COSMIC RADIO SOURCES OBSERVED AT 600 Mc/s

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Summary

A survey of cosmic radio emission at 600 Mc/s using a beam 3°·3 wide has been made over most of the celestial sphere between declinations 90 °S. and 51 °N. Discrete sources numbering 49 were located having flux densities of about 1×10^{-24} W m^{-2} (c/s)$^{-1}$ or more. Of these, 18 do not appear to have been reported previously, including 12 which lie within $\pm 2°$ of the galactic plane.

Most of the sources seem to be associated with other sources or with irregularities of the background radiation. There seems to be no sharp boundary between discrete sources and such irregularities. Many of the new sources are likely to be clouds of thermally emitting H II.

I. Introduction

A survey of cosmic radio emission at 600 Mc/s has been made over most of the celestial sphere between declinations 90 °S. and 51 °N. from a field station near Sydney, N.S.W. This communication presents the data on the localized sources found during the survey.

The results have been obtained using a narrow pencil beam of width 3°·3 between half-power points. Although narrower beams have been employed, the observations have generally been confined to limited regions of the sky and even the most extensive pencil beam surveys have not included the southern Milky Way, a region rich in radio sources. The most comprehensive surveys of discrete sources have been made with interferometer techniques at frequencies of the order of 100 Mc/s. The use of a beam at a much higher frequency tends to highlight spread sources and sources with unusual spectral characteristics such as 20N4A (Cygnus-X, Piddington and Minnett 1952). A number of new sources of large angular width and with peculiar spectra have been found. The spectral characteristics will be discussed in another communication.

II. Experimental Methods

(*a*) *The Aerial System*

The aerial system used was a paraboloid 36 ft in diameter used as a transit telescope. It has previously been described (Kerr, Hindman, and Robinson 1954) in connexion with hydrogen line observations at 1420 Mc/s. The feed system was a single dipole and reflector plate. A direct measurement of aerial gain has not been made, but it is unlikely that such a measurement could improve greatly on the estimate made as follows: using the Sun as a steady, and quite

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powerful, source of radiation a plot was made of the power response in the main aerial beam. The finite angular size of the Sun is not sufficient to change the plot appreciably from that given by a point source. If we neglect side and back aerial lobes for the time being, the "nominal gain" over an isotropic radiator may be determined with an accuracy of a few per cent. by a process of graphical integration.* This was found to be 3800. The real gain was then found from an estimate of the proportion of radiated power in the main beam (the aerial assumed transmitting), which was 0·65. The overall aerial gain was therefore 2500.

The relationship between the aerial declination setting and true declination was found to vary with the setting, owing to changes in the sag of the structure. A correction table derived by Kerr, Hindman, and Robinson was used; this was based mainly on visual sights of stars, using radio observations on the Sun to relate the mechanical and radio axes of the aerial.

The directional accuracy for strong, isolated sources is about $\frac{1}{2}°$ in both Right Ascension and declination. However, when the source is weak or is close to other emitting regions, the accuracy is reduced.

A second, smaller aerial (6 ft diameter) was used in conjunction with the large aerial to act as a temperature reference level. The receiver then measured the difference in flux received by the two aerials. The second aerial was pointed at the south celestial pole so as to receive a steady signal in its main beam. The passage of parts of the sky with high brightness temperatures through the side lobes has a negligible effect so that the total received signal does not vary appreciably. Its feeder system was adjusted to have the same loss (3.dB) and to be subjected to approximately the same temperature fluctuations (due to ambient temperature changes) as the main feeder.

(b) *The Receiver*

The receiver operated on the Dicke system of switching at 25 c/s between the two aerial feeders. Apart from changes necessitated by the new operating frequency most of the equipment is similar to that already described (Piddington and Minnett 1951) for operation at 1210 Mc/s. A determination of the receiver sensitivity was made before and after each series of observations, using a matched termination in place of the aerial. The termination could be heated through a known temperature range.

(c) *Observations*

Observations were made by setting the main aerial to a given declination and recording the level of intensity over a period of several hours. For the most part satisfactory conditions occurred only between about 2200 hours and 0600 hours local time. Occasionally the main aerial was pointed at the South

* It should be noted that this is purely a graphical process involving no data other than the relative response of the aerial in different directions. The physical basis may be better seen by imagining the aerial transmitting the same amount of power as an isotropic radiator. If the aerial response is such that the power radiated in the centre of the main beam is n times the average over the whole sphere, then the aerial gain is n.

Pole to give a fixed reference level. This level could not be assumed a zero level for other declinations, however, because aerial side lobes picked up different amounts of ground radiation for different aerial positions. The zero level for each declination was taken as the " cold " part of the sky, well clear of the Milky Way. Extrapolating the measured spectrum of the cold sky gives a brightness temperature of about 4 °K at 600 Mc/s and suggests that the method used is quite safe provided that it is remembered that all brightness temperatures measured are above an unknown minimum of a few degrees.

The receiver output was automatically recorded, together with Right Ascension noted at hourly intervals. An example of a record made at Dec. 49°·9 S., R.A. between about $13^h\ 00^m$ and $19^h\ 00^m$ is shown in Figure 1. This shows the powerful source in Centaurus and later the galactic crossing which provide receiver input temperatures of about 10 and 50 °K respectively. This record is discussed below.

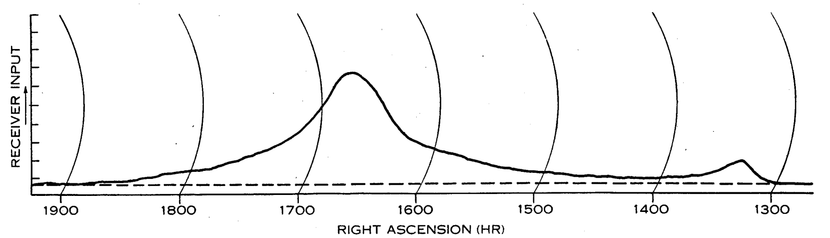

Fig. 1.—Record taken at Dec. 44°·9 S. between R.A. $13^h\ 00^m$ and $19^h\ 00^m$. The Centaurus source (13S4A) and its " link " with the main galactic radiation is shown. The receiver input temperature is about 8 °K per division.

The receiver sensitivity was measured before and after each record by means of a matched load which could be heated to temperatures of the order 100 °C. It was found that under ideal conditions sources giving flux densities of 10^{-24} W m^{-2} (c/s)$^{-1}$ could be detected with reasonable ease.* However, many records were far from perfect, owing to interference, and even after several repetitions good records were not obtainable for some parts of the sky. It may be assumed that most of the region within about 30° of the Milky Way was satisfactorily surveyed except beyond declinations 51 °N. and 70 °S. The region south of 70° is difficult to survey because of the slow rate of transit of any sources ; this accentuates the effects of random drifts. However, some runs were made through the Magellanic Clouds and the results are given.

III. Results

In Table 1 are listed 49 sources observed at 600 Mc/s. Previous lists of radio sources have frequently described them as " discrete ", implying the existence of an isolated physical entity. It is unlikely that all of the present sources are discrete in that sense ; many of them, particularly those lying near the galactic plane, appear on the records as localized maxima above strong

* This corresponds to a beam brightness temperature of 2·8 °K.

background radiation. Their degree of association with the background radiation cannot be determined but each represents a reasonably well-defined maximum of intensity.

Also listed is the flux density of solar radiation on three occasions. This is included in the hope that the quiet Sun* may soon be used as a standard source of radiation by means of which different workers may check their aerial and receiver characteristics. The same consideration applies to the Moon (at higher frequencies) and to outstanding cosmic radio sources whose spectra may soon be known.

The sources are given a reference number and, when available, an International Astronomical Union number (Pawsey 1955). When they appear to coincide with a previously observed source for which no I.A.U. number is available the observer's initials and own reference number are given. These are as follows: HBH—Hanbury Brown and Hazard (1953); M—Mills (1952); BWSS—Bolton *et al.* (1954); AG—Allen and Gum (1950); BSS—Bolton, Stanley, and Slee (1954); KKM—Kraus, Ko, and Matt (1954); DLS—Denisse, Leroux, and Steinberg (1955); NRL—Haddock, Mayer, and Sloanaker (1954); M(1955)—Mills (1955).

For spread sources the constellation listed is that of the highest intensity level, when available, or of the centre. The approximate dimensions (R.A. $\times$ Dec.) are given to the contours of lowest intensity of these sources. When only one dimension is given this is the largest, the other being not greater than the aerial beamwidth. For spread sources the total flux density is found only by a process of integration. For this reason the value given is the maximum aerial temperature: this value is obtained after subtracting the mean background aerial temperature.

IV. Notes on the Sources

Source 1.—Mills (1954) working at 85·5 Mc/s has identified a source at R.A. $03^h\,20^m{\cdot}6$, Dec. $-37°\,23'$ with NGC 1316. This is probably the same source, although the difference in position, which is near the limit of experimental error, suggests that there may be a contribution from the surrounding region which has a different spectrum.

Source 2.—Near limit of sensitivity; seems spread $\sim$5° in direction of changing declination. Agrees in position with HBH.8.

Source 3.—Near limit of detection; seems spread in direction of changing R.A.

Source 7.—This is probably the giant emission nebula 30 Doradus at R.A. $05^h\,40^m$, Dec. $-69°{\cdot}1$, lying within the Large Magellanic Cloud. This identification was made by Mills (1955) using a narrower ($\sim$1°) beam; he observed a strong maximum at R.A. $05^h\,40^m$, Dec. $-69°{\cdot}3$. The different radio positions

* As we move towards the next sunspot maximum the " quiet Sun flux density " (that is, the minimum flux density over a period of a few days or weeks) will increase steadily. Intercomparison of measurements made at different times can be made by using the daily values of solar flux density published in the *Quarterly Bulletin on Solar Activity* published by the International Astronomical Union.

TABLE 1

LIST OF SOURCES

Reference No.	Designation or Previous Identification	Constellation	Position of Centre: Celestial Coordinates (Epoch 1950) R.A. (h m)	Dec. (°)	Galactic Coordinates l (°)	b (°)	Approx. Angular Size (°)	Max. Aerial Beam Temp. (°K)	Flux Density (both polarizations × 10^{-24} W m^{-2} $(c/s)^{-1}$)	Remarks
1	03S3A	Fornax	03 23	−37½	206	−55	—	—	3·1	Probably NGC 1316 (Mills 1954)
2	HBH.8	Perseus	04 00	+48	120	− 2	~5	~3	—	Weak, spread source
3	——	Perseus	04 02	+40	126	− 8	~5	~3	—	Very weak and appears spread
4	M04+1	Orion	04 50	+10	157	−18	—	—	1·0	
5	05N2A	Taurus	05 30	+22	152	− 4	—	—	12·5	NGC 1952 (Crab Nebula)
6	05S0A	Orion	05 32	− 5½	177	−18	—	—	3·0	NGC 1976 (Orion Nebula)
7	M(1955)	Dorado	05 37	−69	246	−31	—	—	3·4	Probably 30 Doradus (Mills 1955)
8	——	Taurus	05 40	+28	151	0	—	—	—	Not seen on later runs
9	BWSS.D	Orion	05 42	− 1	174	−14	~5×5	7	—	Spread source
10	——	Orion	05 50	+22	154	− 1	~12	7	—	Spread source
11	06N2A	Gemini	06 13	+23	156	+ 4	—	—	2·2	IC 443
12	——	Monoceros	06 30	+ 6	173	0	10×20	7	—	Suggests part of galactic structure
13	——	Monoceros	06 33	+ 5½	174	0	—	—	4·0	May be NGC 2237
14	——	Gemini	07 15	+27	159	+19	—	—	~1	Poor record
15	08S4A	Puppis	08 20	−42	227	− 2	—	~5	—	
16	AG	Vela	08 36	−45½	232	− 2	18×15	56	—	Large galactic feature
17	BSS.119	Vela	09 10	−41½	233	+ 5	—	~8	—	
18	BWSS.G	Hydra	09 15	−10	209	+27	—	—	1·5	
19	09S1A	Hydra	09 18	−11½	211	+27	—	—	0·8	
20	——	Leo	09 45	+19	182	+49	5×0	5	—	Poor record
21	——	Carina	10 49	−59½	256	− 1	6×0	39	—	
22	——	Centaurus	11 40	−58½	262	+ 2	—	~3	—	

23	——	Crux	12	10	−62	266	0	—	~3	—	
24	12N1A	Virgo	12	29	+12½	261	+74	—	—	3·6	NGC 4486
25	——	Centaurus	12	38	−64½	269	− 3	—	~6	—	
26	——	Centaurus	13	18	−63	274	− 1	—	~11	—	
27	13S4A	Centaurus	13	22	−43	278	+18	—	—	13	NGC 5128 plus spread source
28	13S6A	Centaurus	13	40	−60	277	0	—	~6	—	
29	——	Centaurus	14	07	−61½	280	− 1	—	~30	—	
30	KKM.Hya0	Hydra	14	50	−29	301	+25	—	—	1	
31	——	Circinus	14	58	−59	287	− 2	—	14	—	
32	16S6A	Norma	16	08	−60	293	− 7	—	5	—	
33	——	Ara	16	40	−46	307	− 2	—	22	—	May contain NRL 19
34	16N0A	Hercules	16	45	+ 6	351	+29	—	—	1	
35	M17–3	Scorpius	17	10	−39	315	− 1	—	10	—	
36	NRL12	Scorpius	17	25	−35	320	− 2	—	25	—	
37	17S2A	Sagittarius	17	44	−29	328	− 1	—	—	29	Has been proposed as galactic nucleus
38	DLS	Ophiuchus	17	45	+ 7½	360	+16	6	11	—	Spread source
39	——	Scorpius	17	50	−45	314	−11	6	5	—	Spread source
40	NRL10 & 11	Sagittarius	18	01	−22½	335	− 2	—	—	7	
41	NRL4	Sagittarius	18	14	−16½	342	− 2	—	—	4	Perhaps Omega Neb. NGC 6618
42	——	Hercules	18	26	+18	14	+12	—	5	—	
43	KKM.Sct.A	Scutum	18	32	− 8	352	− 1	—	—	4	
44	M19+0	Aquila	19	04	+ 8	9	− 1	—	—	6	
45	——	Aquila	19	22	+13½	16	− 2	—	—	3	
46	19N4A	Cygnus	19	58	+40½	44	+ 5	—	—	37	Original Cygnus–A source
47	20N4A	Cygnus	20	24	+40½	46	+ 1	6	90	—	Original Cygnus–X source
48	HBH.21	Cygnus	20	49	+51	57	+ 4	—	—	~3	
49	NRL21	Cygnus	20	57	+44¾	54	− 1	—	~5	—	Suggested identification NGC 7000
Sun	——	——	—		—	—	—	—	—	3100	Feb. 1, 1955
Sun	——	——	—		—	—	—	—	—	3900	Sept. 13 and 14, 1955

are no doubt caused by the spread of bright areas around 30 Doradus; the flux density received from these areas depends on the aerial beamwidth and the spectral characteristics. The emission is probably thermal, from ionized hydrogen, and the maximum lies within 1° of that for line emission by neutral hydrogen observed by Kerr, Hindman, and Robinson (1954).

Source 9.—A clearly defined spread source whose contours may just adjoin those of the Orion Nebula (source 6).

Source 10.—This appears to be a source spread $\frac{1}{2}$–1 hour in Right Ascension and perhaps a couple of degrees in declination. It may merely be the two sources recognized within the area (Crab Nebula and IC 443) with a little additional radiation from another source lying between them.

Source 12.—This large, weak source lying along the galactic plane between $l \sim 165°$ and $l \sim 185°$ may be a substantial part of the galaxy. It does not show very close agreement with the contours of Reber (1948) for 480 Mc/s radiation; these extend from $l \sim 143°$ to $l \sim 180°$.

Source 13.—This is a source within the spread source 12. It may be identified with NGC 2237 (Mills, personal communication).

Source 16.—With the sensitivity and aerial beam of the 600 Mc/s radiometer this emission appears as a large but completely isolated source, roughly circular in shape. It extends along the galactic plane from $l \sim 222°$ to $l \sim 244°$ with maximum intensity at $l=232°$, $b=-2°$. Its existence and approximate location were inferred by Allen and Gum (1950) from measurements at 200 Mc/s with a 25° wide aerial beam; they did not separate it from the general galactic emission. It is also a very conspicuous object at 85·5 Mc/s (Mills, personal communication). Finally, it approximately coincides in position with one of the main regions of 1420 Mc/s H I line emission (Christiansen and Hindman 1952).

Source 21.—This is a source spread about 6° along the galactic plane but having no measurable width across the plane. Although a very conspicuous object at 600 Mc/s it has not been reported previously; high frequency surveys have not included this portion of the sky and the object is not outstanding at lower frequencies. At 85·5 Mc/s, Mills (personal communication) finds several rather weak sources of small angular size which would probably not be resolved by the 3° beam.

Sources 22, 23, 25, 26, 28, 29, 31, 32, 36, 37, 40, 41, 43, 44, 45.—These sources may be discrete or may be maxima of the general galactic radiation. They are all in regions where the background is bright and non-uniform. Their apparent size is consistent with point sources but they might have dimensions up to a few degrees.

Source 32.—The position found is in Norma but the position of 16S6A is just across the border in Triangulum Australis.

Source 35.—The previous identification given M17–3 may not refer to the same source, or combination of sources, since it was at R.A. $17^{h}\ 20^{m}$, Dec. $-39°$ (about 2° away). McGee, Slee, and Stanley (1955) found a source at R.A. $17^{h}\ 13^{m}$, Dec. $-38°$ which is closer, and Haddock, Mayer, and Sloanaker (1954) found one at R.A. $17^h\,17^m$, Dec. $-36°$ which is further away. There may be a combination of sources in the region.

Source 38.—This spread source may be discrete or part of the background to which it appears to be attached. It is evident in the contour plots of Denisse, Leroux, and Steinberg (1955) and Kraus and Ko (1955).

Source 40.—This is probably M20 which is at R.A. $17^h\,59^m$, Dec. $-23°$, together with radiation from nearby objects including M8. The identification has been made at 3200 Mc/s by Haddock, Mayer, and Sloanaker (1954).

Source 46.—There may be several sources here. Hanbury Brown and Hazard (1953) report a source at R.A. $20^h\,44^m$ and Denisse, Leroux, and Steinberg (1955) a source at R.A. $20^h\,57^m$; all declinations are about $50°\frac{1}{2}$.

Sun on February 1, 1955.—The flux density found here should not be compared with the 600 Mc/s Sydney measurements given in the *Quarterly Bulletin on Solar Activity*, since the latter are unreliable as far as absolute level is concerned (Smerd, personal communication). If we take into account the increase in flux with frequency it accords well with the 545 Mc/s Nederhorst result for the same day of 2900 units of flux compared with our 3100 units.

V. Variation of Intensity Along the Galactic Plane

Most of the newly discovered sources lie on or near the galactic plane. It is possible, therefore, to convey an impression of their relative positions, extent, and emission strength by plotting receiver input against galactic longitude

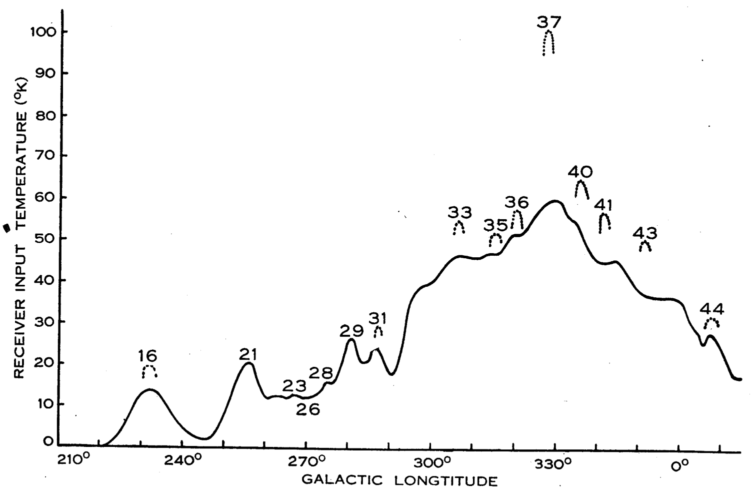

Fig. 2.—Variation of intensity along the galactic plane. Maxima (sources) within a few degrees of the plane (but not on it) are shown by dashed lines.

for zero galactic latitude. This is done in Figure 2 for longitudes between 210 and 360°, the various sources being marked by their reference numbers listed in Table 1. The maxima which do not lie exactly on the galactic plane but within a few degrees of this plane are also shown, by dotted lines. These include the outstanding maximum at $l=328°$ in the direction of the galactic centre. When a source lies near the galactic plane and partly overlaps it (for example, source 44) it appears as a dotted maximum above a maximum in the full curve.

Figure 2 shows the concentration of sources near the galactic plane from which it may be inferred that they have a galactic origin, possibly in H II regions. The sources are nearly as numerous in the southern portion of the galaxy as towards the galactic centre. This provides general evidence of an origin in H II regions, as these are known to be numerous in the southern sky.

VI. Discussion

Early observations of radio sources were made using interferometers having numerous very narrow beams. That they were observed at all indicated that the sources were of limited angular extent and it was generally assumed that they were discrete. Subsequently some sources were found to be associated with irregularities in the background emission. A noteworthy feature of the present survey is that nearly all the sources are associated with such irregularities, often to a high degree. Thus in many cases a more apt term than " discrete sources " might be localized maxima. The effect is more apparent at high than at low frequencies, although, of course, any association between different radiating regions is independent of frequency. The apparent enhancement at high frequencies must result from different emission (and perhaps absorption) spectra of different regions.

Table 2

POSSIBLE ASSOCIATIONS OF RADIO AND VISIBLE SOURCES

Radio Source	Nebula BBW	Celestial Coordinates 1955		Dimensions (m)
		R.A. (h m)	Dec. (°)	
21	25500	10 43	$-59\frac{1}{2}$	450×330
26	27500	13 30	-62	45×45
29	28100	14 07	-61	61×83
31	28802	15 12	$-59\frac{1}{4}$	39×51

An example of association is source 27 (13S4A) in Centaurus which has been identified with the extragalactic object NGC 5128. An extended source, about 2° in diameter and concentric with the original source, has been found by Bolton *et al.* (1954). Our source must include both of these and also shows background emission from a narrow region which joins the main galactic emission some 15° away from the source. The linkage with the Galaxy is evident in the record reproduced in Figure 1.

The survey shows 18 sources which do not appear to have been listed previously. Of these, 12 lie within $\pm2°$ of the galactic plane. It is likely that most of the latter are thermally emitting clouds of ionized hydrogen. This is suggested by their proximity to the galactic plane and by the fact that they show up better at the relatively high frequency used. There is some evidence that four of the new sources are at least associated with visually observed H II regions.

VII. Possible Associations

A superficial comparison of the radio results with visual observations of southern H II regions made by Bok, Bester, and Wade (1954) has been made and four likely associations found. These are listed in Table 2.

A much more detailed comparison is necessary before any actual identification of radio and visual emitting regions is made.

VIII. References

Allen, C. W., and Gum, C. S. (1950).—*Aust. J. Sci. Res.* A **3**: 224.

Bok, B. J., Bester, M. J., and Wade, C. M. (1954).—Catalogue of H II regions in the Milky Way. Harvard Observatory and Boyden Station Rep.

Bolton, J. G., Stanley, G. J., and Slee, O. B. (1954).—*Aust. J. Phys.* **7**: 110.

Bolton, J. G., Westfold, K. C., Stanley, G. J., and Slee, O. B. (1954).—*Aust. J. Phys.* **7**: 96.

Brown, R. Hanbury, and Hazard, C. (1953).—*Mon. Not. R. Astr. Soc.* **113**: 123.

Christiansen, W. N., and Hindman, J. V. (1952).—*Aust. J. Sci. Res.* A **5**: 437.

Denisse, J. F., Leroux, E., and Steinberg, J. L. (1955).—*C.R. Acad. Sci., Paris* **240**: 278.

Haddock, F. T., Mayer, C. H., and Sloanaker, R. M. (1954).—*Nature* **174**: 176.

Kerr, F. J., Hindman, J. V., and Robinson, B. J. (1954).—*Aust. J. Phys.* **7**: 297.

Kraus, J. D., and Ko, J. C. (1955).—*Nature* **175**: 159.

Kraus, J. D., Ko, J. C., and Matt, S. (1954).—*Astr. J.* **59**: 439.

McGee, R. X., Slee, O. B., and Stanley, G. J. (1955).—*Aust. J. Phys.* **8**: 347.

Mills, B. Y. (1952).—*Aust. J. Sci. Res.* A **5**: 266.

Mills, B. Y. (1954).—*Observatory* **74**: 248.

Mills, B. Y. (1955).—*Aust. J. Phys.* **8**: 368.

Pawsey, J. L. (1955).—*Astrophys. J.* **121**: 1.

Piddington, J. H., and Minnett, H. C. (1951).—*Aust. J. Sci. Res.* A **4**: 459.

Piddington, J. H., and Minnett, H. C. (1952).—*Aust. J. Sci. Res.* A **5**: 17.

Reber, G. (1948).—*Proc. Inst. Radio Engrs., N.Y.* **36**: 1215.