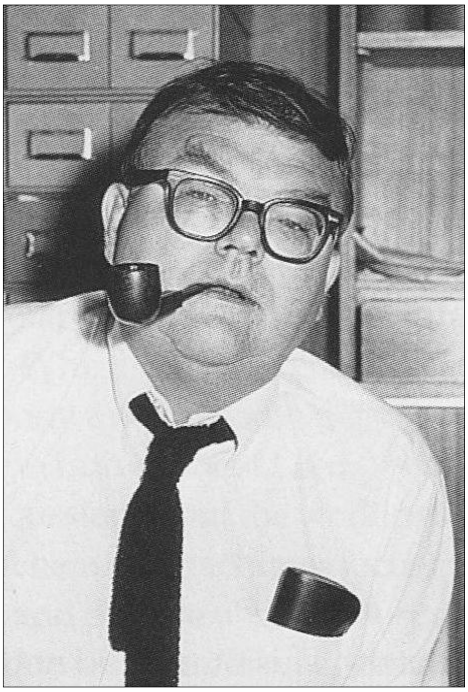

Figure 4: Olin Eggen (courtesy: Mount Stromlo Archives).

research projects was unbelievably attractive to him. In hindsight, he noted it was one of the best decisions he ever made.

2 NUCLEOSYNTHESIS

Butcher began his Ph.D. on a study of nucleosynthesis in the Galaxy under the supervision of Mike Bessell, a young astronomer who was making a name for himself in the study of stellar astrophysics, and Alex W. Rodgers (1932–1997), who was to become the Director of the Observatory in 1986. Butcher had chosen his topic before he even arrived. The theory that stars convert light elements into heavier ones via nuclear reactions had been worked out by Burbidge, Burbidge, Fowler and Hoyle (1957). They had shown that the different elements came from different nuclear processes in different stars. When Butcher came on the scene the key question was:

> Is the result the same throughout the whole history of the Galaxy, or is there evidence of secular, relative abundance evolution for elements produced by nuclear reactions under very different conditions?”

Butcher wanted to measure differential chemical abundances in dwarf stars of r- and s-process elements, which are produced in different stars and over widely-differing timescales.

However, he soon discovered that the available gratings in the 74-in Coudé spectrograph were not suitable for the work. With advice and help from Bessell and Rodgers he put together in the Coudé one of the first high-resolution Echelle spectrographs in astronomy (Butcher, 1971). What he found was that over a very large range of ages and over mean abundance levels differing by a factor of 30, basically there was very little or no measurable difference in the relative abundances (Butcher, 1972; 1975).

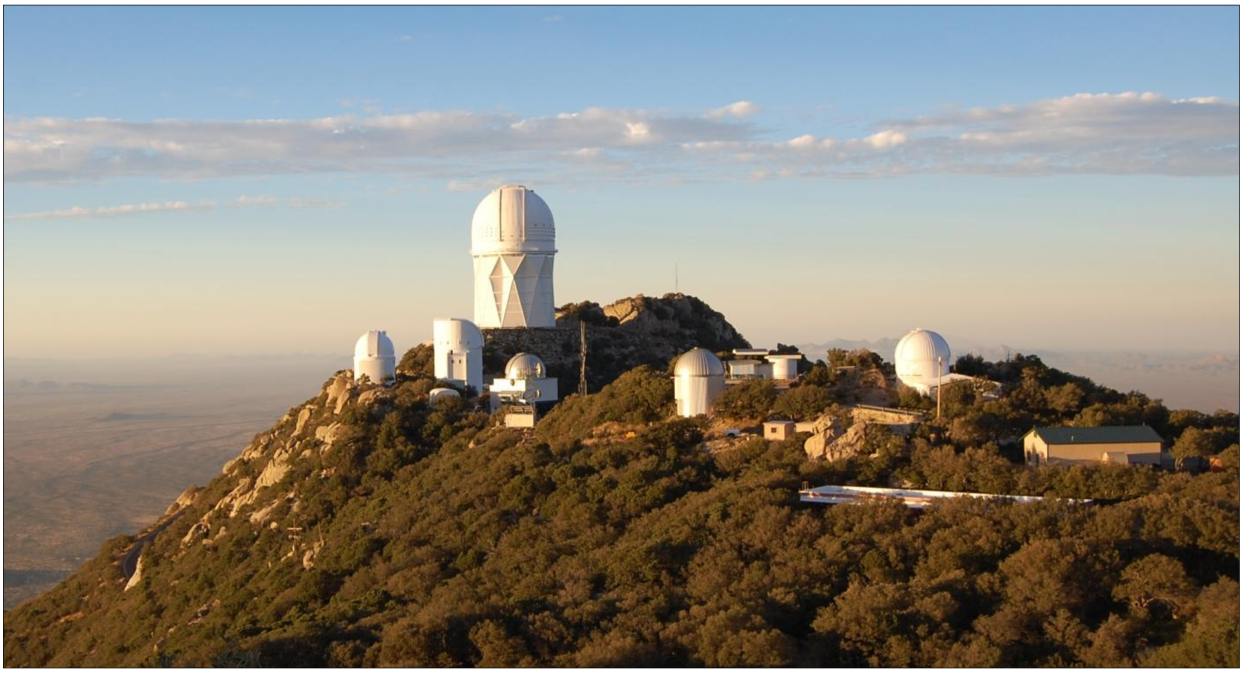

Figure 5: Kitt Peak National Observatory (www.cesl.arizona.edu/node/864).

This approach to doing research, of developing new instrumental capabilities to make new observations possible, characterized the rest of Butcher's professional career.

3 KITT PEAK

On a visit to Mount Stromlo in 1973, Peter Strittmatter from the University of Arizona in Tucson offered Butcher a job following the defence of his thesis. Butcher left Mount Stromlo in September 1974 to work at the Steward Observatory as a Bart Bok Fellow. While in Tucson he became friends with Gus Oemler and Roger Lynds at the Kitt Peak National Observatory (Figure 5), and joined them on the Kitt Peak staff in September 1976. Lynds had a particular interest in the new panoramic digital detectors and was kind enough to involve Butcher to help test and implement them on the telescope.

Oemler interested him in trying to observe the evolution of galaxies over cosmic time. They decided to try to use the new digital detectors to look at rich galaxy clusters, which were ideal targets for the relatively small fields of view of these early vidicon and Charge Coupled Devices (CCDs). He noted:

> It is hard to appreciate today that in the 1970s, received wisdom was that galaxies formed early and essentially didn't evolve visibly over recent cosmic time.

But he thought S0 galaxies (which are disc systems without any significant current star formation) might just be very old spiral galaxies in which the gas had all been converted into stars. Oemler felt that might be the case, but that probably in clusters their gas gets stripped away by the ambient cluster medium. To try to test the two hypotheses for the origin of S0 galaxies, they used the new detectors to observe what was happening. To their surprise they found lots of blue galaxies in clusters at modest redshifts, which should not have been there according to all the then-current ideas. Some of the galaxies had changed dramatically in recent cosmological times (Butcher and Oemler, 1978; 1984).

Senior astronomers were scathing about the claim and dubbed it the 'Butcher-Oemler effect'. If you had an effect named after you, he noted,

> ... that tended to mean that nobody believed it and it wasn't going to turn out to be correct in the long run. So it was not a positive thing to have a Butcher-Oemler effect at that time.

It was an unpleasant period in Butcher's life.

In the early 1980s, Barry Newell at Mount Stromlo teamed up with Ph.D. student Warrick Couch (now Director of the Australian Astronomical Observatory) to study a dozen high-redshift galaxies, taking the photometry from deep photographic plates mostly from the 3.9-m Anglo-Australian Telescope at Siding Spring Observatory. According to Couch (2006), this work made the very important step of independently confirming the Butcher-Oemler effect and showed it to be widespread and hence generally a universal property of rich, centrally-concentrated clusters at redshifts >0.2.

Further confirmation came several years later. Butcher noted that, "Gus Oemler found that Zwicky had seen the phenomenon visually on his photographic plates from Palomar." Fritz Zwicky (1898–1974) was often right, and that gave Oemler the courage to continue to lobby

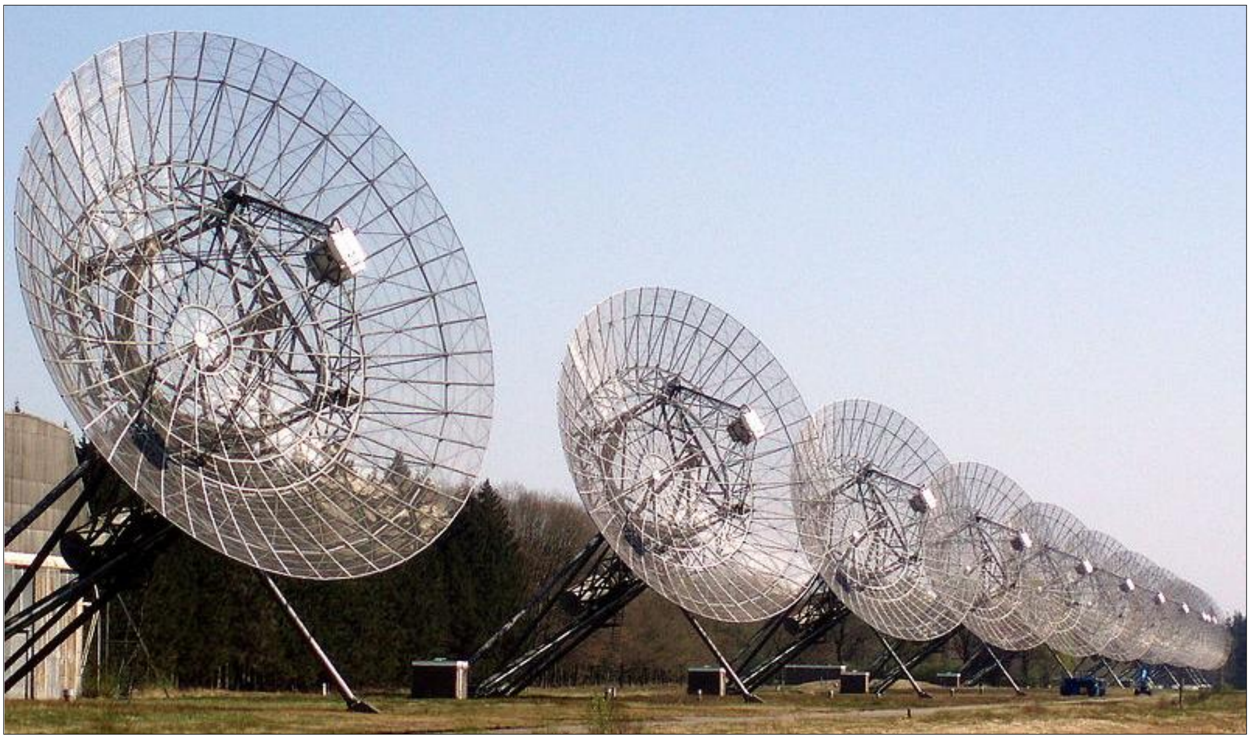

Figure 6: The Westerbork Synthesis Telescope at the Westerbork Radio Observatory (en.wikipedia.org).

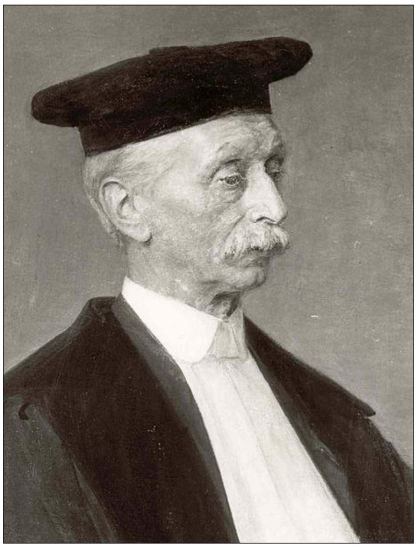

Figure 7 (left): The Kapteyn Astronomical Institute at Groningen University (www.astro.rug.nl/~weypaert/zernike_gebouw.gif).
Figure 8 (right): Jacobus Kapteyn (en.wikipedia.org).

his colleagues about the reality of the evolution. Today, undergraduate astronomy textbooks carry a description of the Butcher-Oemler effect.

Butcher stayed at Kitt Peak until September 1983. While there, he worked to perfect CCD detector systems and spearheaded their use for imaging and multi-aperture spectroscopy for observing very faint high-redshift galaxies. He also was project scientist for several new observing instruments, including an early spectrograph for obtaining spatially-resolved spectra at resolutions approaching the diffraction limit.

4 IN THE NETHERLANDS

By 1983 Butcher had moved to a position at Kitt Peak where he was influential in determining policy, but even so he decided that it was time to try something new. Earlier, in November 1982, because of his expertise in astronomical instrumentation, he had a visit from Professor Dr Harry van der Laan, Chairman of the Dutch National Committee on Astronomy as well as Chairman of the Board of the Netherlands Foundation for Radio Astronomy (ASTRON). At that time ASTRON operated the Dwingeloo and Westerbork Radio Observatories (Figure 6), managed a university grants program, and was the Dutch centre for developing a new optical observatory on La Palma (in the Canary Islands), together with the U.K. and Spain. Van der Laan represented the community in negotiations with the British on the development of the Isaac Newton Group of telescopes on La Palma and the James Clerk Maxwell sub-millimetre telescope in Hawaii. At the time, the Dutch astronomers were setting up an inter-university working group at the Kapteyn Observatory in Roden (just south of Groningen), whereby technical staff from Groningen and Leiden were seconded to the group, but they needed someone to lead the effort. That person would also have a full professorship at the Kapteyn Astronomical Institute at Groningen University (Butcher, pers. comm., 18 November 2013).

Van der Laan asked Butcher to consider a job in the Netherlands specifically to help out in a collaboration with the U.K. to build a new observatory on La Palma. Butcher's instrumentation background was what motivated them to offer him a professorship at the Groningen University. He moved to Groningen (Figure 7) in October 1983. Groningen has long had a strong reputation in astronomy. Between 1878 and 1921 Jacobus C. Kapteyn (1851–1922; Figure 8) was at Groningen and because of the rather poor conditions in the low, coastal country, he set up an astronomical laboratory. The purpose of the laboratory was to reduce observations obtained by him and his colleagues overseas. It was only after WW II that the Dutch astronomers moved in a big way into radio astronomy, which has no hindrance from the weather. The drive was spearheaded by Jan Oort (1900–1992; Figure 9) at Leiden (van Woerden and Strom, 2006).

Butcher was to live in the Netherlands for over twenty-five years, taking out Dutch citizenship. Shortly after he arrived in Groningen, a solar physics group reported the first observations of global oscillation modes in the nearby star Alpha Centauri, which indicated significant departure from model predictions. If correct, this would have consequences for the then-open solar neutrino problem, as well as age estimates for stars, the Galaxy and possibly the Universe. Such global oscillations in the Sun are excited by convection and the equivalent in other stars held out a promise of being able actually to measure the interior structures and evolutionary stages for individual stars. Here was a chance to build on work done for La Palma with the Queensgate Instruments Company, to develop a very stable Fabry-Perot Interferometer and design and implement one of the first stellar seismometers (Butcher and Hicks, 1985). Observations with the 3.6-m European Southern Observatory Telescope on Cerro La Silla, Chile, were compared with model predicttions for Alpha Centauri and found to be in agreement (Pottasch, Butcher and van Hoesel, 1992). In the meantime, the solar neutrino problem was resolved with new neutrino physics rather than the structure of the Sun. Butcher decided to move on to other investigations.

In Groningen, Butcher also explored the possibility of using stellar abundances to develop a radioactivity chronometer for the Galaxy. The idea was

> ... to see whether I couldn't find a long lived radioactive element that I could measure. The Galaxy was thought at the time to be over 15 Gyr old, so I needed an atomic species having a single unstable isotope with a comparable half-life with which to develop a chronometer, with thorium being the obvious choice.

He used the sensitive Coudé spectrograph at the 3.6-m telescope at ESO La Silla to measure its abundance relative to stable elements in stars of different ages (Butcher, 1987). He did not find any variation over the age range of his sample stars, and concluded that perhaps the Galaxy was rather younger than people in stellar evolutionary circles had been thinking.

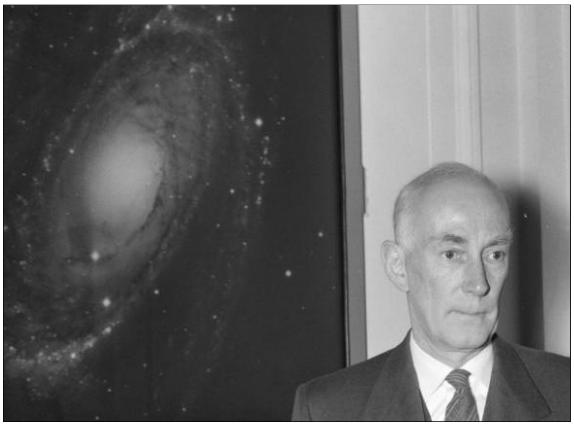

Figure 9: The visionary Dutch astronomer, Jan Oort (en.wikipedia.org).

5 INVOLVEMENT WITH ESO

In the mid-1980s, Butcher became involved at the European Southern Observatory (ESO) in developing the scientific specifications for what would become the Very Large Telescope or VLT (see Figure 10). The design of an efficient, high-resolution stellar spectrograph was a major challenge and led to the development in Groningen of an innovative prototype instrument, later called FRINGHE, a heterodyned holographic spectrometer (Douglas, Butcher and Melis, 1990). The idea was to image the Fourier Transform of the spectrum onto a two-dimensional CCD detector, thereby to gain both throughput (Jacquinot) and multiplex (Fellgett) advantages. It was a way of making a cheap, quite high-resolution spectrometer for the VLT. They tested the concept and it worked well. But the available detectors were relatively small, so the wavelength coverage that one could achieve in a single integration was also limited. In the end, ESO chose a conventional, much more expensive solution, Utraviolet and Visual Echelle Spec-

Figure 10: ESO's Very Large Telescope at Cerro Paranal, showing the buildings that house the four 8.2-m telescopes, which can be used individually or as an interferometer (en.wikipedia.org).

trograph (UVES), giving wider wavelength coverage.

6 ASTRON

By 1991 Butcher was again looking for a change, but with his family settled in the Netherlands the options were limited. He was offered the Directorship of the Netherlands Foundation for Research in Astronomy (ASTRON), a Government-financed National Research institution in Dwingeloo that specialised in radio astronomy but was starting to develop visible-light instrumentation as well. He would spend September 1991 to January 2007 managing ASTRON.

Dutch astronomers were divided at the time as to whether future investments should focus on optical astronomy using facilities at La Palma and ESO, or on radio astronomy, which would at least allow new forefront facilities to be located in the country. The compromise reached was for modest investments in both.

Early ideas for a high sensitivity HI telescope emerged in ASTRON in the 1990s, led by Jan Noordam, Ger de Bruyn and Robert Braun (Ekers, 2012; Noordam, 2012; pers. comm., 23 January 2014). A brief review of the Square Kilometre Array (SKA) from its pre-1990 roots and the global vision which emerged, at the Very Large Array (VLA) 10th anniversary meeting in 1990, to the major international project we have today is given by Ron Ekers (2012). Ekers was a strong proponent for the continued exponential growth in the collecting area (or sensitivity) of radio telescopes based on the discovery arguments of U.S. historian of science, Derek de Solla Price (1963). He argued that to maintain the exponential growth it was necessary to continually introduce new technology as refining existing technology plateaued out. By 1993, the idea of the SKA came under serious discussion in the Netherlands. Butcher ensured that Dutch R & D at ASTRON would focus on the necessary technologies and scientific development. These included the development of aperture and focal plane phased array detection, new correlator approaches, and a long-term enhancement programme for the Westerbork Radio Telescope.

Butcher also took the initiative to develop a Memorandum of Understanding (MOU) for international collaboration in the technology needed to build the SKA, and this agreement was signed by eight institutions from six countries in 1997 (Ekers, pers. comm., 23 January 2014).

One of the major outcomes of the ASTRON program was the Low Frequency Array (LOFAR). It is only possible to provide a brief early history of LOFAR in this paper. A longer more comprehensive history of LOFAR is being prepared by the author and will be published as a separate paper. According to Butcher (pers. comm., 18 November 2013) and van Haarlem (pers. comm., 18 November 2013), the early history of LOFAR is complex as it grew out of discussions of the SKA project and also involved a number of different groups (the Naval Research Laboratory, MIT's Haystack Observatory and the National Radio Astronomy Observatory in the USA, and the Commonwealth Scientific and Industrial Research Organisation in Australia). In 1997, following an Oort Workshop of science drivers for the SKA held in Leiden, George Miley, Professor of Extragalactic Astronomy at the University of Leiden

> ... suggested it as a way of bridging the gap to the SKA and using phased array technology already under development at ASTRON at the time. (van Haarlem, ibid.).

Butcher noted that the politics of science in the Netherlands was such that it was desirable to get U.S. partnership as it was seen by the Dutch government as a stamp of approval. He approached U.S. astronomy groups, such as the NRL. However, this situation changed rather dramatically when 9/11 took place in the U.S. Butcher (pers. comm., 18 November 2013) noted that "... it became politically unimportant all of a sudden in the Netherlands to have U.S. partners; the best partners would all be European."

In order to stimulate the economy, in 2002, the Dutch government decided to invest in 'knowledge infrastructure'. LOFAR fitted nicely into the scheme of things and in December 2003 it received a grant of €52 million (Butcher, ibid.). However, according to van Haarlem (pers. comm., 18 November 2013), "... the funding in the Netherlands, was closely tied up with the development of physical infrastructure in the Netherlands." As a result, the collaboration with the former partners who had insisted on a radio quiet location in the Southern Hemisphere ended. New partnerships were entered with Germany, France, the UK and Sweden. The International LOFAR Telescope (ILT) has been running since 2010. Apart from stations in the Netherlands (see Figure 11), it has stations in Germany (5), France (1), the UK (1) and Sweden (1). Poland has plans to join the consortium. Rene Vermeulen is the Director of the ILT.

The SKA was subsequently shared between Australia/New Zealand and South Africa. One of the outcomes was the successful establishment of the Murchison Widefield Array (MWA) located in Western Australia (Tingay, et al., 2013). According to Ekers (pers. comm., 23 January 2014),

> ... the MWA project began when the U.S. (MIT) and Australian partners left LOFAR. Despite the breakup of the initial LOFAR collaboration, Harvey had a huge and positive impact on the International SKA project through his involvement in the OECD and the IAU working group on large scale facilities.

LOFAR is one of the world's largest radio telescopes having sensitivity in the frequency domain 15–240 MHz, where the ionosphere causes major imaging difficulties. The problem with conventional radio telescopes has been that much of the cost is in the steel of the giant dishes that move. The cost of steel is not going down with time, so such mechanical systems are and will stay very expensive. Jan Noordam and Jaap Bregman at ASTRON pointed the way to the solution and LOFAR followed their advice, whereby the costs are shifted much towards electronics and software. That means, Butcher (2011) noted, that

> ... because of Moore's law, it'll get cheaper with time rather than more expensive. And so the idea was to build a telescope with no moving parts, in which the pointing and focusing is done in software, and with the antennas very low to the ground to mitigate RFI. The resulting instrument is much less expensive than conventional designs at long wavelengths and will continue to decrease in cost at any radio wavelength as technology advances.

In fact, the cost benefit and the use of new technology in a pathfinder for the SKA was a major motivation to build the telescope, and it is also making high-quality observations at these frequencies possible for the first time.

LOFAR has an ambitious science program in four fundamental applications: the epoch of reionization; extragalactic surveys and their exploitation to study the formation and evolution of clusters, galaxies and black holes; transient sources and their association with high-energy objects such as gamma-ray bursts; and cosmic ray showers and their exploitation to study the origin of ultra-high energy cosmic rays (Röttgering, 2006).

Butcher received a Knighthood in the Order of the Netherlands Lion in 2005 for interdisciplinary science, innovation and public outreach achieved in LOFAR.

7 SECOND COMING

In September 2007, almost 33 years after he had finished his Ph.D. at Mount Stromlo Observatory, Butcher returned as its Director. About four and a half years earlier, in January 2003, the Observatory had been engulfed in fires that were so severe that they left a trail of devastation that had never been seen before. Only the charred remains of the once-magnificent telescopes stood as silent witnesses in their burnt-out domes, and the $4 million Near Infrared Field Spectrograph (NIFS) that was undergoing final testing before being shipped to the Gemini North Telescope in Hawaii was turned into a blackened melted mass. According to Penny Sackett (2013), the Director at that time,

Figure 11: Harvey Butcher with one of the LOFAR antennas (after Schilling, 2004).

> When the damage was assessed it was clear that we had lost all our research facilities—that is, all our research telescopes on the mountain, all our library facilities and our workshop where we had built instruments for our telescopes and telescopes for other organisations.

It was a difficult time for Sackett and a lesser person would have probably thrown his/her hat in and walked away. Instead she stood her ground and did an excellent job in organising the reconstruction of the main buildings and getting the Observatory back on its feet before she left in May 2007 to take up the position of Chief Scientist of Australia.

On his arrival in September 2007, Butcher (Figure 12) began where Sackett had left off. He built on the foundations that Sackett had laid after the fires. On reviewing the Observatory's programs and facilities Butcher found two internationally-significant projects that had begun dur-

Figure 12: Harvey Butcher and Sydney Observatory Manager Toner Stevenson at Mt Stromlo (www.Sydney observatory.com.au/2011/toner-reports ...).

Figure 13: Professor Mike Dopita and WiFeS (info.aiaa.org/ Regions/Int/Sydney/Web%20Pages/Past_Events.aspx).

Figure 14: Professor Brian Schmidt's Skymapper Telescope at Siding Spring (info.aiaa.org/).

ing the Sackett years and were under construction: Michael Dopita's Wide Field Spectrograph (WiFeS–see Figure 13) and Brian Schmidt's 1.35-m SkyMapper Telescope (Figure 14). Both were highly innovative projects. Butcher reasoned that placing the WiFeS on the 2.3-m telescope would give it a new lease of life for 6–8 years, until international competition caught up with it.

The SkyMapper project was to be used for producing a map of the southern sky with a telescope, using detectors and filters that promised to revolutionise the field of galactic archaeology. The Near-Infrared Integral-field Spectrograph (NIFS) and the Gemini South Adaptive Optics Imager (GSAOI) projects led by Peter McGregor were doing very well on the 8-m Gemini telescopes overseas. Butcher found that not only were senior staff scientifically productive, but they were clearly very capable of leading ground-breaking new international projects at the highest level. He felt that in concert with scientific discovery, the instrumentation program would be the way forward to resurrect the Observatory's international reputation after the fires. It was time, he believed, to focus on strategy.

Butcher began by working out a five year plan. He talked extensively to staff, both academic and technical/operational, and by December 2007 he had drawn up a plan that built on the foundations laid by Penny Sackett. The priorities for his directorship were:

> First, to recruit new, young researchers of the highest international standing by using the ARC Fellowship programs and the School's endowment funds. Second was to complete the construction, commissioning and scientific exploitation of the new SkyMapper (Southern Sky Survey) and Wide Field Spectrograph (WiFeS) instruments. And third, the realization of the [full financial] participation in a major international project to develop a next generation very large telescope, assumed to be the Giant Magellan Telescope (GMT).

One of the first things he did was to devise plans to recruit high-profile Postdoctoral Fellows and mid-career researchers. The first of the Fellows was Chiaki Kobayashi, an expert in the numerical simulation of galaxy evolution. Butcher also enticed two mid-career astronomers to come back to Mount Stromlo. One was Martin Asplund, who had left in 2007 to assume the Directorship of the Max-Planck Institute for Astrophysics in Garching, Germany. The other was Lisa Kewley, a Stromlo graduate who was working in the U.S.A. Both returned in 2011. He also began a program to attract good students to take up honours and Ph.D. studies at Mount Stromlo, very much as Bart Bok did when he was the Director decades earlier (see Bhathal et al., 2014).

8 GIANT MAGELLAN TELESCOPE

Penny Sackett, the previous Director, had signed up the Australian National University (ANU) to the Giant Magellan Telescope (GMT) project in 2006. It is a billion-dollar project with full operations planned from ~2020. The effort currently is a collaboration of ten partner institutions: seven in the U.S.A. (Harvard University, Carnegie Institution, University of Chicago, University of Arizona, University of Texas at Austin, Texas A&M and the Smithsonian Astrophysical Observatory), all of which have built and operated large telescopes previously; one in Korea (the Korea Astronomy and Space Sciences Institute, a Government-run centre); and two in Australia (the ANU, and Australia Astronomy Ltd). However, at the time the ANU could contribute only a limited amount to show its commitment to the project. Unexpectedly, the Global Financial Crisis (GFC) in 2008 was a blessing in disguise for Mount Stromlo astronomers. In response to the GFC the Australian Federal Government set up the Educational Investment Fund (EIF) as part of an economic stimulus package to not only tackle the long-standing chronic need of Australian universities for additional and upgraded infrastructure but also to improve education generally.

Butcher saw an opportunity and proposed full participation in the GMT to the Vice-Chancellor, Ian Chubb. Somewhat to his surprise, Chubb enthusiastically agreed to have ANU propose the project, and in fact went on to chair the Mount Stromlo delegation at the formal interview with the evaluation panel. The ANU proposal was for A$88.4 million, to include A$65 million as their contribution to the international project (i.e. to be sent to the project office in Pasadena and yield a 5% access for ANU researchers plus 5% access through Astronomy Australia Ltd. for the whole university community, including ANU).

The EIF proposal was successful, and a contract was signed with the Government on 10 February 2010. Butcher (pers. comm., 18 November 2013) later noted: "This I view as probably my most important and enduring achievement as Director." It is a valuable complement to the Federal Government's investment in the SKA.

Butcher's next priority was engineering. With his long experience in technology management, he revitalized the engineering group and pursued opportunities for building instruments for the GMT (Figure 15). He used A$21.4 million from the grant to complete a new wing of the Advanced Instrumentation Technology Centre (AITC). This will enable it to do R&D so as to compete for large international engineering projects.

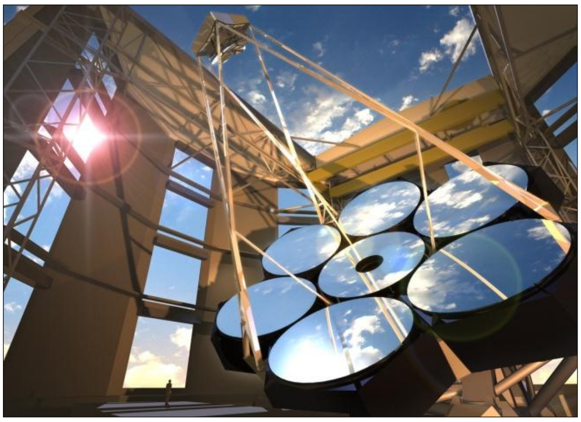

Figure 15: The Giant Magellan Telescope (www.gmto.org/Resources/GMT-1-large.jpg).

The completion of the AITC with funding from the EIF–GMT grant allowed Mount Stromlo not only to appoint new engineering staff but also to compete for one of only two or three first-light scientific instruments. Peter McGregor (Figure 16) led a team, with systems engineer Simon Parcell, to propose and win an instrument, the Giant Magellan Telescope Integral-Field Spectrograph (GMTIFS), that essentially is an evolution and combination of the NIFS and GSAOI instruments previously built for the Gemini observatories. The international evaluation panel organized by the GMT project office judged it the best-prepared and most convincing of the six or seven instruments proposed.

The aim of GMTIFS is to allow medium-resolution spectra to be taken of galaxies in the early Universe, of the surrounds of black holes and of exo-planet systems. It will map such objects in the near infrared at the highest spatial resolution possible with the GMT (diffraction limited or as close as achievable—in any case delivering some ten times sharper images than the Hubble Space Telescope can take). GMTIFS relies on a functioning adaptive optics system on the telescope, and because of this Butcher early on made the decision to have Mount Stromlo involved in adaptive optics technologies, and to compete for contracts to help design and build the adaptive optics system on

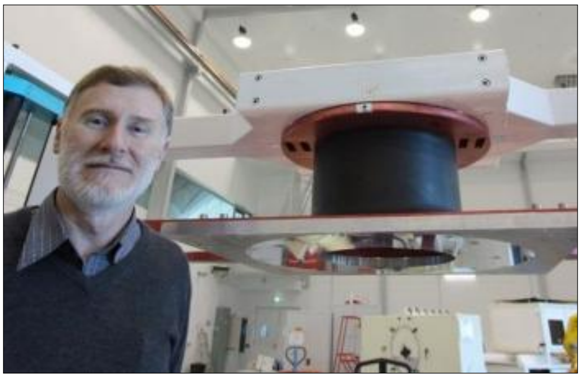

Figure 16: Professor Peter McGregor inside the massive new instrument assembly hall at Mt Stromlo (sciencewise.anu.edu.au/articles/astronomy%20opportunity).

the GMT. In that way he felt they could best guarantee that GMTIFS would end up scientifically productive at the earliest possible stage. He recruited adaptive optics specialists from overseas—Rod Conan from Canada and François Rigaut and Celine D'Orgeville from France, via Chile, as well as system engineers, project managers and optics specialists—to complement his existing in-house expertise.

Since Mount Stromlo did not have an established reputation in adaptive optics, he needed to build a working system to show that his team could really perform. He was aware that the EOS-Space Systems company at Mount Stromlo was involved in satellite laser ranging measurements. They had developed an ability to detect and monitor the orbits of space debris to unprecedented accuracy, which they hoped to turn into a profit-making business (saving commercial and military satellites from collisions with space debris). He came to the conclusion that the Observatory's effectiveness could be dramatically improved if they implemented an adaptive optics system on the EOS-Space Systems laser ranging telescope. He entered into a MOU on 10 November 2009, jointly to invest and work together to develop an adaptive optics demonstrator system on the 1.8-m EOS-Space Systems (EOS-SS) telescope at Mt Stromlo. From the Observatory's side Butcher reasoned, it would also demonstrate their capability to deliver on a potential contract for parts of the adaptive optics system on the GMT. As part of the ANU contribution Butcher agreed to host the EOS-SS R&D team at the AITC. The contract was signed on 29 August 2011.

As soon as the EIF-GMT was granted Butcher did a stock-take and critical analysis of the financial affairs of the Research School of Astronomy and Astrophysics. He realized that in the long term it would be unrealistic to expect the School to finance the technical program from the School's operating budget. He had to find a solution to this problem, which would become acute following the expiry of the EIF-GMT grant in 2014. The solution came from the new Australian space initiative announced by the Federal Government.

9 SPACE RESEARCH

On 12 November 2008, the Government released its report, *Lost in Space? Setting a New Direction for Australia's Space Science and Industry Sector*. The report recommended a return to investment in a national space effort, in particular to train a new generation of engineers with knowledge of space technologies and satellite operations.

Realizing that the engineering protocols, tools and test facilities would be very similar to what the Observatory would need for GMT instrumentation, Butcher thought this could be the way to acquire additional funding. He subsequently spent a great deal of his time following the EIF award, networking into the space community. And he agreed with Government to use some of the EIF funding to provide a national engineering capability at Stromlo, not only for GMT and astronomy but also for space research.

In its 2009–2010 Budget, the Government announced the establishment of a Space Policy Unit which would oversee the A$48.6 million Australian Space Science Program's four years of activity. However, it specifically excluded funding for astronomy since the Government felt that astronomers had received enough support, for the SKA and GMT projects. Nevertheless, Butcher cleverly used his contacts to get the Research School to participate in and acquire funding from five projects: Antarctic Broad-Band, led by Aerospace Research Pty. Ltd.; Australian Plasma Thruster, led by ANU Physics; Space Debris Detection and Monitoring Systems, led by EOS-Space Systems Pty. Ltd.; Greenhouse Gas Monitor, led by VIPAC Engineering & Scientists Pty. Ltd.; and GRACE Follow-on, led by ANU Earth Sciences and Physics. These collaborations would establish Mount Stromlo and the AITC as an important player in the space research field, and hopefully lead to larger projects in the future.

10 SIDING SPRING OBSERVATORY

Butcher's next priority was Siding Spring Observatory. His view was that the ANU telescopes would have a useful research life of perhaps another five to seven years, or at least until the SkyMapper Southern Sky Survey could be completed. At that point, unless budget increases were forthcoming, ANU would be forced to abandon the site. He therefore undertook four initiatives.

First, he convinced ANU to transfer responsibility for site maintenance to its Division of Facilities and Services, which had formal responsbility for the basic maintenance of the other university buildings and grounds. The transfer left the Research School responsible only for its own operational telescopes—the 2.3-m and the 1.35-m SkyMapper.

Second, he arranged for the original team of engineers led by Herman Wehner, who had worked with Don Mathewson (the Director of the Observatory from April 1979 to May1986) to dedesign and build the 2.3-m telescope (see Mathewson, Hart, Wehner, Hovey and van Harmelen, 2013), to return from retirement and refurbish the instrument (see Figure 17). In particular, its drive system electronics, originally devel-

Figure 17: The team that originally designed and built the 2.3-m Telescope and came out of retirement to refurbish the instrument. From left to right: Professor Don Mathewson, Hermann Wehner, John Hart, Gary Hovey and Jan van Harmelen (after Mathewson et al., 2013).

oped by Gary Hovey, had run out of spare parts and could no longer be kept in regular, reliable operation. With a very minimal budget but a great deal of dedication and intimate knowledge of the system, the team brought the telescope system back to a state at which it might remain operational for another five to seven years.

Third, a conviction that learning to observe hands-on with small telescopes is important to the education of young astronomers led Butcher to attract several other research institutions to Siding Spring. To the Anglo-Australian Observatory (AAO), University of New South Wales instruments and the Las Cumbres Faulkes telescope would be added facilities from Korean, Polish and several more U.S. institutions. Siding Spring would become an international observatory, similar to, if smaller in scale than, the Mauna Kea Observatory on Hawaii or the Roque de los Muchachos Observatory on La Palma. Each new facility would contribute to communal site maintenance costs but otherwise enjoy a rent-free site; in exchange, each would grant ANU astronomers a level of observing access. Even when the Research School would have to abandon its own facilities, its students would be able to carry out projects at Siding Spring.

Finally, the Anglo-Australian Agreement between the British and Australian Governments would come to an end on 30 June 2010, providing an opportunity to reorganise activities at Siding Spring. The 3.9-m telescope and headquarters in Sydney would henceforth be called the Australian Astronomical Observatory (still with the initials AAO and same logo!) and become a Division of the Department of Innovation, Industry, Science and Research of the Australian Federal Government. Its new purpose would be to operate observing facilities for Australian astronomers and support Australian access to international observatories. Butcher proposed that it would be logical, given the AAO mission and its transition to an all-Australian organisation, for the Government to consider taking over the operation and maintenance of all national facilities at Siding Spring. After all, the AAO would likely remain far and away the largest facility and have the most staff on the site, hence would have the most to lose when the ANU could no longer manage the site at an appropriate level. Butcher even proposed that rather than duplicate engineering and office facilities, the new AAO could move to Canberra and co-locate with the Research School at Mount Stromlo. Unfortunately, the senior echelon at the ANU would not consider relinquishing management control of the Siding Spring campus and the astronomical community feared that ANU might come to dominate the AAO program, so neither proposal gained support.

The future of the Siding Spring Observatory was advanced during the Butcher years, but was not fully resolved.

During Butcher's Directorship the main thrust of the scientific research programs was in galactic archaeology (content and evolution of galaxies), observational cosmology (content and evolution of the whole cosmos) and the astrophysics of stars, planets and black holes. The group of academic researchers at the Observatory could be compared with the best anywhere in the world. They reaped the recognition they deserved.

Brian Schmidt (Figure 18) topped the list of researchers at Mount Stromlo by being awarded the 2011 Nobel Prize for Physics, jointly with U.S. astronomers Adam Riess (Johns Hopkins University) and Saul Perlmutter (University of California, Berkeley) for their ground-breaking research on the accelerating Universe (Bhathal, 2012). It was almost 96 years since an Australian had won a Nobel Prize in Physics—the first and only other Nobel was won by the father and son team, William and Lawrence Bragg, for their work on X-ray crystallography (Jenkin, 2008).

Ken Freeman (Figure 19) is probably the most prolific author of high-quality papers at Mount Stromlo, and indeed of the whole astronomical community in Australia. He has been a trend-setter in several areas of astronomy and astrophysics. With Joss Bland-Hawthorn of the University of Sydney, he is celebrated as the father of the field of 'galactic archaeology' and is recognised as an early proponent of the theory

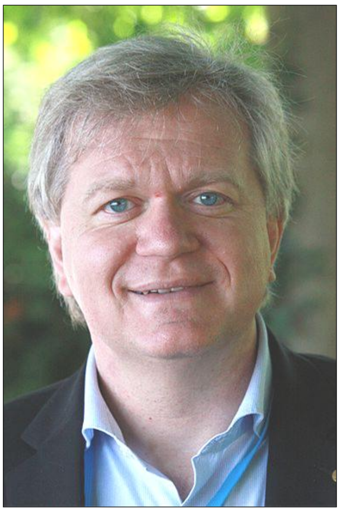

Figure 18: Professor Brian Schmidt (en. wikipedia.org).

that dark matter must form a large fraction of the mass of galaxies. He is a Fellow of the Australian Academy of Science and the Royal Society of London and in 2012 was awarded the prestigious Prime Minister's Prize for Science for his entire *oeuvre*. In January 2013 the Australian Academy of Science awarded him the Matthew Flinders Medal. Also in January 2013 he was awarded the prestigious Henry Norris Russell Lectureship by the American Astronomical Society in recognition of a lifetime of seminal contributions to astronomy, including work on the structure and dynamics of galaxies including our Galaxy.

Butcher (2011) noted:

> In 2009 we were placed number 10 in the world in space science by the Thomson-Reuters citation ranking—ahead of Cambridge, UC Berkeley and Harvard. At the start of 2012 Mount Stromlo Observatory and the Research School were supporting an Australian Research Council Centre of Excellence, two ARC Laureate Fellows, three ARC Future Fellows, an ARC Research Fellow, a DECRA Early-Career Fellow, 17 ARC Discovery grants, an ARC-LIEF grant and a major EIF grant worth $88.4 million. The Observatory has two Fellows of the Royal Society of London and memberships of the national academies of the U.S., Netherlands and Spain, as well as the Australian Academy of Science.

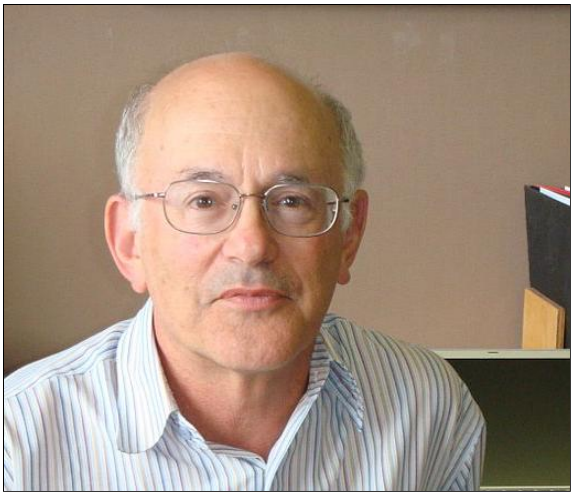

Figure 19: Professor Ken Freeman (en.wikipedia.org).

In January 2013, Butcher retired from the position of Director of the Mount Stromlo Observatory, after nearly five and a half years at the helm. Ken Freeman (2013), a senior member of the academic staff at the Research School of Astronomy and Astrophysics, has this to say about Butcher's directorship:

> He left Stromlo stronger than he found it. The place is scientifically more vibrant than it was, and the morale is generally very good.

His major achievement as the Director of the Observatory was to achieve full participation in the international Giant Magellan Telescope, and he placed the Observatory in a position to reap the benefits of discoveries in the era of very large telescopes by this and future generations of Mount Stromlo astronomers.

11 ACKNOWLEDGEMENTS

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AN HISTORICAL PERSPECTIVE ON THE SUSPECTED METEORITE IMPACT SITES OF TENNESSEE.
1: THE DYCUS STRUCTURE

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Abstract: The Dycus Structure is one of two suspected meteorite impact sites in Tennessee, USA, and first came to the attention of geologists during the 1940s, but it was only investigated in 1951 when Robert M. Mitchum conducted research at this site for a M.S. in geology through Vanderbilt University. The few subsequent investigations that have occurred at this site have revealed it to be oval in shape rather than circular, with the central uplift located near the north-eastern end of the site, reminiscent in many ways of the lunar crater Schiller. The Dycus Structure may have been formed at the same time as the nearby Flynn Creek impact site, by an asteroidal body that impacted at an oblique angle.

Keywords: Dycus Structure, Tennessee, possible impact site, oblique impactors, Schiller lunar crater, R.M. Mitchum

1 INTRODUCTION

Impact cratering was an important feature of the early Solar System, but it took many years before geologists and astronomers were willing to seriously entertain the idea that some of the craters identified on the Earth were of extra-terrestrial origin and not the result of volcanic activity or other geological processes (e.g. see Boon and Albritton, 1936; 1937; Bucher, 1936; Dietz, 1963; Hoyt, 1987; Mark, 1987; McCall, 1979; Melosh, 1989). Now terrestrial impact-cratering is universally accepted (e.g. see Grieve and Pilkington, 1996; Koeberl, 2009), and Hey (1966) and O'Connell (1965) amongst others have produced catalogues of meteorite craters. There are currently around 230 confirmed or suspected meteorite impact craters in the USA (Classen, 1977), the first of which was described by Safford in 1869. This is located at Wells Creek in the state of Tennessee in the south-eastern United States (Berwind, 2007).

In addition to Wells Creek (see Ford et al., 2012; Wilson, 1953; Wilson and Stearns, 1966, 1968), Tennessee has one other confirmed impact crater, Flynn Creek (Evenick et al., 2004; Ford et al., 2013; Milam and Deane, 2005; Milam et al., 2006; Roddy, 1997; Schieber and Over, 2005), and two suspected impact sites, the Dycus Structure (Deane et al., 2006; Schedl et al., 2010) and the Howell Structure (Born and Wilson, 1939; Deane et al., 2004; Ford et al., 2015). As Figure 1 indicates, all of these sites are found in the Highland Rim Physiographic Province which surrounds the Nashville Central Basin in middle Tennessee (see Deane et al., 2004; Deane et al., 2006; Roddy, 1963; Wilson and Stearns, 1968). Specifically, the Dycus Structure is located in the northern section of the Eastern Highland Rim Escarpment. Although meteorite impacts most certainly also occurred in the eastern and western sections of the state, the structural features of those that occurred to the east of the Highland Rim in the deformed rocks of the Appalachians have been obliterated (Woodruff, 1968), while impact craters in the western part of the state have been covered by coastal plain marine and transitional sediments during the formation of the Mississippi Embayment (Miller, 1974).

Interest in the known and suspected Tennessee impact sites has waned over time and only sporadic field work has taken place in the decades since their recognition as sites of interest.

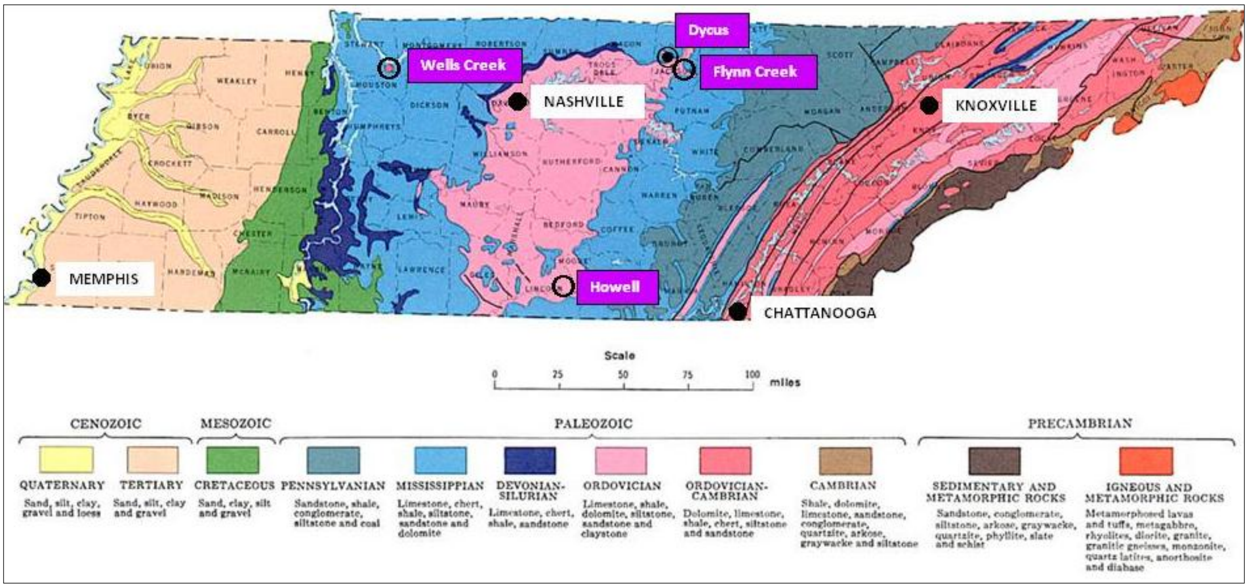

Figure 1: Generalized geological map of Tennessee showing the locations of the four largest cities (black dots) and the two confirmed and two suspected meteorite impact sites (black circles). The Dycus Structure, which is the focus of this paper, is marked by the circle and black dot. All four confirmed or suspected impact sites are located on the Highland Rim (Wells Creek), a Highland Rim outlier remnant (Howell), or on the Highland Rim escarpment (Dycus and Flynn Creek). The Highland Rim is the sky blue region on the map (base map after Tennessee Department of Environment & Conservation, Division of Geology, 1966).

Hopefully in the near future the Dycus and Howell Structures will be shown to be actual impact sites or their alternative origins will be determined. In this paper we review the evidence that has been assembled to date for the Dycus Structure.

2 THE DYCUS STRUCTURE

2.1 Introduction

Although the Dycus Structure is located only 13 km north-northwest of the Flynn Creek impact site and in the same county of Tennessee (Jackson), it is a surprisingly long drive from one site to the other due to the remote location of the Dycus Structure and the difficulty involved in navigating the highly dissected terrain of the Highland Rim Escarpment along which these two sites are located. This structure has not been subjected to the intense scrutiny that Wells Creek, Flynn Creek, or even the Howell Structures in Tennessee have received over the years, and its initial discovery apparently went unrecorded (see Deane et al., 2006). The earliest written work on the Dycus Structure is in an unpublished M.S. thesis submitted to Vanderbilt University in 1951 by Robert M. Mitchum. This structure was still not well known afterwards, and it is not even mentioned in the Tennessee Division of Geology's 1974 publication, *The Geologic History of Tennessee*, even though an entire section of the publication is dedicated to "Cryptoexplosion Structures in Tennessee" (see Miller, 1974: 55–58).

2.2 Historical Context

According to Deane et al. (2006: 1)

> Richard Stearns (Prof. Emeritus, Geol. Dept., Vanderbilt Univ.) believes his colleague, Dr Charles W. Wilson, Jr. was told about, or discovered, the Dycus Disturbance while conducting field work in Jackson County sometime in the 1940s …

Later Mitchum (1951: 1), one of Wilson's graduate students, wrote that early in 1950 he and Wilson investigated "… a local structural disturbance in the Ordovician rocks of Jackson County, Tennessee …" Figure 2 is a view of the area. The most intensely-disturbed section is located in the forested area in the center of the photograph. Wilson considered this structural disturbance warranted further investigation, and he wanted to determine whether it should be included in the growing list of U.S. cryptovolcanic structures (ibid.).

Although the Dycus Structure had been known for a few years before his field work commenced, Mitchum (ibid.) stated that no research had been carried out to determine its origin. He described the known structure in detail, including the stratigraphy of the local rocks, and completed a geological map of the disturbed area that was included in his thesis and is shown here in Figure 3. This map shows that the structure is just over 760 meters by 885 meters, and based on his analysis Mitchum (1951: 2) concluded that it was the result of a meteorite impact.

2.3 Structural Features and Age

The Dycus Structure is located in the northern part of middle Tennessee on the edge of the Nashville Central Basin, adjacent to the Eastern Highland Rim Escarpment, and stands out from

Figure 2: A view of the Dycus Structure looking northeast. The zone of greatest disturbance is in the forested area in the center of the photograph. The ridge approximates the northern boundary of the structure (photograph: Jana Ruth Ford).

the surrounding regional terrain:

> The regional dip of the area is so slight that, except for local minor irregularities, the rocks appear horizontal in the field. The occurrence of a localized area of intense deformation such as the Dycus disturbance in ordinarily relatively undisturbed strata is of more than casual interest. (Mitchum, 1951: 13).

Later investigators agreed with this description:

> This province is characterized by very flat-lying, Middle to Upper Ordovician to Lower Mississippian-aged sedimentary strata. In a major unconformity, the Silurian and most of Devonian is absent … Regional folding and faulting are rare within this area … Unfortunately, hill slopes are commonly covered with rubble, detrial material from overlying formations, and vegetation, so exposures are limited. (Deane et al., 2006: 1).

O’Connell (1965: 35) stated that the Dycus Structure was Ordovician in age. Rock exposures in the disturbed area were primarily limestone that ranged from Ordovician to Mississippian in age (Mitchum, 1951). The Chattanooga Shale, so prominent in the nearby Flynn Creek impact site, occurred near the tops of high hills in the region of the disturbance, but it was not present in the area mapped by Mitchum. The northern and north-eastern sections of the disturbed area were covered by rubble containing the Mississippian chert that was usually found to cap high hills in the surrounding area. The chert was not found to occur in place within the intensely-deformed part of the structure (ibid.).

Mitchum (1951: 15) noted that the Dycus Structure was a “… very localized structure.” The portion he investigated and determined to be disturbed approximated a half-circle with a radius of only 610 meters. He wrote that “… about half the structure is covered by rubble and debris from younger formations …” (ibid.), and he assumed that the entire structure was probably circular in plan. During his investigation Mitchum (ibid.) wrote that he found the following elements present (in order from the center of the structure to its periphery):

> (1) A small, relatively subordinate central uplift occupied the approximate center of the disturbance and marked the area of most intense deformation.
> (2) Surrounding and subordinating the uplift was an annular depressed area that was accompanied by buckling and tight folding. The

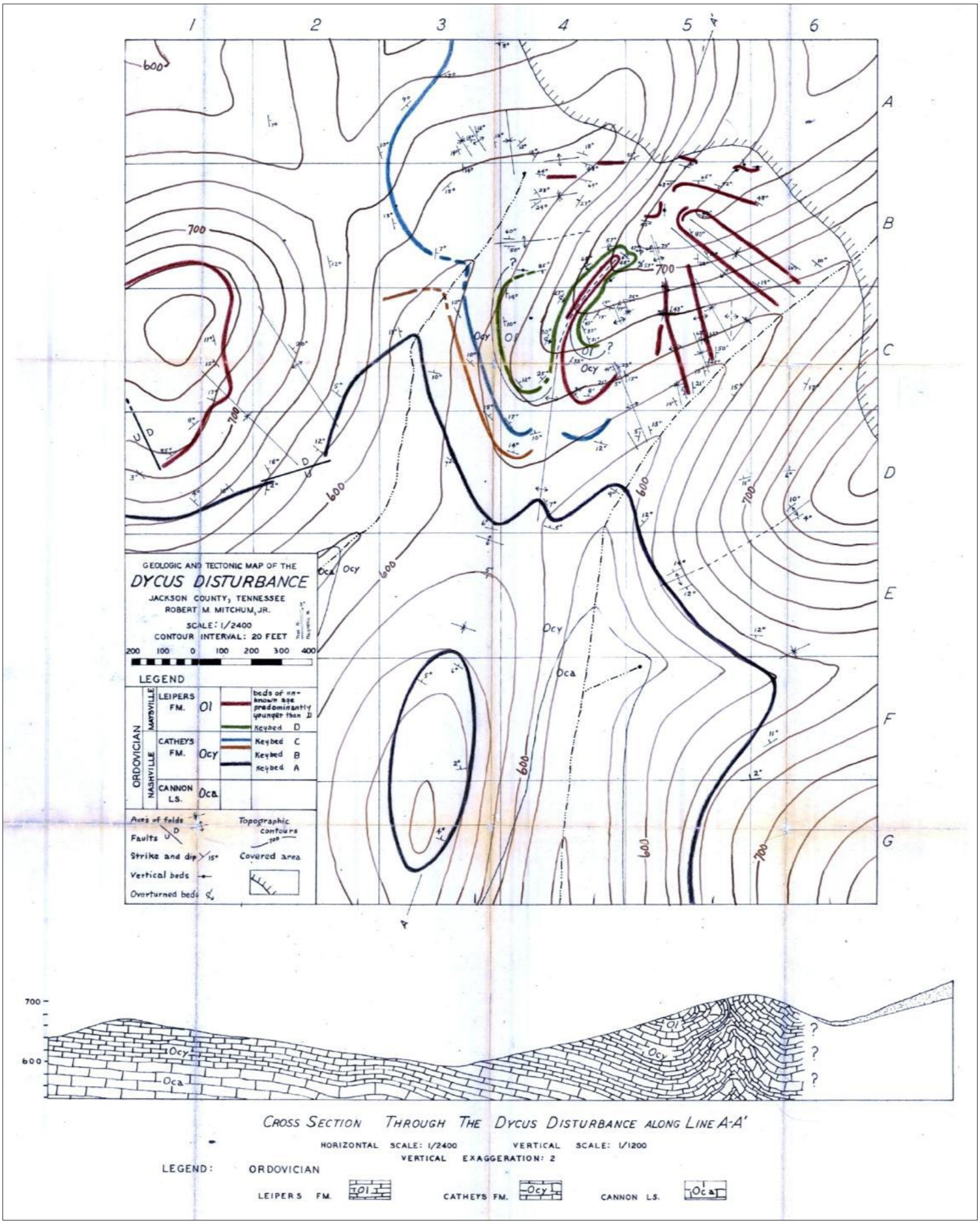

Figure 3: A geological map of the Dycus Structure. A cross-section through the structure along line A–A′ is included at the bottom of the figure (after Mitchum, 1951).

axes of the folds were roughly radial from the central uplift. The down-bowing had greater magnitude than the uplift, both vertically and horizontally, so that the center of the structure, although higher than the surrounding depressed area, was still lower than its normal altitude in this vicinity.

(3) A gentle ring-shaped anticline occurred on the outer periphery of the down-warped area. This peripheral fold surrounded the central area for at least three-fourths of the circumference of the exposed half-circle.

(4) At least two normal faults occurred outside the ring-shaped anticline.

(5) Outside the area of intense disturbance the rocks dipped gently toward the center of deformation. This dip died out with increasing distance from the center.

Most of the radial folds seemed to have a common origin in a small section of the structure that was just over 90 meters across, and Mitchum (1951: 16) referred to this as the "… focal point of the Disturbance …" He also noted that although no pattern of deformation could be established, tight folding, high dips, faulting and shearing could be discerned in this area along with some brecciation that was apparently connected with the folding and faulting. The folding "… was very intense and produced crumpling rather than well-defined folds …" (ibid.). Slickensides were found mostly along the tight folds (ibid.).[1]

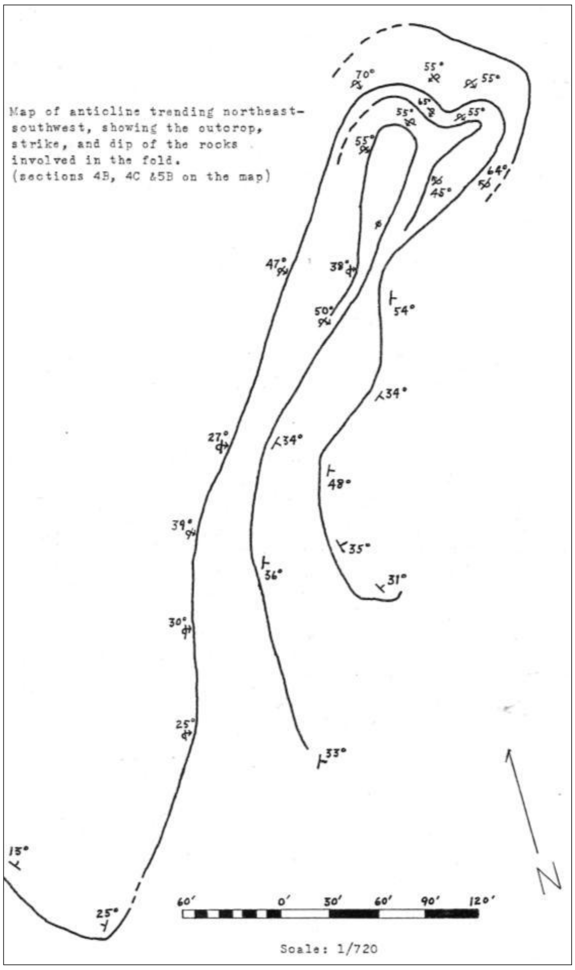

Figure 4: Map of anticline trending northeast-southwest, showing the outcrop, strike, and dip of the rocks involved in the fold (after Mitchum, 1951: 21). This map includes sections 4B, 4C & 5B from the 1951 geological map shown in Figure 3.

Mitchum (ibid.) considered this intense folding to be the most important feature of the Dycus Structure, more so than the faulting or brecciation. This intensely-disturbed area

> … has been lifted above the immediately surrounding annular depressed area. Although no indisputable evidence has been found to prove that the uplift has actually occurred, there are certain lines of evidence that strongly support such a possibility. (Mitchum, 1951: 17).

Basal granular facies of the Leipers Formation were found at an altitude of some 230 meters in the center of the Dycus Structure instead of at an altitude of 190 meters where the same facies was found outside of and to the east of the central area. Mitchum also determined that radial folds surrounding the central area rose toward the center, and

> In several instances the same bed can be traced along the axis of a fold for over 300 feet [90 meters], the extremity of the exposure nearest the center being at least 70 feet [20 meters] higher than the outer extremity, (ibid.).

Deane et al. (2006: 2) observed that this zone of maximum deformation "… is the most impressive part of the Dycus Disturbance to visit, with dips as high as 85°, tight folds, and an overall chaotic nature …"

Mitchum (1951:18) noted that the zone of greatest deformation in the Dycus Structure was apparently 20 to 35 meters higher than the depressed area surrounding it. This area was considered an annular depression although it had been lowered by at least 42 meters below its normal position, and it surrounded what Mitchum referred to as 'the central uplift'. In addition, Mitchum (ibid.) noted that the basal granular facies of the Leipers Formation was at least 43 meters below its normal position found just to the east of this central disturbed area, and

> This down-bowing affects the entire structure and all the other major structural features are subordinate to it. The central uplift, although higher than the surrounding depressed area, is lower than its normal altitude, since the magnitude of the lowering is greater than that of the uplift. The ring-shaped fold is superimposed on the flanks of the depressed area as are the peripheral faults. (ibid.).

However, there was not much deformation on the outer flanks of the depressed area "… except for the gentle to steep dip into the center." (Mitchum, 1951: 19). Moving toward the center, though, Mitchum (ibid.) noted the increasing deformation and radial folds that were superimposed on the structure from the depressed area to the central area of uplift.

A short distance to the north the beds were vertical and then they remained nearly vertical for some distance. Overturned beds were also seen along some of the folds. As an example, an anticline in the east-central section of the disturbance was overturned to the west and an anticline striking northeast-southwest was overturned to the northwest (ibid.). Figure 4 is a map of the anticline trending northeast-southwest, and shows the outcrop, strike, and dip involved in the fold.

Concerning this anticline, Mitchum (1951: 20) stated that "The disturbed attitude of the rocks precludes a complete understanding of the folding …" He noted that it was only as the zone of most intense deformation was approached that the beds were overturned, however

> … it appears that the northwest limb remains overturned and that the dip of the southeast limb gradually increases along the axis, the beds first becoming vertical, then overturned and dipping very steeply to the northwest. Both the northwest and southeast limbs are overturned at this location. Farther to the northeast, the surface manifestations of the fold are terminated where the beds, still overturned, swing around the nose of the fold. (ibid.).

Rock layers were found throughout the Dycus Structure to be tilted at all angles, some vertical, others overturned. Figure 5 includes two photographs of moss-covered rock layers standing vertically, or nearly so, in the disturbed area.

The general fold pattern in the Dycus Structure was radial, and Mitchum (1951: 22) noted the existence of a circumferential anticline on the outer flanks of the depressed area which "… forms a semi-circle around the exposed portion of the disturbance …" This semi-circle had a radius from 365 to just over 425 meters , and the limbs of this ring-shaped anticline showed gentle dips which never exceeded 14 degrees in the central and eastern exposures and never exceeded 20 degrees in the rest of the structure. Although the dips were somewhat steeper and the vertical movement had been greater than elsewhere in the structure, the intensity of deformation was less than in the central zone (ibid.).

Mitchum (1951) noted that there was a syncline located between the dip into the central zone of greatest disturbance and the reversal of the dip on the outer part of the ring-shaped anticline. Its axis was concentrically parallel to that of the anticline, and just over 90 meters from it. Two faults were located on the outer periphery of the ring fold which Mitchum interpreted as being medium to high angle normal faults. Though he was unable to determine the displacement of one of these faults, he noted that

Figure 5: Two views of rows of moss-covered rocks standing on edge in the Dycus Structure. The view on the right is downrange from the photograph on the left: the distant dark rock in the center top of the left hand photograph is the same dark rock slightly to the right of center in the right hand photograph and just beyond the foreground tree. Note the slight change in direction of the rows just beyond the dark rock in the right hand photograph (photograph: Jana Ruth Ford).

a key bed was offset by the fault by at least 6 meters vertically and over 60 meters horizontally. He construed that pre-existing joint planes influenced the orientation of the two faults by offering the least amount of resistance to re-adjustment, thereby causing the lack of expected parallelism with the peripheral folds. The faults along the southwest section of the central zone and the relatively greater intensity of folding of the southwest section of the ring anticline were significant in Mitchum's view, indicating "… a higher degree of deformational intensity in this section than in any other part of the exposed periphery …" (Mitchum, 1951: 24). Breccias composed of angular fragments of limestone up to 7 or 8 centimeters long were found along the fault planes imbedded in a limestone matrix.

Mitchum (ibid.) noted the lack of interesting features beyond the disturbed area. Outside the zone of peripheral faults the rocks were undisturbed, except for a gentle dip into the central area of the disturbance. With increasing distance from the center this dip gradually decreased until the rocks approach their normal approximately horizontal attitude.

2.4 Crypto-Controversies

Bucher (1963: 1242) described a 'cryptovolcanic structure' as being a

> … roughly circular structure … [that] consists of: (1) a central uplift within which the strata are highly contorted and broken up, surrounded by (2) a more or less continuous ring-shaped depression which tends to be bounded and cut by faults.

Dietz (1946: 466; our italics) suggested that "Until the mode of origin of these features is definitely established, the present writer suggests that they be termed "*crypto-explosion*" structures." Dietz (1946: 465) stated that these cryptoexplosive structures were characterized by:

> (1) a roughly circular outline and a radial symmetry which, in some cases, was slightly bilateral; (2) a variation in size from less than a mile [1.6 km] to at least eight miles [12.9 km] in diameter …; (3) an intensely-shattered and jumbled central uplift surrounded by a ring-shaped depression and sometimes by other ring-shaped uplifts and depressions of diminishing amplitude forming a 'damped-wave' structure; (4) the central part of these structures contained sheared, shattered, and powdered rock and, in some cases, 'shatter-cones' which were indicative of explosive shock; and (5) volcanic, plutonic, or hydrothermally-altered rock was not found.

Dietz (ibid.) also noted that "Identified examples of these structures in the United States include the Flynn Creek disturbance in Tennessee, the Wells Creek Basin structure in Tennessee, [and] the Howell disturbance in Tennessee …", while Mitchum (1951: 26–27) argued that the Dycus Structure should be included in this list:

> Any acceptable theory of origin for the structural features in the Dycus area must explain the following: (1) a circular localized area of intense deformation in a region of relatively undisturbed strata; (2) a central uplift which is at least 70 feet [20 meters] above the surrounding depressed area, but which is below its normal position in that region; (3) an annular area depressed at least 140 feet [45 meters] below its normal altitude in that region; (4) a pattern of radial folds superimposed on the depressed area; (5) at least two peripheral faults outside the ring-shaped fold; and (6) the fact that folding is more prevalent than faulting in the structure.

Furthermore, Mitchum (1951: 27) pointed out that there were striking similarities between the Dycus Structure and the general description of a cryptovolcanic, or cryproexplosive, structure:

> The most striking similarities include the localized nature of the disturbance, the roughly circular plan, the central uplift, the annular depressed area, and the ring-shaped folds. The intense structural derangement in the center of the disturbance, as well as the lack of any volcanic materials, conform to the requirements for cryptovolcanic structures.

Mitchum (1951: 28–29) also noted a similarity between "… the ring-shaped folds of the Dycus structure … [and] a series of marginal ring-shaped concentric folds …" that surrounded the central uplift of the Wells Creek Basin. He pointed out that they differed only in size and intensity (ibid.).

However, there also were differences between the Dycus Structure and most other recognized cryptoexplosive structures: (1) Most of the disturbance seemed to be the result of folding rather than faulting; (2) As a result, there was correspondingly less breccia; (3) The intensity of deformation was not as great as is usually found in other structures; (4) The radial folds were more distinct than in most other structures; (5) The central uplift was far less important than the depressed area, both vertically and horizontally (Mitchum, 1951: 27). Furthermore,

> In most cryptovolcanic structures the rocks of the central uplift have been raised above their normal position in the region, but, at Dycus, although the rocks are raised above the immediately surrounding depressed area, they are below their normal position in the region … [and] The movement appears to have been predominately downward. (Mitchum, 1951: 27–28).

Historically, cyptovolcanic or cryptoexplosive structures have been attributed to a variety of causes, most of which were refuted by Mitchum (1951: 30; our italics):

> In the Dycus Disturbance, the high degree of folding and the central uplift would tend to eliminate the collapse of a cavern roof as a possible origin. An origin by the intrusion of a salt dome, or the expansion caused by the hydration of anhydrite, is unlikely, since there are no appreciable salt or anhydrite-gypsum deposits in the rocks of Central Tennessee (Wilson and Born, 1936, p. 829). A natural gas explosion is not likely since the Ordovician rocks of Central Tennessee are not known to have large accumulations of natural gas. Furthermore, according to Wilson and Born (1936, p. 830), a natural gas explosion has never been known to produce a structure similar to the localized circular structures of Tennessee. *The only origins that cannot readily be eliminated are those postulating a cryptovolcanic (gas and steam) explosion and a meteoritic explosion*.

Having said that, he then addressed the cryptovolcanic option:

> The strongest argument against the cryptovolcanic explosion theory is that no igneous materials, alteration products, or metamorphic rocks have been found around any of the true cryptovolcanic structures. Furthermore, they occur in areas marked by lack of volcanism. It seems unlikely, also, that the texture of the rocks near the surface, especially in a limestone section, would be such that it could confine magmatic gases and steam to the point where pressures could increase enough to produce such an explosion. (Mitchum, 1951: 32–33).

Mitchum (1951: 38) then pointed out that

> The facts that the deformational intensity is not as strong as in other structures and that the action was predominately downward, with a relatively minor central uplift, probably add weight to the meteorite hypothesis of origin.

He noted (Mitchum, 1951: 33–34) that most energy during an impact event would be in the form of vibrational shock waves which would radiate outward from the center of the explosion, forming the wave structure that surrounded the uplifted area of most cryptoexplosive structures. However, those structures that are seen today have experienced significant erosion, and so are actually the roots—the basements—of the original explosion craters (ibid.). Mitchum (ibid.) concluded that if the erosion was sufficient, the crater would not be preserved today, and the existing surface would be below the original level where the most intense faulting and brecciation took place (ibid.). The current surface, therefore, would show deformation predominately caused by folding, so if the Dycus Structure was a heavily-eroded impact site, then the fact that the deformation found there was less intense would be readily explained by the fact that the "… impact is a near-surface process, [so] the deformation associated with impact structures dies away rapidly with depth …" (French, 1998: 29). The amount of elastic rebound would decrease with depth, and in the case of a deeply-eroded structure the amount of central uplift probably would be subordinate to the down-bowing action. After accessing the available evidence, Mitchum (1951: 38) concluded that the Dycus Structure

> … may serve as an example of a deeply eroded explosion structure and afford some knowledge of the mechanics of the deformational stress at depth …

2.5 Cratering Mechanics

Although the majority of suggested origins of the Dycus Structure can be eliminated on the basis of the available evidence, to date a meteoritic origin has not been proven. But if, in fact, this is the relic of a meteoritic impact then it must be defined as an aberrant impact structure. This is because examination of Mitchum's 1:2400 scale geological and tectonic map (see Figure 3) shows that the Dycus Structure is not circular, even though the boundary of the structure is not fully defined on this map (Deane et al., 2006: 2). Yet at the time he conducted his thesis research Mitchum (1951: 15) believed that the structure probably was "… roughly circular … [and that the] uncovered portion of the disturbed area is limited to that of an approximate half-circle." He further presumed (ibid.) that about half of the structure was covered by rubble and debris from younger formations, and he also assumed that the "… small, relatively subordinate central uplift occupies the approximate center of the disturbance and marks the area of most intense deformation …" (ibid.).

One important question that immediately arises is why a structure that is only 600 meters in diameter would have any sort of central uplift. Simple craters are small, bowl-shaped structures without central uplifts, while complex craters are larger structures that "… display a different and more complicated form, characterized by a centrally uplifted region, a generally flat floor, and extensive inward collapse around the rim …" (French, 1998: 24). Here on the Earth the transition from a simple to a complex crater occurs at a diameter of around 2 km in sediments and 4 km in massive crystalline rocks (ibid.). Either Mitchum is correct in his assumption that there is a central uplift—which suggests that the structure is larger than is shown on his map—or else the structure is not circular and the uplift, as seen in the cross-section through the Dycus Structure (shown at the bottom of Figure 3), is not centrally located. Later investigations supported this latter conclusion:

> Continuing to the northeast, beyond Mitchum's

> map, the same strata are exposed in Long Branch Hollow and lie well within the 0.6 km radius of this proposed central uplift. Our field investigation in Long Branch revealed flat-lying rock with no deformation. Therefore, the area of maximum deformation does not lie in the center of the structure, but rather defines the northeastern boundary … While we have confirmed the occurrence of the deformation to the northeast, we have extended the northern boundary a couple hundred meters farther north with the discovery of bedding dipping 8° radially away from the structure …. (Deane et al., 2006: 2).

Although the Dycus Structure is slightly larger than Mitchum realized (ibid.), it is oval in shape rather than being circular. The similarity of this structure to the unusual lunar crater Schiller is striking, and is discussed in Section 2.6 below.

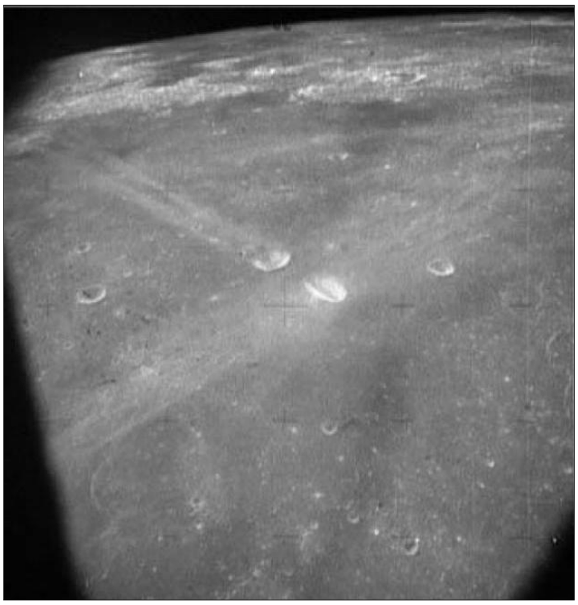

Figure 6: A NASA Apollo 11 photograph showing a close-up of the lunar craters Messier A (left) and Messier (right), with Messier A's two prominent downrange ejecta streaks and Messier's butterfly ejecta (after Forsberg et al., 1998: 1).

Unusual impact craters and structures can result from unusual formation conditions regarding either the impactor, its trajectory, or the target body. Kenkmann and Poelchau (2008b: 1) refer to craters formed by an impact of between 15° and 35° from the horizontal as 'oblique' and those formed by an impact of less than 15° from the horizontal as 'highly oblique'. They continue, noting that "… crater outline is insensitive to the impact trajectory and remains circular with the exception of highly oblique impacts." (ibid.). These very shallow or grazing impacts will result in craters with butterfly-shaped ejecta blankets as shown by the lunar impact crater Messier A in Figure 6 (ibid.). Hessen et al. (2007) found that impact craters 15° or greater from horizontal remain circular, but become increasingly more elliptical as the angle of impact decreases. Ejecta blankets become asymmetrical around 60° from horizontal and develop an up-range forbidden zone around 20° that continues to increase as the angle decreases (ibid.). Since ejecta blankets for terrestrial impact structures, however, are subject to erosion and not likely to be preserved, other "… unequivocal attributes for oblique impact craters such as … elliptical outlines …" can be utilized as indicators of highly-oblique impact (Kenkmann and Poelchau, 2008b: 2).

A detailed examination of the oblique impact scenario for the Dycus Structure will be presented by Beech, Ford, Orchiston and Clendening in a later paper.

2.6 Comparisons with Lunar and Terrestrial Oblique Craters

Kenkmann and Poelchau (2008b: 1–2) discuss oblique impact craters as follows:

> Statistically, 50% of all collisions of asteroids or comets occur at angles of less than 45°, and about 7% at angles less than 15° … Experimental and numerical studies have shown that the distribution of peak shock pressures within the target is asymmetrical in the case of oblique impacts with a concentration down range … With regard to experimental and numerical studies of oblique impact cratering, we infer that this lateral displacement component reflects a shift in the onset of crater collapse and the migration of the up-lifting crater floor down range, i.e. in the impact direction …

These researchers did state, however, that

> … a systematic offset of the central uplift with respect to the crater center could not be verified … [although] unequivocal attributes for oblique impact craters … [include] elliptical outlines … (Kenkmann and Poelchau, 2008b: 2).

In other studies of lunar craters that are considered to be the result of oblique impacts, preliminary results show that in all of these craters the central peak is located away from the geometrical center, with a slight trend that it is offset in the downrange direction (Goeritz et al., 2009).

The lunar crater Schiller is an example of an elliptical crater in which the uplifted area is a linear central ridge that is located at the northern end of the structure (see Figure 7). Schultz (1992) considers that oblong 'Schiller-like' craters are the result of grazing impacts, and an investigation by Herrick and Forsberg-Taylor (2003: 1554, 1557, 1565) of craters formed by oblique impacts produced

> … experimental results that show the rim lowered in the uprange direction and ejecta concentrated in the downrange direction for impact angles below 30° ... the crater becomes highly elongated in the downrange direction … [and] In some cases, the low point of the rim for an oblique impact is at the level of the surrounding terrain …

Other researchers have posed the question, “Is Dycus a secondary of Flynn?” (see Deane et al., 2006: 2), and this aspect also will be discussed later by Beech, Ford, Orchiston and Clendening. Perhaps the relationship between the Dycus Structure and the Flynn Creek impact scar is that they are double craters formed during the grazing impact of a single impactor that skipped on impact similar to the impact that formed the lunar craters Messier and Messier A (Herrick and Forsberg-Taylor, 2003). Messier and Messier A are the only known example of a pair of low angle ricochet craters on the lunar surface (Melosh, 2002). The Dycus Structure is just 16km from Flynn Creek, and Stratford (2004: 22) believes that they may be the result of a double impact. Bottke and Melosh (1996: 389) note that ~15% of all Earth-crossing asteroids should have satellites, and therefore “The steady-state binary asteroid pop-ulation in the Earth-crossing asteroid region is large enough to produce the fraction of doublet craters found on Earth and Venus (~10%).” Rampino and Volk (1996) also discuss the possibility of multiple impact events during the Paleozoic.

Oblique impact events here on the Earth are exceedingly rare, so “It is the rarity of such impacts that potentially makes the Dycus structure so very interesting.” (Martin Beech, pers. comm., September 2014).

The only known confirmed terrestrial impact crater caused by an oblique impact is the Matt Wilson Structure in northern Australia which is described by Sweet et al. (2005) and by Kenkmann and Poelchau (2008a).

Still of questionable origin (see French, 2004) are the ten or eleven elongate depressions in the Pampean Plain north of Rio Cuarto, Argentina that are considered by some to be the possible result of a low angle, highly oblique impact (Bland et al., 2002; French, 2004). However, satellite images revealed “… nearly 400 elongated depressions of nearly identical morphology …” in the surrounding area that are “… aligned with the prevailing wind direction …” (Melosh, 2002: 1037). The Rio Cuarto structures were considered to be aeolian features until impact-produced glasses and two meteorites found in one of the depressions convinced some researchers that these were indeed impact craters (Bland et al., 2002; Melosh, 2002). If these are impact-produced structures, then according to Beech (2014) the most likely scenario involved a coherent mass travelling at low speed, ~5 km/s, with an angle of impact of <5°. However, the origin of these features is still controversial.

According to Melosh (2002: 1037), “The discovery of meteorites and impact-produced glass in the craters swept away all criticism …”, however, the variation in long-axis orientations of these features is “… difficult to reconcile with the break-up and ricochet of a single impactor, but supports an Aeolian formation mechanism …” (Bland et al., 2002: 1110). Two more meteorites found in the depressions were studied and found to be different classes of meteorite, one of which fell around 36,000 years ago and the other >52,000 years ago, rather than fragments of a single impactor (Bland et al., 2002; Melosh, 2002). In addition, while “… it is clear that the glass found at Rio Cuarto is derived from an impact …”, evidence indicates that these glasses “… are representatives of a wide-spread tektite strewn field in Argentina with an age of ~0.48 Ma …” (Bland et al., 2002: 1111). The glass is older than either the meteorites or the craters, which are estimated to be ~ 4,000 years (Bland et al., 2002: 1110; Melosh, 2002).

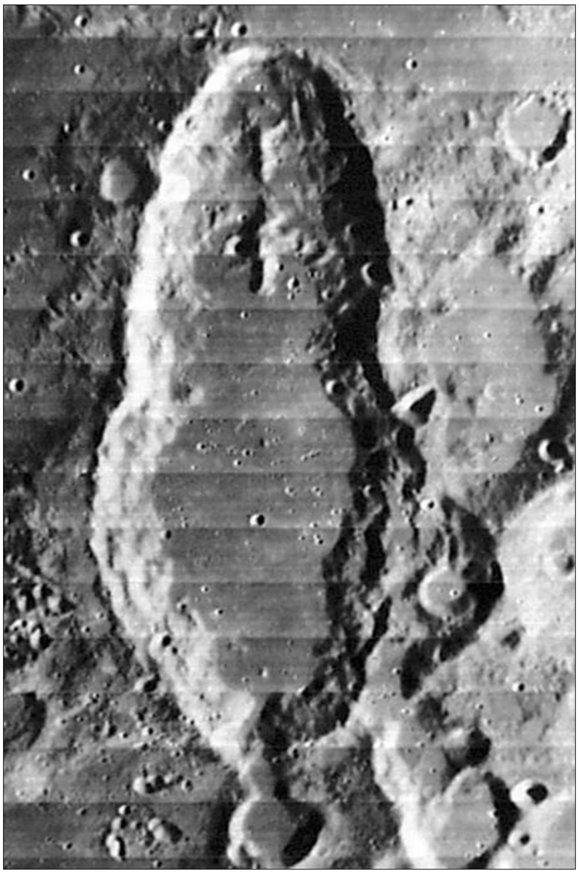
Figure 7: The elongated crater Schiller. Note the uplifted ridge located near the crater’s edge in the top of the photograph (Lunar Orbiter IV image IV-155-H1).

Melosh concludes that Bland et al. (2002) have “… revealed, not an oblique impact crater, but a much larger strewn field of tektites …” (ibid.). Schultz et al. (2004: 236), however, maintain that “… the hypothesis of a recent oblique impact for the RC [Rio Cuarto] materials (and some of the structures) not only remains viable, but is also consistent with data in hand.” These researchers conclude that at least two different impact events with clearly distinguished ages can be recognized at Rio Cuarto, one around 3–6 ka and the other about 114 ka (ibid.). The Rio Cuarto glasses are believed to represent impact melt breccias and "… do not meet the established criteria for tektites …" but incorporate near-surface material which is "… consistent with shallow excavation by an oblique impact (or near-surface break-up) …" (Schultz et al., 2004: 236–237). If the Rio Cuarto elongate structures are proven to be impact generated, then comparison with the similarly-elongated Dycus Structure and Schiller may provide an explanation for these enigmatic structures.

3 CONCLUDING REMARKS

Although first investigated decades ago, the Dycus Structure has received little attention from those researching meteoric impacts (see Deane et al., 2004: 1). Mitchum investigated this site in 1951 and recorded steeply-dipping beds which indicated that some sort of explosive event took place in a small, localized area within a region of Tennessee that is otherwise noted for its horizontal and undisturbed lithology. Gently dipping beds just to the northeast of the area of greatest deformation indicate that though the structure's boundary is likely somewhat farther north than is shown on Mitchum's 1951 map, this structure is not circular. However, the decrease of the bedding angles in this same direction indicates that the boundary does not extend any great distance beyond that which was originally mapped, indicating that it is not large enough to be a complex crater with a central uplift. Shatter cones are a distinctive easily-identified feature of craters caused by meteoric impact (e.g. see Dietz, 1959, 1960; Milton, 1977; Sagy et al., 2004), but no evidence of these was found by Mitchum during his 1951 survey of the Dycus Structure, or by Larry Knox, Marvin Berwind, and the first author of this paper when they visited the site in March 2012. Nonetheless, Mitchum (1951: 38) believes that the accumulated evidence "… adds weight to the meteoritic hypothesis of origin …", while Officer and Carter (1991) feel that there is insufficient information to assess the origin of the Dycus Disturbance.

Clearly what is needed is evidence of shock metamorphism that can be attributed to impact cratering. Planar fractures (PFs) and planar deformation features (PDFs) in quartz grains often are diagnostic of such impacts (French, 1998), as are the high-pressure silica minerals coesite and stishovite, but in deeply-eroded sites like the Dycus Structure all traces of these will have vanished.

As French (2004: 177) has pointed out, our knowledge is incomplete and "The deformation of quartz is a fundamental problem … in shock and impact studies." To date,

> … field and experimental studies of shock-metamorphic features in quartz have concentrated on the unique features (e.g., PDFs) formed at high shock pressures (≥ 5 GPa), which are diagnostic for meteorite impact.
>
> … virtually no information exists on quartz deformation in rocks subjected to still lower shock pressures (e.g., < 5 GPa) where the peak stresses (but not the strain rates) may be similar to those produced under tectonic conditions. (French, 2004: 178).

The greater volume of target rock during impact, primarily the basement rock, is subject to lower pressure shock waves, which raises the questions "What deformation features in quartz are produced by shock waves at pressures, <5 GPa?" and "Can such features (like PDFs) also be used as unique and diagnostic indicators of shock waves and meteorite impact?" (ibid.). If low-shock features unique to impact can be identified, then the question of whether deeply-eroded sites like the Dycus Structure are of meteoritic origin may be resolved.

Regrettably, until such evidence is assembled, the Dycus Structure must remain a suspected impact crater.

4 NOTES

1. Slickensides are smoothly polished rock surfaces with parallel striations caused by frictional movement between the rocks along two sides of a fault. The striations are usually in the direction of movement indicating slippage along bedding planes.

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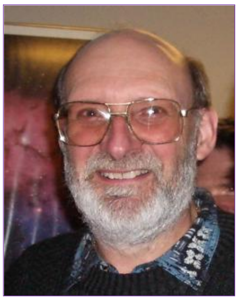

Professor Wayne Orchiston works at the National Astronomical Research Institute of Thailand and is an Adjunct Professor of Astronomy at the University of Southern Queensland in Toowooma, Australia. Wayne is interested in the history of astronomy and in meteoritics, and he welcomed the chance to combine these two research areas by supervising Jana Ruth Ford's Ph.D. thesis, but most of his publications have dealt with historic transits of Venus and solar eclipses, the history of radio astronomy, historic telescopes and observatories, and the history of cometary and asteroid astronomy. Recently, the IAU named minor planet 48471 Orchiston.

Ron Clendening is a geologist working for the Tennessee Division of Geoogy, the Geologic Survey for the State of Tennessee, USA. For the past six years he has worked in producing geological maps for the Division of Geology. Though his primary academic interest is in quaternary geomorphology, his professional work has mainly concentrated on groundwater, environmental and karst geology of the central limestone region of Tennessee. In addition to working as a professional geologist, he also worked as a soil scientist, producing soil mapping products for private interests, as well as local and state government agencies. He is a career-long member of Geological Society of America.

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