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The Structure of the Cygnus Loop at 34.5 MHz

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Abstract. We have observed the large supernova remnant Cygnus Loop at 34·5 MHz with the low frequency radio telescope at Gauribidanur, India. A radio map of the region with a resolution of 26 arcmin × 40 arcmin ($\alpha \times \delta$) is presented. The integrated flux density of the Cygnus Loop at this frequency is 1245 ± 195 Jy. The radio fluxes of different parts of the nebula at this frequency were also measured and used to construct their spectra. It is found that the spectrum of the region associated with the optical nebulosity NGC 6992/5 is not flat at low frequencies, and also exhibits a break at a frequency around 400 MHz. The spectrum of the region associated with NGC 6960 also shows a break but around 1000 MHz, while the spectrum of the region associated with NGC 6974 is straight in the entire frequency range 25 to 5000 MHz. The implication of these results on the basis of existing theories of the origin of radio emission from supernova remnants is discussed.

Key words: supernova remnants, individual—radio continuum

1. Introduction

The large supernova remnant Cygnus Loop, has been studied extensively in the radio frequency domain in the range 200 MHz and above, with high resolution. It was found from these studies that the association between optical and radio features of the object is quite close in some parts. It was suggested that the spectrum of the total integrated flux density steepens above 1GHz and also that the spectrum varies over different parts of the source (Kundu and Becker 1972; DeNoyer 1974). In order to study the variations in the radio structure of the nebula and the spectra of different parts over a wider frequency range it is necessary to extend the high resolution observations to lower frequencies. Such studies may be expected to yield information on the physical conditions and evolution of different parts of the Cygnus Loop. Here we report a study of the structure of this object at 34·5 MHz with a resolution of 26 arcmin × 40 arcmin. The only other high resolution observation at a low frequency (25 MHz) is due to Abranin, Bazelyan and Goncharov (1977).

2. Observations

The observations reported here were made with the low frequency radio telescope at Gauribidanur (Latitude 13°36′12″ N and Longitude 77°26′07″ E). 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 beam widths at 34·5 MHz are 26 arcmin and 40 sec (δ — 14°·1) arcmin in the EW and NS directions respectively. The collecting area is approximately 250 λ^2. The telescope is of the transit type and the beam can be pointed anywhere along the meridian instantaneously, in the zenith angle range $\pm$ 45°, using remotely controlled diode phase shifters. A time-multiplexing system is used to point the beam to eight different declinations sequentially. The smallest time interval necessary to change the beam from one direction to another is of the order of 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. Predetection bandwidths of 30 and 200 KHz and post-detection time constants ranging from 1 to 30s 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 the Cygnus Loop were carried out with 30 KHz bandwidth and a 10s time constant. Drift scans were taken in R.A. from 20^h20^m to 21^h20^m in the dec range 28° to 33°·5 in steps of 24 arcmin. The entire Cygnus Loop was thus covered in a period of two days. As is well known, observations at low frequencies are plagued by various difficulties such as interference due to radio broadcast stations and changing ionospheric conditions. We have found that the broadcast interference is intermittent and has no directional dependence making it very difficult to choose any particular direction or time for observations. The changing ionospheric conditions make it imperative that the observations of a given source be completed in as short a time as possible. We made repeated observations on Cygnus Loop to obtain a consistent set of data with minimum possible effects of ionosphere like scintillation and refraction. A total time of nearly eight months was required to obtain these observations due to the problems mentioned above.

3. Reductions

Each Right Ascension drift scan was calibrated with a standard noise source. The noise source in turn was calibrated using the sources 3C433, 3C436 and sometimes also 3C84. Appropriate corrections for the variation of the gain of the antenna system due to the different declinations of the calibrating sources and the Cygnus Loop were applied. The calibration sources were observed with each observation of the Cygnus Loop. The assumed flux densities of the three sources 3C433, 3C436 and 3C84 are 140 Jy, 62 Jy and 351 Jy respectively. These are obtained by extrapolating the 178 MHz flux densities of Kellermann, Pauliny-Toth and Williams (1969) using the low frequency spectral indices of Roger, Bridle and Costain (1973). Using the calibrated Right Ascension scans, a raw map of the nebula was constructed. The side lobe effects due to the uniform grading of the antenna system were removed by 'cleaning' the map using the technique suggested by Högbom (1974). The two dimensional beam of the telescope is obtained by observing several point sources and also calculated using the measured phase and amplitude distribution across the arrays. The observed and calculated beams agreed to within twenty per cent. This beam was used to 'clean' the map with a dynamic range of about 25. The final map was obtained by convolving the 'cleaned' map with a gaussian beam of 26 arcmin × 40 arcmin, and is shown in Fig. 1. The map is divided into regions A, B and C, as shown in the figure.

The total flux density of the Cygnus Loop was obtained by numerical integration of the entire map. It was pointed out by Moffat (1971) and Dickel and Willis (1980) that there are several point sources within the above field. Most of these sources are believed to be extragalactic. If one assumes a spectral index of − 0·8 then the total estimated flux density due to all these sources turns out to be 40 Jy. The total flux density of the Cygnus Loop after subtracting that due to the extragalactic point sources is 1245 ± 195 Jy. The integrated flux density from each one of the regions designated as A, B and C in Fig. 1 was also found by numerical integration within the appropriate boundaries. The measured values are 660 ± 100 Jy, 469 ± 70 Jy, and 116 ± 18 Jy for the regions A, B and C respectively.

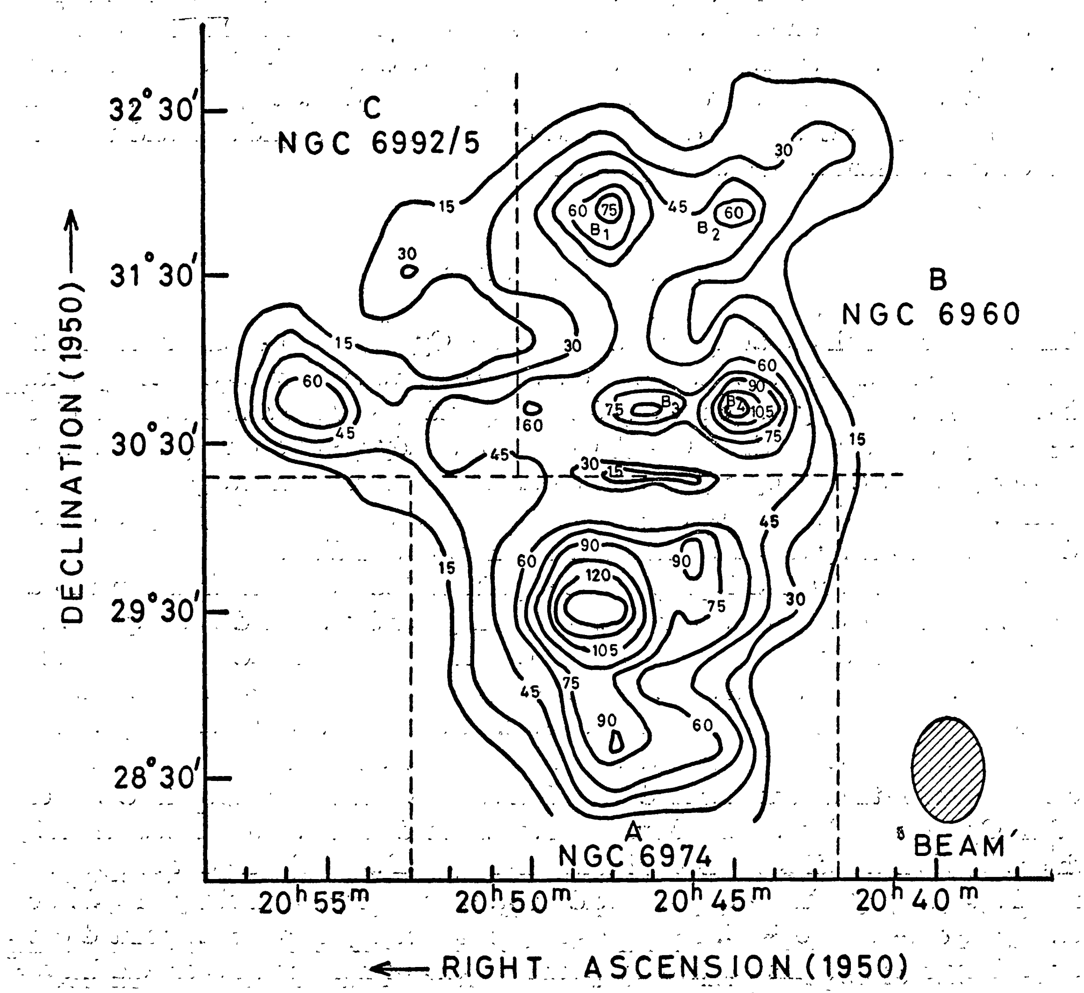

Figure 1. Radio Map of Cygnus Loop at 34.5 MHz. Regions A, B and C are marked with dashed lines. The contour interval is 15 Jy. To get the brightness temperature T_b, multiply the numbers indicated by 620.

4. Radio structure

It can be seen from Fig. 1 that the brightness distribution across the nebula remains quite complex even at low frequencies and shows several maxima of differing intensities. Although there is a broad similarity between our map and that of Kundu and Velusamy (1967) at 195 MHz with similar resolution there are some differences. The intensity variations seem more pronounced in our map. A similar effect was also noticed by Abranin, Bazelyan and Goncharov (1977) at 25 MHz with a resolution of 30 arcmin. The positions and fractional fluxes of the maxima around region C are similar at 34·5 and 195 MHz. The minimum between the two maxima in region C is very clearly seen in our map, and also in most of the high frequency maps, but not in the map of Abranin, Bazelyan and Goncharov (1977). In region B, there are four pronounced maxima in our map. The source B is also very prominent in the 430 MHz map of Kundu and Velusamy (1967). In the map of Abranin, Bazelyan and Goncharov (1977) the maxima in the region B are not clear excepting the one corresponding to our B_4 which is designated as E in their map. The radio emission in the region B extends much beyond the optical nebulosity, to the western side. The structure of region A is similar at all frequencies up to 600 MHz. In this frequency range there is a clear maximum near $\delta = +29°\cdot 5$ and $\alpha = 20^{h}\,49^{m}$. In the maps observed at frequencies above 1 GHz (Moffat 1971; Kundu and Becker 1972; Keen *et al.* 1973), the radiation is diffused and confined to the boundaries and there is no clear maximum at the above position.

5. Discussion of the spectra

The spectrum of the total integrated flux of the Cygnus Loop is shown in Fig. 2. In constructing this plot, all available data in the literature were used. The spectral index in the frequency range 25 to 960 MHz including our measured value of 1245 $\pm$ 195 Jy at 34·5 MHz, is $-0{\cdot}44 \pm 0{\cdot}09$. As already pointed out by Kundu and Becker (1972) and DeNoyer (1974) the spectrum is steeper in the range 1 to 5 GHz with a spectral index of $-0{\cdot}75 \pm 0{\cdot}23$. More measurements of the integrated flux density are necessary to reduce the errors in the spectral indices.

Amongst the many models proposed to explain the radio emission from supernova remnants, the one due to van der Laan (1962) is generally assumed to be applicable to the case of the Cygnus Loop. In this model, the synchrotron radio emission from the remnant is from an enhanced volume emissivity of the interstellar medium due to the compression from the supernova shock. Based on van der Laan's equations, the integrated flux density expected at 34·5 MHz from a thin shell resulting from the compression of the interstellar medium originally in a sphere of 35 pc (the diameter of the Cygnus Loop) is about 600 Jy. We have assumed in the above calculations that the ratio of shell radius to shell thickness is 18 (Moffat 1971), the distance to the nebula is 770 pc (Minkowski 1958) and the average volume emissivity of galactic background is 20×10^{-41} WM^{-3} Hz^{-1} Sr^{-1} (Jones 1973). However, as pointed out by DeNoyer (1974), this method overestimates the compression factor and hence the volume emissivity; this is because one assumes that all the interstellar matter swept up in the lifetime of the supernova remnant is now contained within the thin radiating shell, and that the compression factor can be determined from the observed

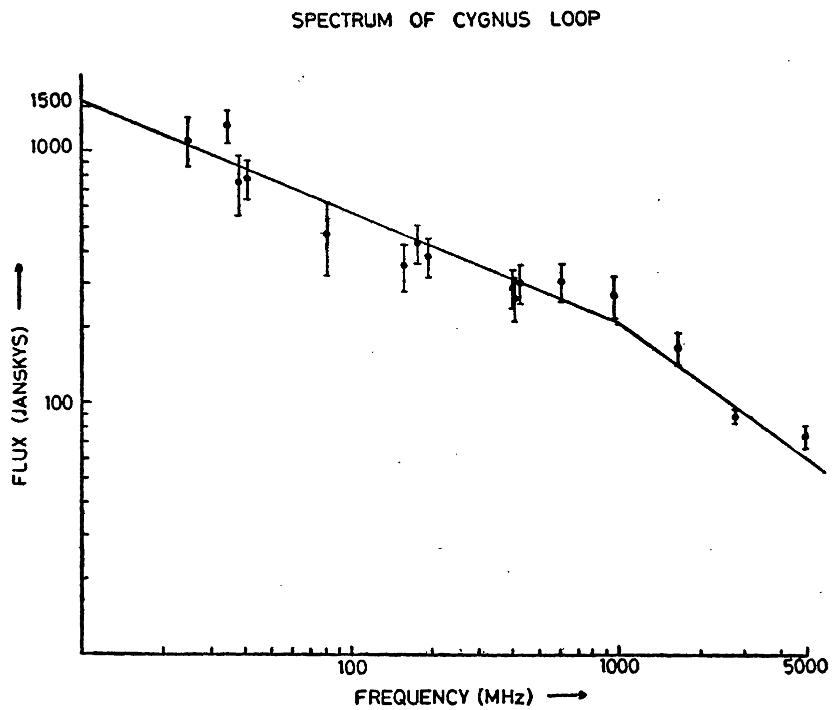

Figure 2. Spectrum of the integrated flux of Cygnus Loop.

shell thickness. It is also possible to estimate the compression factor from the observed ratio of ν_B/ν_s where ν_B and ν_s are the break frequencies in the spectra of the background radio emission and the radio emission from the supernova remnant. DeNoyer (1974) has derived relations between ν_B/ν_s and the compression behind shock, and hence the volume emissivity. The expected integrated flux density on this basis amounts to only 200 Jy at 34·5 MHz.

According to Dickel and Willis (1980) the material in the Cygnus Loop is still being heated by shocks and progressively cooling away from the shocked region by radiation of excited atomic lines. In order to maintain the pressure equilibrium within the shell the gas will contract and this compression will enhance both the magnetic field strength and the particle energies causing an increase in the radio emission as suggested by Duin and van der Laan (1975). Based on the observed densities and temperatures from optical and X-ray measurements, Dickel and Willis (1980) derived a total density enhancement due to the shock plus cooling of about 100, and the consequent increase in the volume emissivity in the filaments as 2×10^5 times the galactic background. In this case the observed integrated flux density at 34 MHz can be accounted for even if the volume occupied by the filaments is about one hundredth of the total volume of Cygnus Loop. Thus, it appears that unless one takes into account the compression due to cooling, the observed integrated flux density from the Cygnus Loop at 34·5 MHz can not be explained on the basis of enhanced volume emissivity of the interstellar medium.

The spectrum of the radio emission from region C is shown in Fig. 3. It can be seen that the slope of the spectrum changes at a frequency around 400 MHz. The spectral index is $-0{\cdot}24 \pm 0{\cdot}10$ in the frequency range 25 to 400 MHz and increases

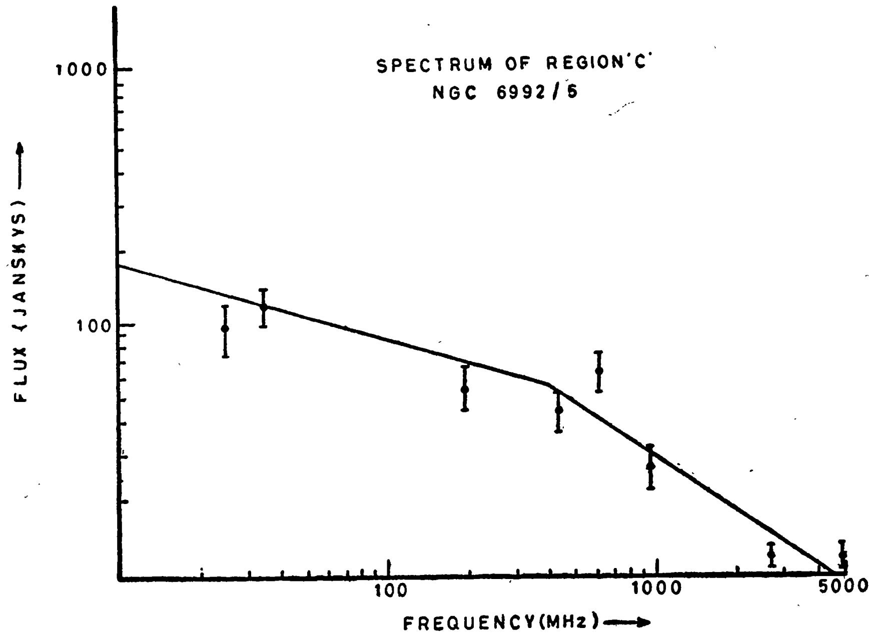

Figure 3. Spectrum of Region C (NGC 6992/5).

to — 0·75 ± 0·15 in the range 400 to 5000 MHz. The radio emission from this region is closely associated with the optical nebulosities NGC 6992/5. This close association suggests that the radio emission may be produced by free-free transitions in the ionized gas. The absence of any polarization at wavelengths above 11cm (Kundu 1969; Moffat 1971) supports this point of view. However, as already shown by Moffat (1971), there is no evidence for any flattening of the spectrum at high frequencies which would occur if a significant part of the radiation were thermal; the emission must therefore be synchrotron radiation. Kundu and Becker (1972) detected strong polarization at 6 cm from this region and interpreted the lack of polarization at longer wavelengths as due to large and variable rotation measure. Kundu and Velusamy (1967) concluded that the spectrum of this region is flat between 38 MHz and 408 MHz. This result depended on an uncertain value of flux density at 38 MHz measured by Kenderdine (1963). A recent measurement of the flux density from this region by Abranin, Bazelyan and Goncharov (1977) showed that the spectral index is — 0·31 between 25 MHz and 1000 MHz. As shown above we find that the spectral index is — 0·24 ± 0·10 in this range if we include our measurement and that of Abranin, Bazelyan and Goncharov (1977) but omit the 38 MHz point due to Kenderdine (1963). It is now clear that the low frequency spectrum of region C is not flat below 200 MHz.

The radio emission from region B is associated with the optical nebulosity NGC 6960. Here the correspondence between the optical and the radio features is not very close as shown by the high frequency maps. The radio spectrum of this region is shown in Fig. 4 and it is similar to that of region C. The change in the slope of the spectrum occurs at a frequency around 1 GHz. The spectral index in the low frequency range is — 0·45 ± 0·10 and that in the high frequency range is — 0·84 ± 0·23. The shape of the spectrum of the region A where the radio emission is associated with the optical nebulosity NGC 6974 shown in Fig. 5 is different from that of the above

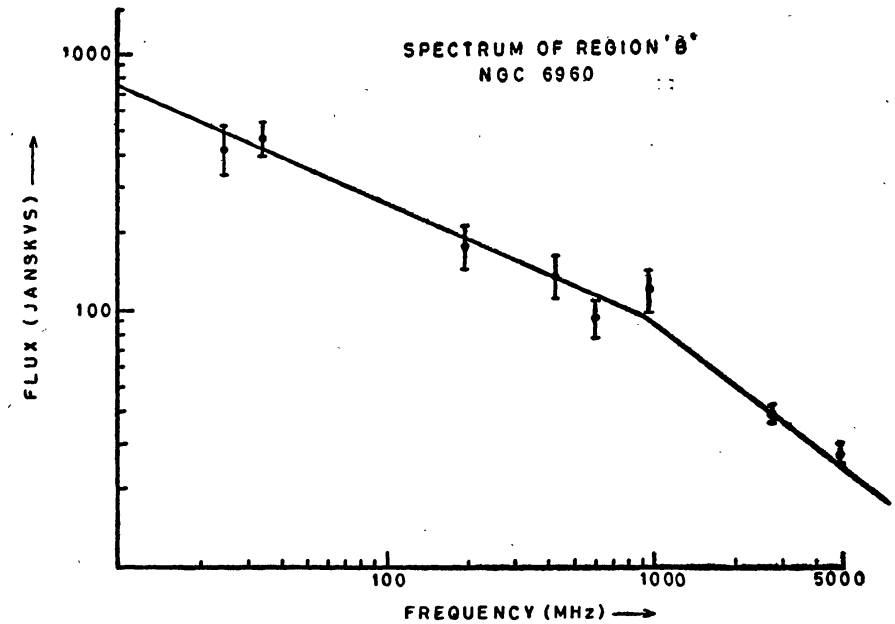

Figure 4. Spectrum of Region B (NGC 6960).

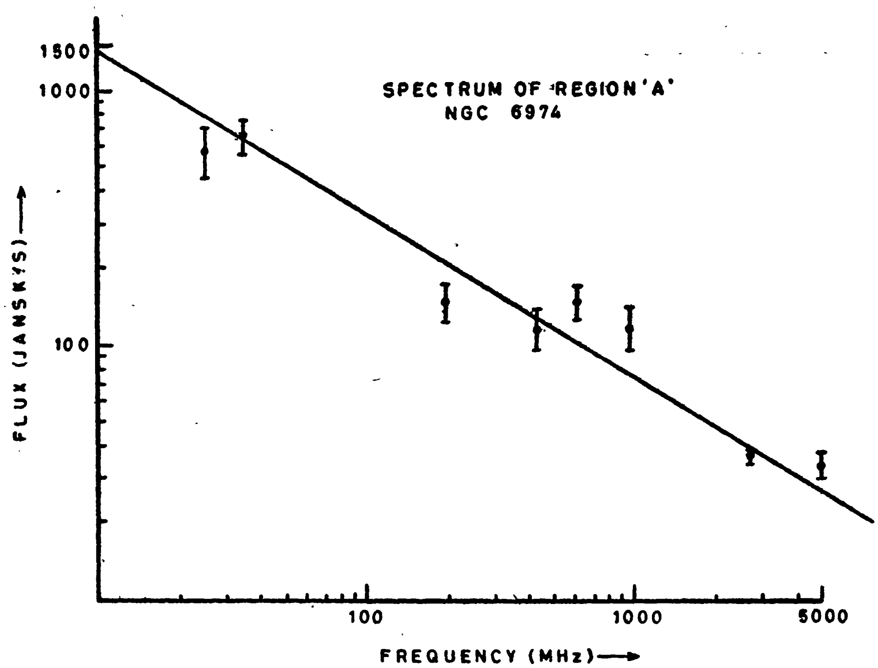

Figure 5. Spectrum of Region A (NGC 6974).

two regions. Here, it is straight without a break in the entire frequency range of 25 MHz to 5000 MHz with a spectral index of $-0{\cdot}59 \pm 0{\cdot}05$. As noted previously, the radio structure of this region appears to be different at high and low frequencies. It is interesting to note that in the region C where there is a well formed shell, the break frequency ($\simeq$ 400 MHz) and the spectral index ($-0{\cdot}24$) are both small. In the region B where the shell is broken, the break frequency moves to a higher value ($\simeq$ 1000 MHz) and the spectrum is steeper with an index of — 0·45.

In the region A where there is no evidence for shell structure, the spectrum is straight without a break in the entire frequency range. This might imply that the radio emission from regions B and C have a common origin, and could be due to compressed cosmic ray electrons and the interstellar magnetic fields. The radio emission from region A on the other hand might be due to the relativistic electrons produced in the supernova remnant itself. It is interesting to note that strong polarization of about 15–25 per cent was detected in the region A by Kundu (1969), Moffat (1971) and Kundu and Becker (1972). The difference in break frequencies in the regions B and C can be attributed to the differing magnetic field strengths. The breaks in the spectra can also be attributed to synchrotron radiation losses. In this case it is possible to estimate the age of the nebula using the expressions derived by Kardashev (1962) relating the break frequency to the magnetic field strength and time. According to Dickel and Willis (1980) the compressed magnetic field strength is about 2×10^{-4} gauss in the filaments. For a break frequency of 1 GHz, this gives a time scale of 2×10^5 yr which is several times the age of the Cygnus Loop. Dickel and Willis (1980) propose that after compression, different parts of the shell can encounter interstellar media of varying densities. If parts of the shell encounter a less dense medium, they may then re-expand reducing the particle energy quickly. Such a process would predict that the spectral breaks would occur at different frequencies for different positions in the remnant. The difference in break frequencies of regions B and C could be due to this reason.

6. Conclusions

(1) The enhanced volume emissivity of the interstellar medium resulting from the compression by the supernova shock alone is not adequate to explain the observed integrated flux density at 34·5 MHz. One has to consider the additional compression due to the cooling of the material heated by the shocks.

(2) The low frequency spectrum of region C (NGC 6992/5) is not flat below 200 MHz.

(3) Both the regions B (NGC 6960) and C (NGC 6992/5) exhibit breaks in their spectra around 1000 MHz and 400 MHz respectively while the spectrum of region A (NGC 6974) is straight in the entire frequency range 25 to 5000 MHz.

(4) The difference in the break frequencies in the regions B and C can be due to different magnetic field strengths in these regions if their spectra are just a reflection of the background radio spectrum of our galaxy. Alternatively, if the breaks in the spectra are due to synchrotron radiation losses, then their difference in the two regions implies dissimilar ambient interstellar densities.

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