

HIGH RESOLUTION OBSERVATIONS OF SUPERNOVA REMNANTS AT 80 MHz

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Abstract

Observations of 10 supernova remnants with a resolution of about 4' arc at 80 MHz have enabled the spectra of several of these objects to be extended to this low frequency. From the results only the well-known supernova remnant G43·3-0·2 (W49B) shows conclusive evidence for curvature in its integrated spectrum at low frequencies in agreement with previous work. Some discrepancy between the conclusions and those from a related survey of small diameter supernova remnants by Dulk and Slee (1972) is noted. Contour maps are presented for five of the more extended sources with a resolution equal to or greater than any previous maps. These results have been compared with higher frequency data in a search for possible changes in spectra across individual sources. G189·1+2·9 (IC443) has been found to have a nearly constant spectral index over most of its extent with perhaps a somewhat flatter spectrum on its southern side.

I. INTRODUCTION

The need for high resolution data for supernova remnants (SNR's) is twofold: to study the objects themselves and to investigate the conditions in the interstellar medium along the line of sight to them. In both cases a knowledge of the spectra of the sources is important. Although many observations have been made with a resolution of a few minutes of arc in the frequency range from 408 to 10 200 MHz, little work has been done at lower frequencies, and in order to provide such data this paper presents the results of observations of 10 SNR's made with a resolution of 4' at 80 MHz using the radioheliograph at the CSIRO solar observatory at Culgoora, N.S.W. Maps are presented for five of the sources studied. Six other extended sources have previously been observed with this instrument by Lockhart (1971) and a number with small diameters by Dulk and Slee (1972).

The spectra of the integrated radiation of some SNR's are known to have sharp turnovers at frequencies below about 100 MHz and the most likely explanation appears to be absorption of their radiation by ionized hydrogen in front of the sources (Bridle and Kesteven 1971; Caswell *et al.* 1971). The origin of the ionization for this gas remains unknown but both galactic cosmic rays and the radiation from supernovae have been suggested. If the ionization is associated with a supernova for which we are now observing the remnant, then the absorption should reflect the structure of the SNR and be evident in a spectral index of the source. The maps presented here have been compared with higher frequency ones when available and no

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evidence for spectral features has been found except in IC 443 (G189.1+2.9), which probably shows a flatter spectrum for the southern side than for the north-eastern shell, in agreement with the conclusions of Colla *et al.* (1971) from data at 408 MHz. The present observations also provide the highest resolution maps yet published for the two sources G33.7+0.0 and G46.8-0.3.

II. OBSERVATIONS AND CALIBRATION

The CSIRO radioheliograph at Culgoora consists of an array of 96 antennas spaced around a circle of 3 km diameter (Wild 1967). The outputs of the individual antennas are multiplexed and summed with appropriate phase delays to form 48 simultaneous beams, each with an effective half-power beamwidth of $3'.7$, which are separated in declination by $2'.1 \sec(\delta + 30^\circ 18')$. These beams are scanned electronically across a $2^\circ.1$ field in right ascension once per second and 60 data points are recorded per scan for each beam. The resultant 60×48 intensity matrix, covering an area about 2° by 2° , is then stored on magnetic tape. In order to acquire sufficient integration to measure the weak SNR's, data were recorded continuously for 15 min and the 900 individual maps were subsequently summed in the computer. When necessary, poor data could be edited, average baselines corrected, etc. during the final map-making process.

The net integration time on each point of the grid was 15 s which resulted in an r.m.s. sensitivity of 5 f.u.* per point. As this mapping technique covers a large area of the sky, it is less sensitive per point than a drift scan technique used on this instrument by Dulk and Slee (1972), but their method restricted the observations to a small extent in declination so that they could not cover many of the moderate-sized SNR's. In either case the uncertainties caused by the ionosphere, as discussed below, will contribute the major uncertainty in the integrated flux densities of the sources.

Calibration of the instrument at 80 MHz is extremely difficult because of ionospheric effects as well as uncertainty in the absolute flux densities of any sources at this frequency. The primary sources used for the calibration of the observations were Taurus A and Hercules A for which flux densities of 1900 and 900 f.u. respectively were adopted (Parker 1968). The resultant flux density scale is a factor of 1.2 higher than that found in a compilation of flux densities and spectra by Conway *et al.* (1963) but the new value appears to be more nearly correct (Scott and Shakeshaft 1971; see also the discussion by Kellermann *et al.* 1969).

Use of the revised flux density scale outlined above can account for some, but not all, of the differences between the present values and those of Dulk and Slee (1972) for the four small diameter sources which are common to both sets of observations; the present data are consistently higher than theirs but, for three of the four cases, the error bars overlap (comparisons for G18.9+0.3 and G21.8-0.5 have not been included here because Dulk and Slee observed only part of these sources). With the small sample of overlap, it is difficult to establish just how much my results are systematically higher than Dulk and Slee's and collectively we have not been able to establish a reason for the discrepancy. Thus there remains an uncertainty of greater

* 1 flux unit (f.u.) = $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$.

than 20% in the absolute flux densities, but it should be emphasized that the overall results are not significantly affected by a factor of this size.

The ionosphere can have several effects at this frequency. Small-scale inhomogeneities, of perhaps 500 m extent, can move across the telescope in a few seconds and cause scintillation effects which are manifested in r.m.s. intensity deviations of up to one-half the amplitude of the mean signal and also in considerable phase changes. (These values are based upon 40 MHz ionospheric data recorded at Brisbane by Preddy *et al.* (1969) and Preddy (1969) and a scaling factor of $1/f$ for frequency (Aarons *et al.* 1967)). Averaged over 15 min, these fluctuations can cause some smearing of the intensity distributions of the source and small changes in the integrated flux density. However, probably a more serious effect upon the integrated flux density is caused by a semi-periodic wave phenomenon in the ionosphere which can vary with periods of 10–60 min (Munro 1950). Thus the calibration can change from source to source and it is difficult to assess the reliability of any one measurement. In order to reduce the uncertainty, data were recorded on three or four days for each source and day-to-day variations of up to a factor of 1.6 were found. In summary, the results for a particular source can be quite uncertain; the quoted errors here indicate the range of measurements for each source and the uncertainty in determining the baseline but include no factor for the adopted absolute calibration.

TABLE 1
PARAMETERS FOR OBSERVED SOURCES

Galactic source No.	Position (1950)		S_{80} (f.u.)	Spectral index α	Source common names
	R.A.	Dec.			
G11.2-0.4	18 ^h 08 ^m 32 ^s *	-19° 27'	99 ± 15	-0.57	
G18.9+0.3	18 21 10	-12 27	143 ± 50	-0.58	Kes 67, MSH 18-18
G21.5-0.9	18 30 47	-10 37	<15	-0.05	
G21.8-0.5	18 30 12	-10 14	291 ± 100	-0.61	Kes 69, MSH 18-113
G33.7+0.0	18 50 05	00 37	101 ± 25	-0.65	4C00.70, HC 13
G35.6-0.0	18 53 52	02 17	<150*	(-0.43)	
G35.6-0.4	18 55 18	02 06	<150*	-0.70	
G39.2-0.3	19 01 32	05 22	76 ± 16	-0.55	3C 396, NRAO 593
G43.3-0.2	19 08 38	09 01	67 ± 12	C†	W49B
G46.8-0.3	19 16 05	12 05	101 ± 50	-0.58	HC 30
G189.1+2.9	06 14 00	22 35	315 ± 150	(-0.45)	IC 443

* For a source diameter of 10' arc.

† Curved spectrum; $\alpha = -0.5$ at higher frequencies.

III. RESULTS

Table 1 lists the galactic numbers and celestial coordinates (1950.0) for the observed sources and the integrated flux densities S_{80} at 80 MHz determined from the observations. The spectra for 10 of the sources are plotted in Figure 1 and the spectral index α for each source (flux density proportional to f^α), as indicated by the fitted line in the figure, is tabulated in the fifth column of Table 1. The final column gives common names for the sources.

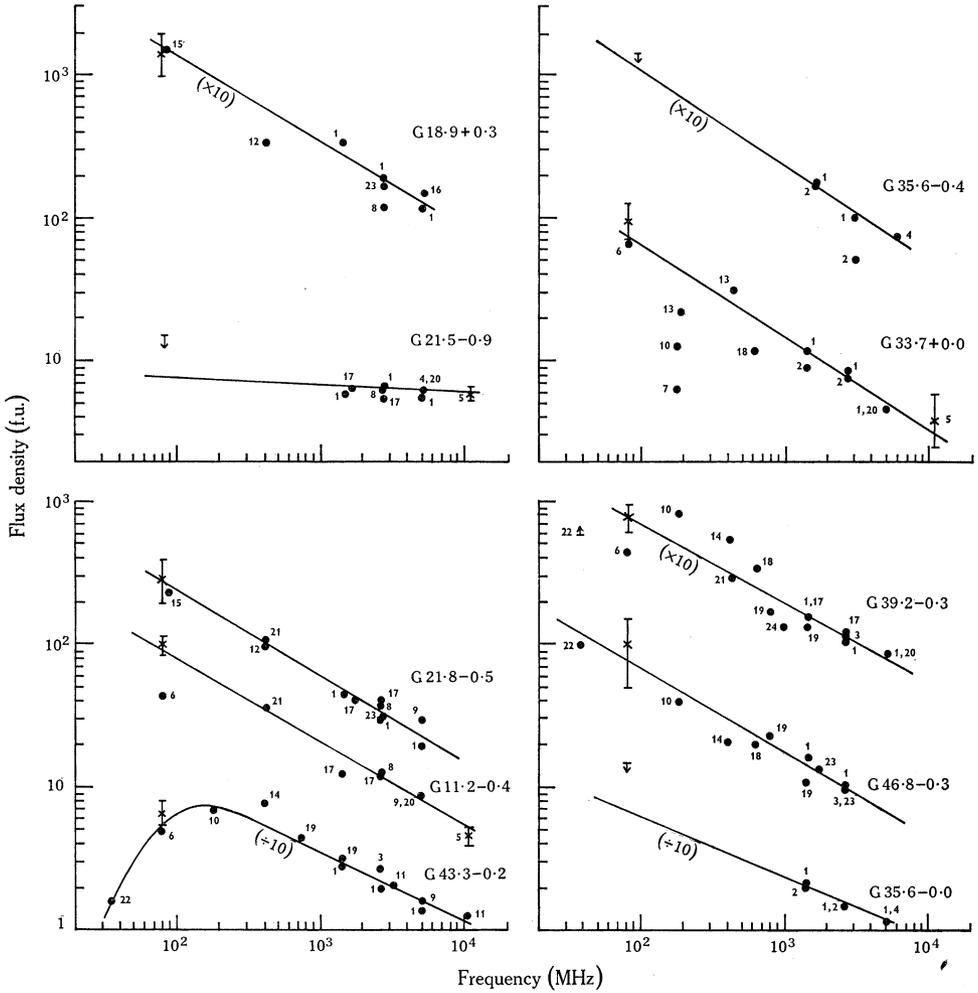


Fig. 1.—Spectra for 10 of the observed sources. Previously published values of flux density (indicated by dots) have not been corrected for any changes in absolute calibration and errors are shown only for the new values. All flux densities for G18·9+0·3, G35·6-0·4, and G39·2-0·3 have been multiplied by 10 while those for G43·3-0·2 and G35·6-0·0 have been divided by 10. References to other data are:

- | | | |
|--|--|---------------------------------|
| 1, Altenhoff <i>et al.</i> (1970); | 2, Beard and Kerr (1969); | 3, Day <i>et al.</i> (1970); |
| 4, Dickel and Milne (1972); | 5, Dickel and Seaquist (unpublished data); | 6, Dulk and Slee (1972); |
| 7, 4C (Gower <i>et al.</i> 1967); | 8, Goss and Day (1970); | 9, Goss and Shaver (1970); |
| 10, Holden and Caswell (1969); | 11, Hughes and Butler (1969); | 12, Kesteven (1968); |
| 13, Kundu and Velusamy (1967); | 14, Large <i>et al.</i> (1961); | 15, Mills <i>et al.</i> (1958); |
| 16, Milne (1969); | 17, Milne <i>et al.</i> (1969); | 18, Moran (1965); |
| 19, Pauliny-Toth <i>et al.</i> (1966); | 20, Reifenstein <i>et al.</i> (1970); | 21, Shaver and Goss (1970); |
| 22, Williams <i>et al.</i> (1966); | 23, Willis (1972); | 24, Wilson (1963). |

Each source is considered individually below.

G11·2-0·4

This small diameter source did not broaden the observed response pattern of the antenna sufficiently to show any structure and so no map was constructed. The integrated flux density is puzzling because although the three values obtained did not fluctuate much from day to day, the average value is approximately twice that found by Dulk and Slee (1972); this is also the only small diameter source for which the two sets of results differ by more than their combined errors. The present value would suggest that the source has a linear spectrum from 80 to 10200 MHz whereas their value predicts considerable low frequency absorption. Clearly more low frequency observations of this source are necessary.

G18·9+0·3

The contour map of this source, presented in Figure 2(a), looks very similar to those obtained with the same resolution at higher frequencies (Willis 1972 at 2700 MHz; Milne 1969 at 5000 MHz). The very extended lowest contour on the high frequency maps could be present on the 80 MHz one but is lost in the noise. The spectral index distribution appears to be constant across the source wherever the intensity is strong enough for an accurate measurement and the integrated spectrum appears to follow a power law.

G21·5-0·9

The point source G21·5-0·9 which has been suggested as a possible SNR (Downes 1971) lay within the area covered by the map of G21·8-0·5 but was not detected. The upper limit for the 80 MHz flux density is therefore 15 f.u. and the source must have a very flat spectrum. No H109 α recombination line has been found for this source, however (Dickel and Milne 1972), so that it is most probably not an HII region. The flat spectrum could indicate either an SNR or an extragalactic quasar.

G21·8-0·5

As for G18·9+0·3, the 80 MHz contour map (Fig. 2(b)) looks virtually identical with those published at higher frequencies (Shaver and Goss 1970 at 408 MHz; Willis 1972 at 2700 MHz; Goss and Shaver 1970 at 5000 MHz). As suggested by Shaver and Goss, the structure and the constancy of the spectral index across the source would suggest that it is actually one shell source with two main components, similar to many other SNR's. Again there appears to be no change in the spectrum of this source with frequency.

G33·7+0·0

The contours of this source (Fig. 2(c)) show a double structure surrounded by a less intense halo. No characteristic shell-like structure is evident but higher resolution is clearly needed. The map appears similar to one in preparation by Dickel and E. R. Seaquist made with a resolution of 2'·6 arc at a wavelength of 2·8 cm using the 46 m telescope at the Algonquin Radio Observatory of the National Research Council of Canada. The weak point source which appears at about 18^h 49^m 10^s, 00° 34' seems to be more prominent at 2·8 cm and probably has a flatter spectrum than the main SNR.

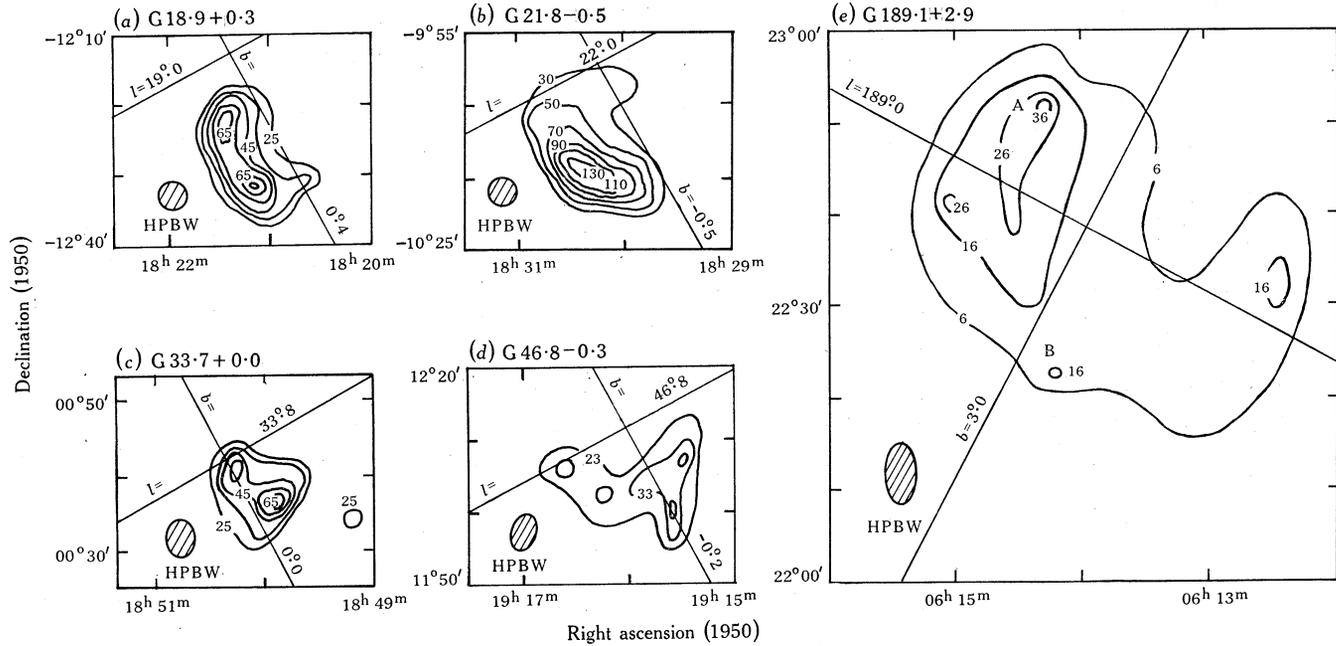


Fig. 2.—Contour maps at 80 MHz for five of the observed sources. Selected contours are labelled in units of 10^3 K brightness temperature, the lowest contour being indicated in each case. The contour interval is 10^4 K for G18.9+0.3, G33.7+0.0, G46.8-0.3, and G189.1+2.9 and 2×10^4 K for G21.8-0.5. The peaks labelled A and B in (e) are points where the spectral index for G189.1+2.9 was determined as described in the text.

G35·6-0·0 and G35·6-0·4

The map of the area containing G35·6-0·0 and G35·6-0·4 did not show the presence of either source. Although G35·6-0·0 has been suggested to be possibly nonthermal by Altenhoff *et al.* (1970), the fact that an H109 α recombination line has been found in this source (Dickel and Milne 1972) would seem to indicate that it is an HII region with a very uncertain spectrum. For G35·6-0·4, if it has a diameter of 10' arc (Beard and Kerr 1969; Altenhoff *et al.* 1970) then its integrated flux density is < 150 f.u., and this is consistent with an extrapolation of the higher frequency spectrum of this source which predicts a value of about 120 f.u. at 80 MHz.

G39·2-0·3

As this source has a small angular diameter, no map is presented and only the integrated flux density is given in Table 1. This flux density is seriously contaminated by the galactic background so that the spectrum, as illustrated in Figure 1, is very difficult to determine. Dulk and Slee (1972) have suggested that there is curvature at around 80 MHz but they have not included in their spectrum the flux densities measured at 178 MHz by Holden and Caswell (1969) and at 38 MHz by Williams *et al.* (1966).

G43·3-0·2

This source was also too small in diameter to show any features. It is well known to have a significant decrease in flux density at low frequencies (Holden and Caswell 1969). The value given here is somewhat higher than that presented by Dulk and Slee (1972) but each flux density is within the quoted errors of the other.

G46·8-0·3

The integrated flux density for this source fits satisfactorily on a spectrum with a constant index of $-0·58$. Because of the low surface brightness of the source, the contour map in Figure 2(d) is quite unreliable. A 2725 MHz map of this source by Willis (1972) shows that the feature seen on the present map is the bright shell on the southern side of a more extended source.

G189·1+2·9

This source, IC 443, although having a reasonably high surface brightness, required special observing because of its close proximity to the extremely bright point source Taurus A. Since the radioheliograph is not a filled aperture there are strong grating lobe responses outside the $2^{\circ}·1$ field of view corresponding to the spacing between two adjacent antennas of 100 m. The individual 13 m dishes have half-power beamwidths of 17° so that the grating response of Taurus A, which is only 9° away from IC 443, was still strong and easily seen on the individual maps. To reduce the effect of the grating response, a "semi-synthesis" was performed by adding together the data from a number of different hour angles as the source crossed the sky. As the array is fixed to the Earth, the grating response will rotate with respect to the source during its motion and the summation will partly cancel the effect. However, because of the limited hour angle coverage of the instrument ($\pm 2^{\text{h}} 20^{\text{m}}$) and the fact that a total of only nine observations were made, the grating responses are not completely removed, although the final map (Fig. 2(e)) is much improved with no obvious spurious features. The integrated flux density of this source is difficult to establish because of

the uncertainties in the background caused by the grating lobes but the result is not incompatible with the spectrum published by Milne (1971) from a recent compilation of data.

The features of the map correspond very closely to those observed by Colla *et al.* (1971) at 408 MHz and these new data support their conclusion that the north-eastern shell has a somewhat steeper spectrum than the southern peak which is prominent on high frequency maps (Dickel 1971; Milne 1971). Because the present data and those at 6640 MHz (Dickel 1971) were obtained with telescopes having nearly the same resolution, the brightness temperatures at the two points A and B in Figure 2(e) were compared directly to find their spectra. The resultant spectral indices were -0.48 for point A and -0.29 for point B, in agreement with results of Colla *et al.* and similar to those found for the distribution of the spectral index across IC443 by Hill (1972). Thus it appears that the spectrum of the bright north-eastern shell of IC443 does not have a turnover at low frequencies, as was suggested by Kundu and Velusamy (1968) from low resolution data.

In summary, for the five SNR's which are extended enough to map, the results presented here show no spectral structure at low frequencies for any of the sources except possibly IC443. The integrated flux densities of the 10 observed SNR's generally fit well onto the spectra determined from higher frequency observations, only W49B showing conclusive evidence for spectral curvature at low frequencies and G11.2-0.4 requiring clarification. These two sources, W49B and G11.2-0.4, join the well-known sources G348.5+0.1 (CTB37A) (Lockhart 1971), G31.9+0.0 (3C391) (Bridle and Kesteven 1971; Caswell *et al.* 1971), and possibly G89.1+4.7 (HB21) (Erkes and Dickel 1969) as being the only definite SNR's with spectral curvature out of the approximately 80 known. This conclusion disagrees with that of Dulk and Slee (1972) who found that a large fraction of the 20 sources they observed had a noticeable decrease in flux density at 80 MHz. However, it should be noted that, as well as their use of a lower scale for calibration, several of their sources (e.g. G337.0-0.1, G337.8-0.1, and G41.1-0.3) are at least partly thermal (Wilson *et al.* 1970; Dickel and Milne 1972; Willis 1972) making interpretation of the spectra uncertain. Furthermore, the flux density measurements of several others (e.g. G39.2-0.3; see Fig. 1) are too scattered to establish any definite shape of the spectrum.

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