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Mills 1953 Events: Baade Correspondence, Construction of Prototype Mills Cross and American Association for the Advancement of Science end December 1953

(1): *Mills and Baade correspondence 20 March 1953*
Mills had written to Baade on 20 March 1953 with some details of his upcoming publication, "The Radio Brightness Distribution over Four Discrete Sources of Cosmic Noise" which discussed the four sources: Cygnus A, Taurus A, Virgo A and Centaurus A.

As background, he sent Baade a preprint concerning the decisive paper showing that the so-called radio stars had a finite size, in many cases several arc min. Thus, the nomenclature of "radio stars" was clearly inappropriate. His new results were obtained using the radio link interferometer, centred at Badgerys Creek near Sydney. The interferometer spacings varied from 60 m to 10 km with an orientation of E-W. In addition, limited observations were made at other azimuths (164 deg at 1 km and 24 deg at 1 plus 2 km). "These [spacings] are adequate to orient the major and minor axes of the sources approximately without giving much information about their distributions in these directions." The angular resolution was about one arc min.

The paper would be finally submitted to the *Australian Journal of Physics* on 3 August 1953, published at the end of 1953, "The Radio Brightness Distribution Over Four Discrete Sources of Cosmic Noise" with the four sources: Cygnus A, Taurus A, Virgo A and Centaurus A. Except for Cygnus A, two-dimensional contours could be derived for the sources. The frequency was 101 MHz. For the other three sources, the relevant baselines were in the range 0 to 5 km; no detectable fringes were observed at the 5 and 10 km baselines for the three extended sources. (See Chapter 21 for the Cygnus A discussion- the size derived for this source by Mills was about 1.1 arc min.)

Mills explained to Baade:

> The enclosed tracings [see Fig. 1 below] are outlines of the estimated half brightness contours for the three radio sources in Taurus, Virgo and Centaurus. Cygnus has too low an elevation for me to attempt anything but E-W measurements. Perhaps the most striking thing is the near coincidence of the Centaurus source with the band of obscuring matter in NGC 5128 i.e. with the late type spiral, if your suggested

> interpretation of the structure of the nebula is correct. Also the Taurus source appears to agree very well with the shape of the Crab Nebula …

Mills stressed that the "contours are very rough and are based on the assumption that the sources are symmetrical [ie no phase information was available] [and] elliptical …" The impressive "radio-pictures" that were included in the Mills December 1953 (*Australian J Physics,* vol 6, p 452) publication are shown in Fig. 2. The images have an unconventional orientation with east to the right, not the usual orientation with east to the left.

Robertson et al (Robertson, P., Cozens, G., Orchiston, W., Slee, B., & Wendt, H. (2010). Early Australian optical and radio observations of Centaurus A. *Publications of the Astronomical Society of Australia*, *27*(4), 402-430., p 402) have pointed out a problem with the orientation of the Centaurus A image published by Mills.

> It is likely that the use of the simplifying symmetry assumption as well as the limited baseline orientations distorted the estimated source distribution. Comparison with high-resolution measurements of the inner radio lobes shows they are oriented at 90 deg to that estimated by Mills.

Mills's published image of Taurus A did not suffer from the same orientation error.

Numerous modern high resolution radio images have shown that the inner lobes are perpendicular to the prominent optical dust lanes. For example, Neff, Eilek and Owen (2015, p 87) have published impressive 327 MHz images made with the Jansky Very Large Array with angular resolutions in the range 10 to 60 arc sec.

In the publication by Mills (1953), his conclusion follows the assertion made earlier to Baade:

> The central concentration of the Centaurus source appears to be definitely associated with the central portion of the galaxy NGC 5128, and in particular with the obscuring band which crosses the galaxy. Since we might expect to find a concentration of gas in this region it would appear that this source also, along with Cygnus, Taurus, and possibly the Virgo sources, could have its origin in interstellar gas; and again the temperature seems too high and the spectrum unlikely for a thermal origin.

In his 2006, autobiographical text ("An engineer becomes astronomer." *Annu. Rev. Astron. Astrophys.* 44: 1-15), Mills mentions the problems of the Centaurus A observations of 1953: "[The simple two-dimensional models] gave very misleading information for Centaurus A because of the complexity of the source, the limited number of observations, and the absence of phase information."

(2): *The prototype Mills Cross in early 1953*

Mills was not pleased by Bowen's criticism and doubts of his proposed new instrument. In the 2006 autobiographical text in *Annual Reviews*, Mills wrote:

There was opposition to the idea in the Laboratory for some technical reason that I never really understood, and perhaps a political reason, which I could well understand [originating from Bowen][1]. However, Pawsey supported me and gave approval for the construction of a small experimental model to explore the technique. He also assigned the laboratory's brightest young Technical Officer, Alec Little, to help and this was the beginning of a long and fruitful association.

But Mills's small prototype instrument demonstrated the capabilities of the Mills Cross approach. Mills and Little described the prototype, "A High-Resolution Aerial of a New Type", in the *Australian Journal of Physics* in 1953. The paper was submitted (6 May 1953) a few months before Mills departed to the US. The remarkably straight forward method of operation is shown in Fig 1 of Chapter 22. Mills and Little gave an illuminating explanation:

> … When the arrays comprising the two arms of the cross are connected in the same phase [there is an enhanced response at the overlap at the centre, but the total solid angle over reception is very large.] [A]dvantage may be taken of the presence of signals in both aerials from the central region and their phase coherence for, if the arrays are now connected in antiphase, there will be no response from this central region, while the "spokes" of the diagram will be unaffected. If, therefore, the connections between the arms of the cross are switched rapidly between the two conditions, a source which is in the solid angle common to both beams will deliver a modulated signal at the switching frequency, while the signal from a source which is received by one aerial alone has no modulation imposed. After amplification and detection, the modulated signal may be picked out by a phase-sensitive detector and used to deflect a pen recorder. The recorder then gives the integrated signal from within the central region so that, in effect, a pencil beam is produced which has a size determined by the maximum dimension of each array.

[1] Bowen has written in several reports (e.g. Sullivan 1984, Bowen's article "The Origins of Radio Astronomy in Australia"): "Mills made the first suggestion of a cross-type antenna in 1952. It was a highly intriguing proposal but, if my memory is correct, not even Mills was completely convinced that it would work in the first instance. Obviously, a trial was called for [the small Potts Hill prototype]." Mills told Goss in the 1990s that he vigorously disagreed with this assertion that he had doubts since he had used this effect to get rid of confusion with the original Badgerys Creek instrument in 1951. Bowen concluded his text: "With this instrument Mills demonstrated that the principle of the cross antenna was sound." In Sullivan (1984, *The Early Years of Radio Astronomy*, p. 147) Mills has written in his contribution "Radio Sources and the logN-logS Controversy": "Our work [with the new cross] was delayed somewhat by the skepticism of the powers-that-be and I remember being informed with great authority [likely Bowen] that my proposed "Cross" could not possibly work."

Even with an 8-degree resolution, the Potts Hill prototype was a major success. Many problems were solved and useful lessons were learned, helping to produce a reliable finished product at Fleurs in 1954 with the full Cross. Mills and Little concluded their short paper in 1953: "... [T]he principle of operation is sound and has demonstrated the feasibility of a full antenna … [The new antenna] will be capable of surveying about half the sky with a resolution of less than 1 degree."

As Mills's departure date for the US in early August 1953 approached, he prepared a detailed proposal for the full cross and presented it to Pawsey for approval, "Large Aerial for Metre Wavelength". He wrote: "Linear interferometers have been shown to be unsatisfactory for future development and a pencil beam is required." The beam size of about one degree had been chosen since the extended background of the galaxy showed structure down to about one degree and most sources were less than 15 arc min in size. A few extended sources of order one degree had also been detected. Mills predicted that with a beam of 0.8 deg, 2400 radio sources could be detected.

The prototype had shown that the beam could be displaced ± 40 degrees from the zenith; thus more than half the Milky Way and the Magellanic Clouds were accessible. The working frequency would be close to 80 MHz; the final frequency chosen was 85.5 MHz.

(3): *Smith and Mills at the AAAS* ***(American Association for the Advancement of Science) meeting, December 1953***

The Section D meeting—astronomy—began Saturday afternoon (26 December) at the American Academy of Arts and Science in Boston. The session was also sponsored by Section B of AAAS—Physics. Smith and Mills had produced lengthy abstracts on "Discrete Sources of Cosmic Radio Waves".

Smith spoke first. He began:

> Radio waves from outside the earth carry information about the universe in the same way as the light studied in conventional astronomy. The information we receive often concerns regions entirely different from the visible regions, since radio waves may be emitted, absorbed, or reflected from extremely tenuous gas clouds, such as the solar corona, hydrogen clouds in interstellar space, and, as we now know from various peculiar types of nebulae.
>
> The first observations of extra-terrestrial radio waves led to the suggestion that the radiation came from the ionised hydrogen clouds in interstellar space. Although it has been shown that part of the galactic radiation originates in this way, recent experiments have shown that there are discrete sources of radio waves, both in our galaxy and in extra-galactic nebulae. Since the first experiments of Hey, Bolton and Stanley, and Ryle and Smith, surveys have been made in various ways in England and

> in Australia which have shown the existence of some hundreds of discrete sources. It has now become an important task of radio astronomy to investigate the location in space of the various different types of source, and to try to understand their physical nature.

Smith pointed out that at the longer wavelengths it was advantageous to use interferometer techniques due to confusion problems. Sensitivity was not the problem,

> … but rather the difficulty of obtaining resolving power without making antennas of impossibly large areas. Two new antenna systems are now being put into use which spread over a large area of ground without actually filling it. The Australian one described by Mills has achieved a very small effective beam width. The Cambridge interferometer, of the same area as the Manchester paraboloid, has a larger beam width than the Australian antenna, but has instead the advantages of high-resolution interferometers. A narrow beam width is necessary for discrimination between adjacent radio sources, so that the number of sources detected by any equipment will vary inversely with the beam width.

Smith emphasised the advantages of the planned 2C antenna, at 3.7 m; no mention was made of the issue of confusion, i.e. the number of beam widths per source was not discussed.

Bernard Y. Mills continued at the AAAS as the second speaker**:**

> Identifications with astronomical objects have now been suggested for nearly two dozen extra-terrestrial sources of radio waves. Excluding the moon and the sun, these objects fall into three categories: (1) normal galaxies, (2) gaseous nebulae within our galaxy and (3) abnormal galaxies.
>
> Galaxies similar to our own appear to emit radio waves with an intensity roughly proportional to their total light emission. Identifications have been suggested for ten radio sources with such galaxies. These sources are all very weak, however, except for our own galaxy, which produces nearly half of the total power received from the entire sky. The more intense sources belong to classes (2) and (3). In the second category two have definitely identified with galactic nebulosities. These are the source in Cassiopeia, the most powerful in the sky, with a very faint filamentary nebulosity of a previously unknown type, and the source Taurus A with the Crab Nebula, the expanding shell of an old supernova. Three other such identifications are reasonably well established. The spectrum of the Cassiopeia nebulosity reveals a very high internal velocity dispersion, as does also that of a very similar nebulosity in Puppis for which an identification is also suggested.

Mills stressed a major problem faced by the radio astronomers at the end of 1953: there was vast uncertainty in the “physics of the radiating process”.[2] Mills continued: “Recent Australian experiments have been directed partly at this problem by determining the extents of the radiating areas and their radio frequency spectra. Approximate shapes and sizes (from 1 min of arc to several degrees) have been determined for 14 sources.”

Following Smith’s example, Mills described his new instrument being constructed in Australia at Fleurs, operating at 3.4 m with a beam of 0.8 degree: “The use of a pencil beam of such a high resolution is indicated by some of the angular size measurements [made earlier at CSIRO], which suggests a fine structure in the distribution of cosmic noise.”

The final session of the radio astronomy symposium was held on Sunday afternoon, a panel organised by George Harrison, Dean at MIT, with panel members including Merle Tuve of Carnegie Institution and Gordon Little of Jodrell Bank, discussing the current status of radio astronomy.

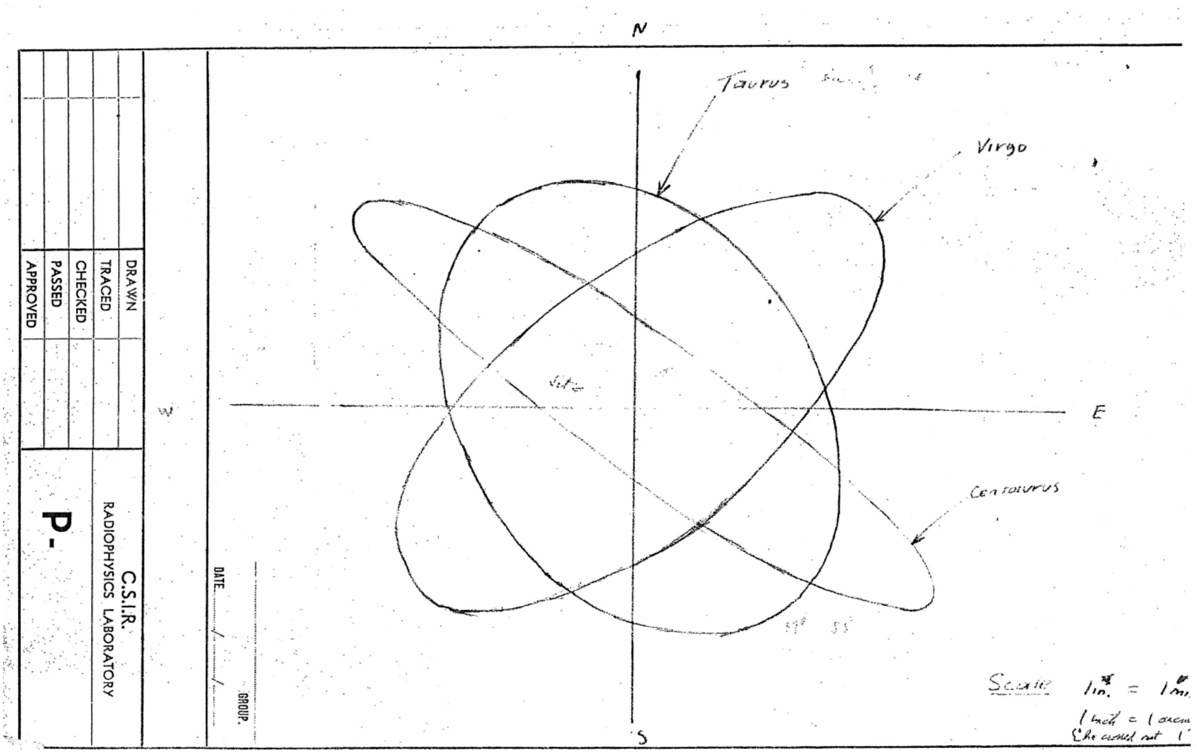

Fig 1 – Tracings of the shapes of the three sources Taurus A, Virgo A and Centaurus A in 1953 at 101 MHz at Badgerys Creek and additional sites with baselines 60 m to 10 km, included in the letter from Mills to Walter Baade from 20 March 1953. Angular resolution about 1 arc min. The six arc min Taurus A source is the inner double lobe source (Neff et al 2015). Due to problems with limited baseline coverage in the data, the orientation of the Centaurus A image has an error of 90 deg. (See main text)

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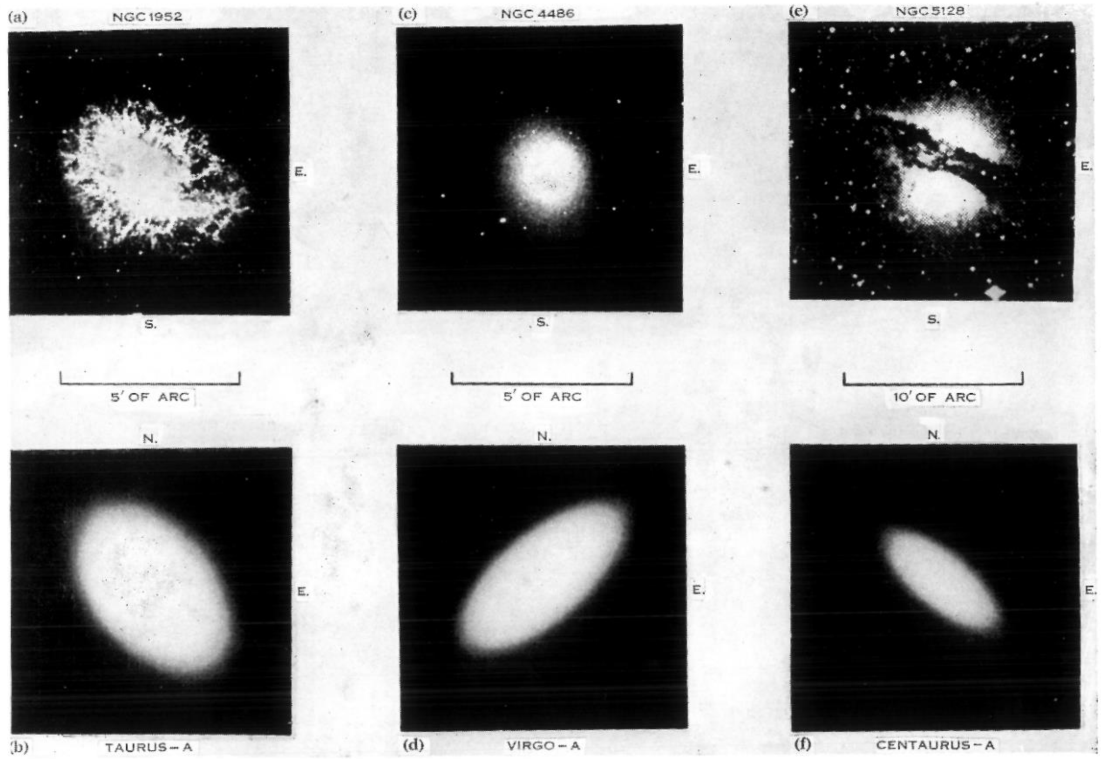
[2] See Chapter 34



Photographs of the associated nebulae compared directly with " radio pictures " of the sources constructed from the observational data.

Fig 2 Following Sullivan, 2009 (*Cosmic Noise* p 350) From Mills 1953: "Radio pictures" of three radio sources, compared to photographs of their optical counterparts). Each radio picture is a representation of three derived properties of the radio source (lengths of major and minor axis and orientation). Relative brightness is not shown – the "fuzziness" along the edge of each ellipse has been added for verisimilitude. Note the unconventional orientation of the images with east to the right, instead of the left. The orientation of the Centaurus A image is in error by 90 deg.