J. Astrophys. Astr. (1982) 3, 207–216

Observations of the Supernova Remnants HB 9 and IC 443 at 34·5 MHz

K. S. Dwarakanath, R. K. Shevgaonkar and Ch. V. Sastry
Raman Research Institute, Bangalore 560080 and *Indian Institute of Astrophysics, Bangalore 560034*

Received 1982 February 1; accepted 1982 June 30

Abstract. We have observed the extended supernova remnants HB 9 (G 160·5 + 2·8) and IC 443 (G 189·1 + 2·9) at 34·5 MHz with a resolution of 26 arcmin × 40 arcmin. A map of HB 9 is presented. The integrated flux density of HB 9 at 34·5 MHz is 750 ± 150 Jy. The spectral index in the frequency range from 34·5 MHz to 2700 MHz is found to be constant (− 0·58 ± 0·06) without any spectral break such as was reported earlier by Willis (1973). There is no significant variation of the spectral index across the remnant. The integrated flux density of IC 443 at 34·5 MHz is 440 ± 88 Jy. The spectral index in the frequency range from 20 MHz to 10700 MHz is − 0·36 ± 0·04. The reduction in flux at very low frequencies (10 MHz) is attributable to free-free absorption in the interstellar medium and/or in the H II region S 249.

Key words: supernova remnants—spectral break—free-free absorption

1. Introduction

Extensive observations of supernova remnants (SNRs) exist at high radio frequencies, and have provided significant information on the origin of the radio emission and the evolution of SNRs. It is important to extend these observations of SNRs to low frequencies from several points of view. Low-frequency observations will give information not only on the structure of the sources themselves, but also on the intervening medium. One can investigate the changes in the continuum spectrum caused by the effects that are intrinsic to the SNRs such as changes in the relativistic electron spectrum, while turnovers in the low-frequency spectra can also give information about physical conditions in the medium causing the absorption. It may also be possible to derive information about the interaction of the SNRs with their immediate surroundings.

We have recently initiated a programme of observations of extended SNRs at 34·5 MHz. Our observations of the Cygnus Loop have already been published (Sastry, Dwarakanath and Shevgaonkar 1981). The present paper deals with the results of observations of the two SNRs HB 9 (G 160·5 + 2·8) and IC 443 (G 189·1 + 2·9). The SNR HB 9 is believed to be at a distance of 1·8 kpc (Caswell and Lerche 1979) and its angular extent is about 2°·5 (Kallas and Reich 1980). Its optical counterpart is a faint nebulosity marking the periphery of the remnant. Soft X-ray observations of the nebula by Tuohy, Clark and Garmire (1979) indicate an age of nearly 15,000 yr.

IC 443 is a shell-type SNR with the optical counterpart similar to the radio shell. It is thought to be at a distance of 1·5 kpc (Duin and van der Laan 1975). X-ray observations by Parkes *et al.* (1977) indicate an age of approximately 12,700 yr for this remnant.

2. Equipment and observations

The observations reported here were made with the low-frequency radio telescope at Gauribidanur (Longitude 77° 26′ 07″ E and Latitude 13° 36′ 12″ N). The telescope can be operated in the frequency range 25 to 35 MHz. The antenna system of the telescope consists of two broad-band arrays arranged in the form of a 'T'. The half-power beamwidths at 34·5 MHz are 26 arcmin and 40 sec($\delta - 14{\cdot}1$) arcmin in the east-west and north-south directions respectively. The collecting area is approximately 250 λ^2. The telescope is of the transit type and using remotely-controlled diode phase shifters, the beam can be pointed anywhere along the meridian in the zenith angle range ± 45°. A time-multiplexing system is used to cycle the beam through eight different declinations sequentially, the beam being changed from one direction to another in a few milliseconds. The receiving system extracts the in-phase (cos) and the quadrature (sin) correlations between the two arms for each one of the eight beam positions. Pre-detection bandwidths of 30 and 200 kHz and post-detection time constants ranging from 1 to 30 s are available. The output of the receiving system is recorded in both analog and digital forms. Full details of the telescope will be published elsewhere.

The observations of HB 9 were made with a 200 kHz bandwidth and a 10 s time constant. Drift scans were taken in R. A. from $4^h\ 20^m$ to $5^h\ 20^m$, in the declination range from + 43° to + 49° in steps of 24 arcmin. Thus the region of HB 9 could be covered once in two days. Each scan was calibrated using the apparent source due to the combined emission from 3C 129 and 3C 129·1. To minimise ionospheric effects such as refraction, absorption and scintillation, and also interference due to terrestrial broadcasts, repeated scans were taken over many days and checked for consistency. Using the calibrated scans, a raw map of HB 9 was constructed. The map thus obtained was CLEANed to eliminate sidelobe effects and the 'CLEAN' components were convolved with a gaussian beam to obtain the final map.

In the case of IC 443 drift scans were taken in R.A. from 6^h to $6^h\ 30^m$, in the declination range + 21° to + 23°. The rest of the procedure was as described above excepting that 3C 192 was used as the calibration source.

3. Results and discussion

HB 9

The map of HB 9 at 34·5 MHz is presented in Fig. 1. The notable features of the map are: (1) the elongation in the northern direction around 5^h R. A. and (2) the strong region in the centre of the map at $4^h\ 54^m$ R.A. and 46° 06′ in Dec. (The double source 3C 129 + 3C 129·1 is seen towards the south-west of HB 9). The only other low-frequency map of this nebula is that due to Williams, Kenderdine and Baldwin (1966) at 38 MHz with a resolution of 45 arcmin. The peak of emission seen on the 38 MHz map coincides with the intense peak of HB 9 in our map. In the

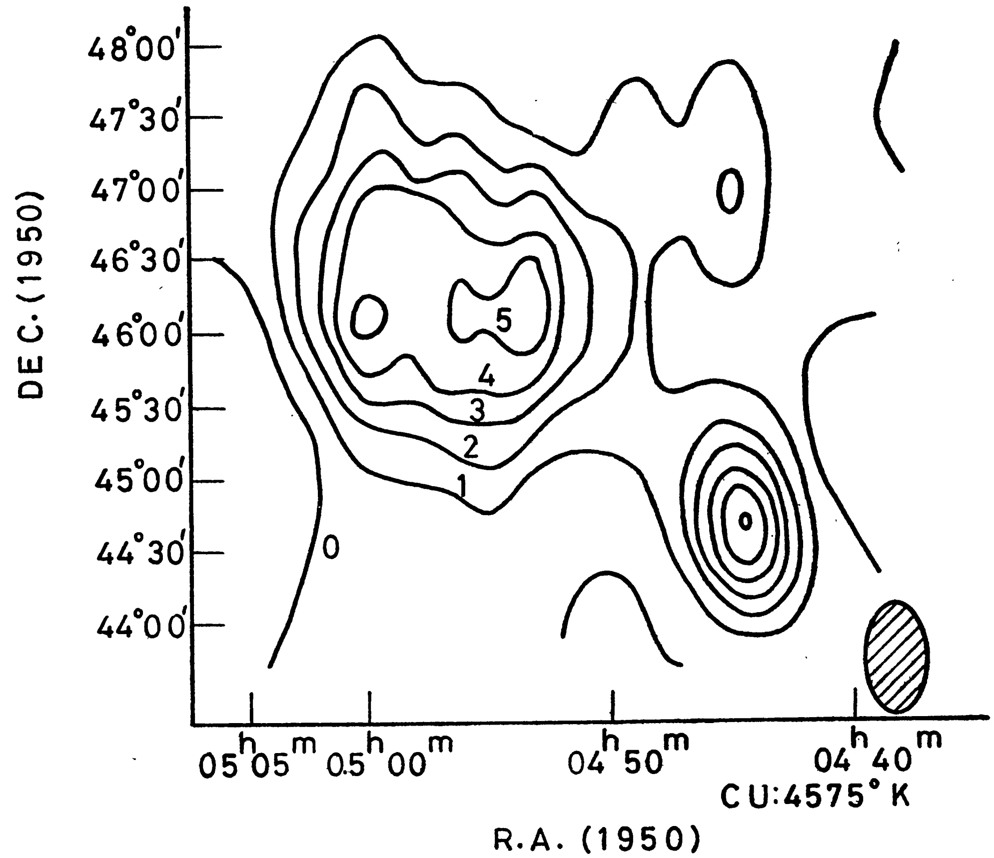

Figure 1. HB 9 at 34.5 MHz. The half-power beam is shown at the bottom right-hand corner.

map of Dickel and McKinley (1969) at 610 MHz, observed with 16 arcmin resolution, there are intense emission features extended in R.A. which are not present in our map. These features are also not present in the 2·7 GHz map of Willis (1973) which has a resolution of 10 arcmin. We believe the ridge of emission extending in the northerly direction to be real since it also appears in the 1·4 GHz map of Felli and Churchwell (1972), Willis (1973), and Kallas and Reich (1980). We have convolved the 21-cm Effelsberg map of Kallas and Reich (1980) to our beam and found that the convolved map agrees quite well in appearance and position with our map within the errors of observation. It therefore appears that the structure of the source remains similar over the frequency range from 34·5 MHz to 1·4 GHz. We have integrated over our map from $4^h\ 48^m$ to $5^h\ 04^m$ in R.A. and 44° 54′ to 47° 54′ in Dec. to obtain the integrated flux density. The double source (3C 129 + 3C 129·1) which is very near to HB 9 both in R.A. and Dec. was used as a calibrator. The flux density of (3C 129 + 3C 129·1) at 34·5 MHz is 190 Jy according to Kellerman, Pauliny-Toth and Williams (1969). The correction to the above flux density to bring it to the absolute scale of Baars *et al.* (1977) is only two per cent. Willis (1973) listed four point sources at 2·7 GHz, all presumably extragalactic, in the field of HB 9. Their total contribution at 34·5 MHz is 60 Jy if the spectral index ($S \propto \nu^{\alpha}$) is — 0·8 between 34·5 MHz and 2·7 GHz. The integrated flux density of HB 9 at 34·5 MHz, after correcting for the contribution of the point sources mentioned above, is 750 ± 150 Jy.

The spectrum of the integrated flux density of HB 9 was investigated previously by Bazelyan, Braude and Meg' (1967) and by Willis (1973). Bazelyan, Braude and Meg' conclude that the spectral index in the frequency range from 40 to 160 MHz is — 1·3 while for frequencies above 160 MHz it is — 0·44. Willis used all the available data in the frequency range from 10 MHz to 2·7 GHz, except the values of Bazelyan, Braude and Meg'. According to Willis, the spectrum shows a break around 1000 MHz with the values of spectral index being — 0·44 below, and — 1·1 above, 1000 MHz. The flux densities measured by Bazelyan, Braude and Meg' are very high compared to the general trend, and further they did not map the region. We therefore omit all their values in further analysis. The values of flux densities, at various frequencies, used by Willis (1973) do not conform to any common scale and we have made an attempt to bring all values to the scale defined by Baars *et al.* (1977). Table 1 shows

Table 1. Spectrum of HB 9.

Frequency (MHz)	Flux* (Jy)	Flux† (Jy)	Reference
10·03(1)	600(4)		Caswell (1976)
13(1)	810 ± 140		Andrew (1967)
34·5(6)		750 ± 150	present value
38(2)	550 ± 110	700 ± 70	Williams, Kenderdine and Baldwin (1966) Haslam and Salter (1971)
92(1)	395 ± 150		Hazard and Walsh (1960) Haslam and Salter (1971)
158·5(1)	80		Brown and Hazard (1953)
178	250 ± 50	300 ± 60	Bennett (1964); 19 per cent correction‡
408	190 ± 40	202 ± 43	Haslam and Salter (1971); 6·5 per cent correction‡
610·5	157 ± 26	164 ± 27	Dickel and McKinley (1969); 5 per cent correction‡
960	160 ± 30	165 ± 31	Harris (1962); 3 per cent correction‡
1420(3)	84 ± 6	84 ± 6	Reich (personal communication)
1660	80 ± 20	82 ± 21	Willis (1973); 3 per cent correction‡
2700	47 ± 9	48 ± 9	Willis (1973); 1·1 per cent correction‡
5000(5)	36 ± 8		DeNoyer (1974)

* Flux quoted in the reference cited.
† Flux (on the scale defined by Baars *et al.* 1977) used to obtain the spectrum of HB 9 (Fig. 2).
‡ Percentage corrections indicate the amounts by which the quoted flux values were increased to bring them to the scale defined by Baars *et al.* (1977).
(1) Large beam ($\gtrsim 2°$). Region of HB 9 not well defined. Confusion from 3C 129 + 3C 129·1.
(2) Integration of the 38 MHz map of Williams, Kenderdine and Baldwin (1966) over the region of our 34·5 MHz map. The 18th contour (= 15,066K) in the map published by Williams, Kenderdine and Baldwin (1966) has been taken as the baseline level.
(3) See Kallas and Reich (1980) for a map of HB 9 at 1420 MHz.
(4) Bridle and Purton (1968) quote 800 ± 200 Jy for HB 9 at 10·03 MHz. Their value also suffers from the drawbacks mentioned in Note (1). Hoewever, it is to be noted that they quote 270±55 Jy for 3C 129 while the value expected on the basis of constant spectral index is 574 Jy (Kellermann, Pauliny-Toth and Williams (1969). Incorporating this factor, flux of HB 9 would be 1700 Jy which is very close to the value expected from the spectrum indicated in this paper.
(5) Calibration scale used by these authors is not clear.
(6) Since the observations were made in the correlation mode of the telescope, there is no ambiguity of the baseline here. The telescope does not respond to zero-order spatial frequency.

the values after renormalization, together with those quoted in the original papers. The reasons for discarding some values are indicated at the end of the table. Original references are cited against each frequency. Using the values given in Table 1 the spectral index of HB 9 has been computed. The spectrum is consistent with a power law over the whole frequency range from 34·5 MHz to 2·7 GHz and the spectral index is $-0{\cdot}58 \pm 0{\cdot}06$. The spectrum is shown in Fig. 2.

A spectral index map of HB 9 was made by comparing our 34·5 MHz map and the 1·4 GHz Effelsberg map of Kallas and Reich (1980) convolved to the same beam. This spectral index map is shown in Fig. 3. It can be seen that the spectral index is constant over the major portion of the source within the limits defined by the 1·4 GHz map.

The poor resolution of our map precludes a detailed comparison of the optical and radio emission from HB 9. Nevertheless, it should be pointed out that an optical feature extends northwards (Willis 1973), at the position where the radio contours also show elongation in the same direction as seen in our map. The optical surface brightness is greater in the southern parts of the nebula where the radio emission is also comparatively strong as, for example, seen in the 21-cm Effelsberg map. As already pointed out, the radio structure and the spectral index remain relatively constant throughout the nebula in the frequency range from 34·5 MHz to 1400 MHz. This implies that there is no significant thermal emission from any part of the nebula. Also, the relativistic electron energy spectrum appears not to change in different parts of the remnant.

IC 443

The shell structure of this SNR is unresolved by our beam. Our map shows peak emission at the position of 6^h 14^m 30^s in R.A. and 22° 36′ in Dec. The observed

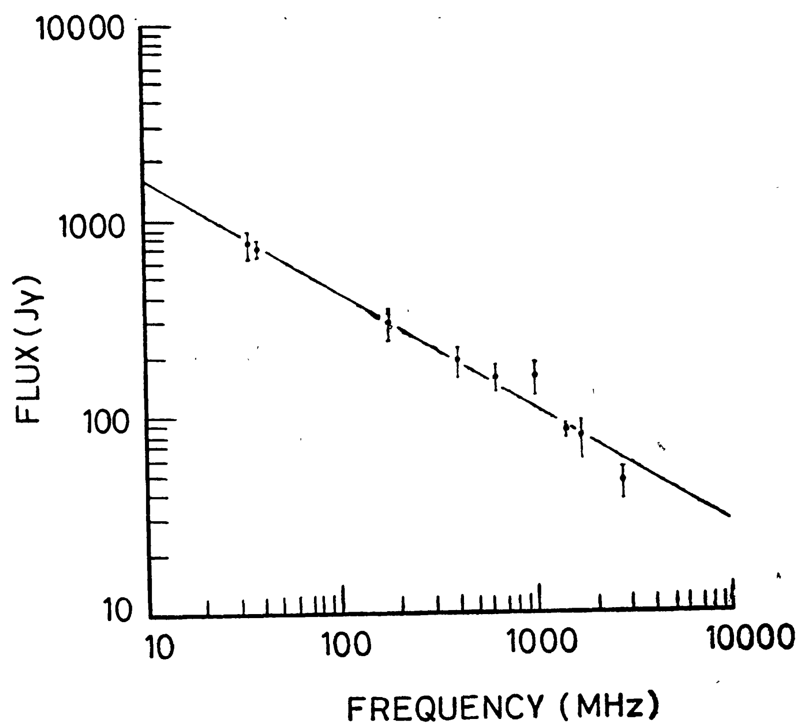

Figure 2. Integrated flux-density spectrum of HB 9.

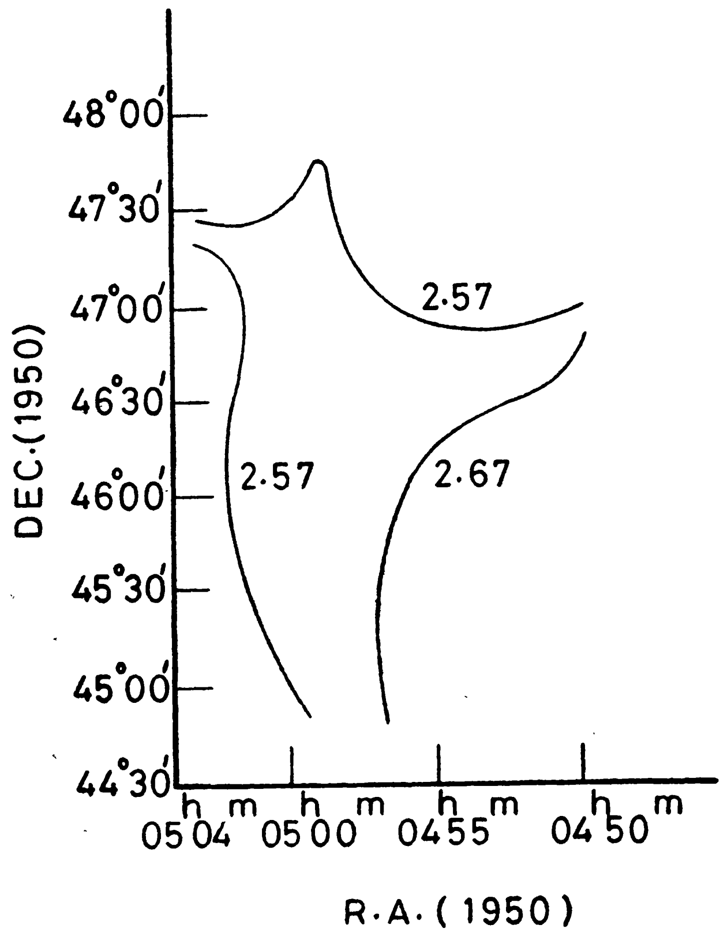

Figure 3. Spectral-index map of HB 9. Only significant contours are plotted. Numbers ($-\beta$) near each contour indicate temperature spectral indices ($T \propto \nu^{+\beta}$, where $\beta = \alpha - 2$).

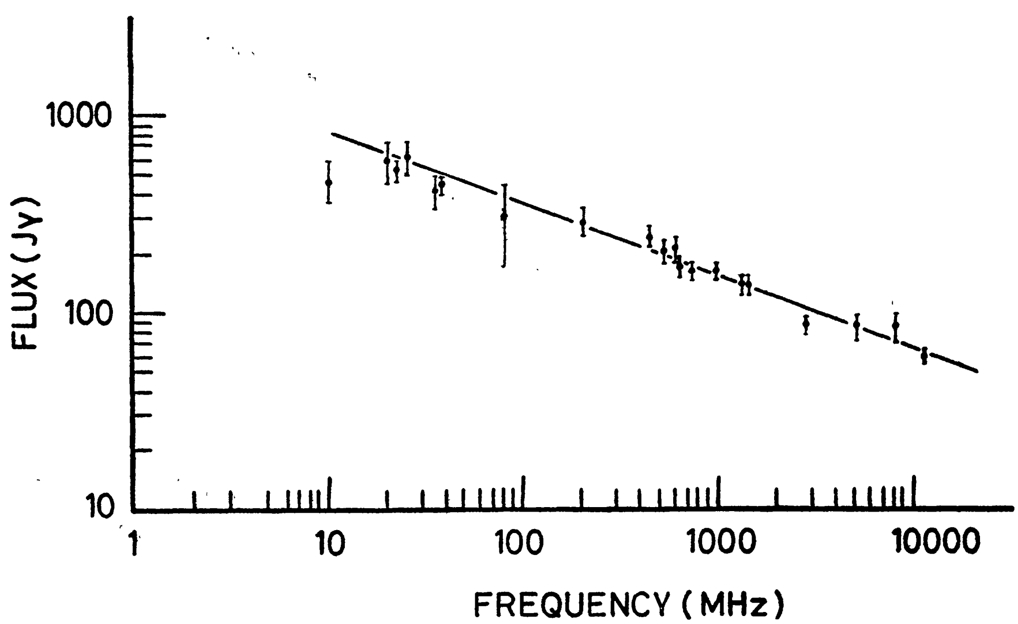

Figure 4. Integrated flux-density spectrum of IC 443.

half-power widths of the source in R.A. and Dec. are 29 arcmin and 43 arcmin respectively. We have convolved the 21-cm map of Duin and van der Laan (1975) to our beam and found that the position of the peak emission and the widths are approximately the same as those observed by us. The integrated flux density of IC 443 has been estimated using 3C 192 as a calibrator. The flux density of 3C 192 at 34·5 MHz is assumed to be 85 Jy on the KPW scale (Kellermann, Pauliny-Toth and Williams 1969). The measured integrated flux density of IC 443 at 34·5 MHz is 440 ± 88 Jy. In Table 2 we have listed all the flux densities of IC 443 used for the purpose of obtaining the spectral index in the frequency range from 10 MHz to 10·7 GHz, along with the references. Some of these values were however discarded for the reasons indicated (see notes under Table 2). The spectral index computed between 20 MHz and 10700 MHz is − 0·36 ± 0·04.

Table 2. Spectrum of IC 443.

Frequency (MHz)	Flux† (Jy)	Reference
10·03	480 ± 120	Bridle and Purton (1968); Caswell (1976)
20	600* ± 144	Braude *et al.* (1969)
22·25	535* ± 65	Roger, Costain and Lacey (1969)
25	630* ± 132	Braude *et al.* (1969)
26·3[2]	263 ± 23	Viner and Erickson (1975)
34·5	440* ± 88	present value
38	460* ± 46	Williams, Kenderdine and Baldwin (1966)
80	315* ± 150	Dickel (1973)
195	290 ± 45	Kundu and Velusamy (1968)
430	245 ± 30	Kundu and Velusamy (1968)
513	205 ± 27	Bondar *et al.* (1965)
610	215 ± 32	Dickel and McKinley (1969)
635	173* ± 17	Milne and Hill (1969)
740	164 ± 15	Bondar *et al.* (1965)
750[1]	190 ± 25	Hogg (1964)
960	165 ± 10	Bondar *et al.* (1965)
1400[1]	170 ± 20	Hogg (1964)
1410	131* ± 13	Milne and Hill (1969)
1420	138 ± 15	Hill (1972)
2700	88* ± 9	Milne and Hill (1969)
3000[1]	100^{+5}_{-15}	Hogg (1964)
5000	85 ± 13	Kundu and Velusamy (1969)
8000	85 ± 17	Howard and Dickel (1963)
9400[2]	16 ± 4	Yamashita and Watanabe (1968)
10700	60 ± 5	Kundu and Velusamy (1972)

† Since most of the authors have not explicitly stated the flux value(s) assumed for the calibrator(s) used, all flux values are quoted here as stated by the respective authors. However, the spectral index obtained between 20 MHz and 2700 MHz using only those flux values (marked with an asterisk) which could be brought to the scale of Baars *et al.* (1977) agrees within the error limits with the spectral index obtained using all the values.

(1) The value of flux quoted by Hogg appear to be consistently higher. Since it is not clear what calibration is adopted by Hogg, these values have not been considered in obtaining the spectrum.

(2) These values are lower than those indicated by the general trend by factors of about 2·5 and 4. They have not been used in obtaining the spectrum.

Note, however, that flux measurements of IC 443 made around 1960 and earlier have not been considered in preference to recent well-calibrated measurements made near the corresponding frequencies. See, Milne and Hill (1969) and references therein.

The expected flux density at 10 MHz on the basis of this spectrum is 820 Jy whereas the flux density observed by Bridle and Purton (1968) is 480 ± 120 Jy. (The flux density quoted by these authors is 400 ± 100 Jy. A 20 per cent increase in flux density to bring it to the KPW scale has been adopted as suggested by Roger, Bridle and Costain 1973). This reduction in flux is probably not due to absorption by regions within the source since in this case the turnover in the spectrum would be more gradual. The optical depth required to reduce the 10 MHz flux from 820 Jy to 480 Jy is about 0·5 if the absorption is external to the source. In this case it could be due to (1) the interstellar medium (ISM) and/or (2) one or more ionized hydrogen regions (H II regions) along the line of sight.

Assuming the picture of the ISM put forward by McKee and Ostriker (1977) it is easy to see that almost the entire free-free absorption in the ISM will be caused by the cold neutral medium (electron density, $n_e = 0{\cdot}042$, electron temperature, $T_e = 80$ K, filling factor, $f = 0{\cdot}024$) and the warm ionized medium ($n_e = 0{\cdot}17$, $T_e = 8000$ K, $f = 0{\cdot}23$). Assuming the distance to IC 443 to be 1·5 kpc, we obtain an optical depth of 0·3 at 10 MHz for the values of n_e, T_e and f assumed above. With the uncertainties inherent in these parameters the difference in the observed and calculated optical depths is not really significant.

We now explore the second possibility that H II regions are responsible for the observed absorption. For a kinetic temperature of 10^4 K, the necessary emission measure of an H II region to produce the required optical depth has to be about 100 pc cm^{-6}. Close to IC 443, in the north-eastern direction, lies the faint H II region S 249. Churchwell and Walmsley (1973) derived an emission measure of 750 pc cm^{-6} for it, assuming a kinetic temperature of 10^4 K. Therefore the absorption along the central line of sight to S 249 should be 6–7 times more than required. However, as the optical position of S 249 is about a degree away from IC 443, it is possible that the line of sight to IC 443 passes only through the outer layers of this H II region. This would be consistent with the derived smaller optical depth. Churchwell and Walmsley (1973) also mention the possibility that S 249 may be a 'fossil Strömgren sphere' with a very low kinetic temperature of 100 K and an emsision measure of 150 pc cm^{-6}. If so, the expected absörption due to this object would be about 100 times more than if it were a normal H II region. The observed absorption would then put an upper limit to the extension of this 'fossil Strömgren sphere'. Assuming the position of the centre of the sphere as that of the quoted optical position ($\alpha = 6^h\ 17^m\ 54^s$, $\delta = 23°\ 06'$, Churchwell and Walmsley 1973), the diameter of the 'fossil Strömgren sphere' is unlikely to be more than about 80 arcmin (note that the major portion of the flux from IC 443 comes from the north-eastern region of the remnant).

It is worth mentioning here, that Georgelin, Georgelin and Roux (1973) suggest an O9 V star (distance 1·9 kpc) to be the exciting star of S 249 and if this is the case the nebula need not be a 'fossil Strömgren sphere'.

4. Conclusions

HB 9

1. The structure of the supernova remnant is essentially the same in the frequency

range from 34·5 MHz to 1420 MHz and there is no significant variation of spectral index across the remnant.

2. The spectrum is straight between 34·5 MHz and 2700 MHz with an index of -0.58 ± 0.06. No evidence is found for the spectral break suggested by Willis (1973).

IC 443

1. The spectrum is straight with an index of -0.36 ± 0.04 in the frequency range from 20 MHz to 10700 MHz. At very low frequencies (10 MHz) there is a reduction in the flux which is believed to be due to absorption in the interstellar medium and/or in the H II region S 249.
2. If S 249 were to be a 'fossil Strömgren sphere' its diameter is unlikely to be more than 80 arcmin.

Acknowledgements

We are grateful to M.K.V. Bappu for his interest and continued support of the low frequency radio astronomy project at Gauribidanur, and to V. Radhakrishnan for useful discussions. We thank C. J. Salter for his valuable suggestions and help during the analysis, and R. Narayan and R. Nityananda for discussions and advice regarding the application of CLEAN to our data. W. Reich is thanked for communication of his 1420 MHz flux density.

References

Andrew, B. H. 1967, *Astrophys. J.*, **147**, 423.
Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., Witzel, A. 1977, *Astr. Astrophys.*, **61**, 99.
Bazelyan, L. L., Braude, S. Ya., Meg', A. V. 1967, *Sov. Astr.*, **10**, 588.
Bennett, A. S. 1964, *Mon. Not. R. astr. Soc.*, **127**, 3.
Bondar, L. N., Krotikov, V. D., Stankevich, K. S., Tseitlin, N. M. 1965, *Izv. Vuz Radiofiz.* **8**, 437·
Braude, S. Ya., Lebedeva, O. M., Megn, A. V., Ryabov, B. P., Zhouck, I. N. 1969, *Mon. Not. R. astr. Soc.*, **143**, 289.
Bridle, A. H., Purton, C. R. 1968, *Astr. J.*, **73**, 717.
Brown, R. H., Hazard, C. 1953, *Mon. Not. R. astr. Soc.*, **113**, 123.
Caswell, J. L. 1976, *Mon. Not. R. astr. Soc.*, **177**, 601.
Caswell, J. L., Lerche, I. 1979, *Mon. Not. R. astr. Soc.*, **187**, 201.
Churchwell, E., Walmsley, C. M. 1973, *Astr. Astrophys.*, **23**, 117.
DeNoyer, L. K. 1974, *Astr. J.*, **79**, 1253.
Dickel, J. R. 1973, *Aust. J. Phys.*, **26**, 369.
Dickel, J. R., McKinley, R. R. 1969, *Astrophys. J.*, **155**, 67.
Duin, R. M., van der Laan, H. 1975, *Astr. Astrophys.*, **40**, 111.
Felli, M., Churchwell, E. 1972, *Astr. Astrophys. Suppl. Ser.*, **5**, 369.
Georgelin, Y. M., Georgelin, Y. P., Roux, S. 1973, *Astr. Astrophys.*, **25**, 337.
Harris, D. E. 1962, *Astrophys. J.*, **135**, 661.
Haslam, C. G. T., Salter, C. J. 1971, *Mon. Not. R. astr. Soc.*, **151**, 385.
Hazard, C., Walsh, D. 1960, *Jodrell Bank Ann.*, **1**, 338.
Hill, I. E. 1972, *Mon. Not. R. astr. Soc.*, **157**, 419.
Hogg, D. E. 1964, *Astrophys. J.*, **140**, 992.

Howard, W. E. III, Dickel, H. R. 1963, *Publ. astr. Soc. Pacific*, **75**, 149.
Kallas, E., Reich, W. 1980, *Astr. Astrophys. Suppl. Ser.*, **42**, 227.
Kellermann, K. I., Pauliny-Toth, I. I. K., Williams, P. J. S. 1969, *Astrophys. J.*, **157**, 1.
Kundu, M. R., Velusamy, T. 1968, *Mon. Not. R. astr. Soc.*, **140**, 173.
Kundu, M. R., Velusamy, T. 1969, *Astrophys. J.*, **155**, 807.
Kundu, M. R., Velusamy, T. 1972, *Astr. Astrophys.*, **20**, 237.
McKee, C. F., Ostriker, J. P. 1977, *Astrophys. J.*, **218**, 148.
Milne, D. K., Hill, E. R. 1969, *Aust. J. Phys.*, **22**, 211.
Parkes, G. E., Charles, P. A., Culhane, J. L., Ives, J. C. 1977, *Mon. Not. R. astr. Soc.*, **179**, 55.
Roger, R. S., Bridle, A. H., Costain, C. H. 1973, *Astr. J.*, **78**, 1030.
Roger, R. S., Costain, C. H., Lacey, J. D. 1969, *Astr. J.*, **74**, 366.
Sastry, Ch. V., Dwarakanath, K. S., Shevgaonkar, R. K., 1981, *J. Astrophys. Astr.*, **2**, 339.
Tuohy, I. R., Clark D. H., Garmire, G. P. 1979, *Mon. Not. R. astr. Soc.*, **189**, 59p.
Viner, M. R., Erickson, W. C. 1975, *Astr. J.*, **80**, 931.
Williams, P. J. S., Kenderdine, S., Baldwin, J. E. 1966, *Mem. R. astr. Soc.*, **70**, 53.
Willis, A. G. 1973, *Astr. Astrophys.*, **26**, 237.
Yamashita, T., Watanabe, T. 1968, *Proc. Res. Inst. Atmos. Nagoya Univ.*, **15**, 75.