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Radio Continuum Observations at 5 GHz of the Supernova Remnant S 147

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Abstract

The old supernova remnant S 147 has been partly mapped at a wavelength of 6 cm with a HPBW of 2!7. The maps reveal a well-defined shell structure and filaments in good positional coincidence with optical structures. The diameter and distance are determined to be 79 ± 15 pc and 1.6 ± 0.3 kpc, respectively. The age is $\sim2\times10^5$ yr and the total energy of supernova explosion is $\sim6\times10^{50}$ erg, if the ambient gas density is 1 cm^{-3}. A straight bright radio ridge is found to be associated with a faint optical filament, where the radio-to-optical emission ratio is much larger than that of any other filaments. This may be due to stronger magnetic fields and higher gas temperature in this filament than others. A brief discussion is made of some compact sources found in the remnants.

Key words: S 147; Shock waves; Supernova remnants.

1. *Introduction*

The supernova remnant (SNR) S 147, located in the direction of the galactic anti-center, is one of the oldest SNRs with a well-defined shell structure, rich in long, developed filaments [see, e.g., van den Bergh et al. (1973)]. Radio observations of this remnant have been available only at low frequencies (e.g., Dickel and McKinley 1969; Haslam and Salter 1971). However, no mapping of sufficiently high angular resolution to permit a detailed study of the object has been made because of its low surface brightness and large extent. This paper presents new radio maps at 6 cm for the southern part of S 147 (sections 2 and 3), and determines its diameter, distance, age, and the total energy of supernova explosion (section 4). A brief discussion is made of compact radio sources of nonthermal spectra in the remnant with a special reference to interaction of a blast shock wave with the interstellar medium.

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2. *Observations*

We have mapped at 6-cm wavelength the southernmost part of S 147 (region I in figure 1) and a small complex region in the north-eastern quadrant (region II). The observations were made using the Effelberg 100-m telescope of the MPIfR in October 1977 and February 1978. The frequency was centered at f=4995 MHz with a bandwidth of 500 MHz. The observations were made in the Dicke switched mode using a helium cooled load. The system noise temperature was about 100 K. The HPBW of the antenna was $2'.6$. Scans were made both along constant right ascension and declination at an interval of $1'.2$ and a scanning rate of $0^\circ.6$–$0^\circ.8$ per minute. Ten independent coverages were made of region I at various polarization angles and six coverages of region II. After reduction all coverages were added to produce maps of total intensity. A considerable number of the scans, about 20 percent of the data, were removed at the reduction stage because of their inferior quality due both to significant interferences and bad weather conditions. The resulting integration time per data point at $1'.2$ interval was approximately 6 s for region I and 3 s for region II. The minimum detectable antenna temperature before smoothing the maps was 1.8 mK for region I and 2.5 mK for region II.

The radio source 3C 123 was used as a pointing and flux calibrator whose flux density at 5 GHz is 16.5 Jy (Baars et al. 1977). We adopt the aperture efficiency of 53% and the main-beam efficiency of 70%, with which the main-beam brightness temperature T_b (in kelvins) is related to the flux density S (in janskies) through $T_b=2.2S$.

To get final maps we used the radio astronomical reduction library, NOD2 (Haslam 1974), the "basket weaving method" (Salter 1977), and the "pressing method" (Sofue and Reich 1979) to remove the scanning effect.

3. *The Contour Maps at 6 cm*

Figures 2 and 3 show the resulting contour maps of total brightness temperatures T_b for regions I and II of S 147. The contour values are T_b in units of millikelvin. The map for region I has been smoothed by a Gaussian function to a HPBW of $2'.7$ to increase the signal-to-noise ratio. Region II has been smoothed to a slightly wider beam of HPBW $2'.8$ because of the poorer quality of the data and less integration time.

In figure 2 a well-defined shell structure is visible corresponding to the southernmost limb of the remnant and displaying good positional coincidence with the optical shell structure (figure 1). In addition, a long arc-shaped ridge is prominent near the top of the figure, running from (RA, Dec)=(05^h37^m, 26°53′) to (05^h40^m, 26°55′) at a peak brightness temperature of 16 mK. This ridge is associated with a bright, long, arc-shaped filament in the optical photograph. Another remarkable ridge follows a straight line from (RA, Dec)=(05^h38^m, 26°40′) to (05^h40^m, 26°50′). The peak brightness temperature is about 20 mK. This ridge is associated with a straight optical filament. However, this straight filament is much fainter in the photograph (figure 1, sensitive around the Hα emission) than the above arc-shaped filament, although stronger in radio emission. This contrast is also true if we compare this filament with the arc-filament representing the southernmost edge of the SNR at around (05^h40^m, 26°30′).

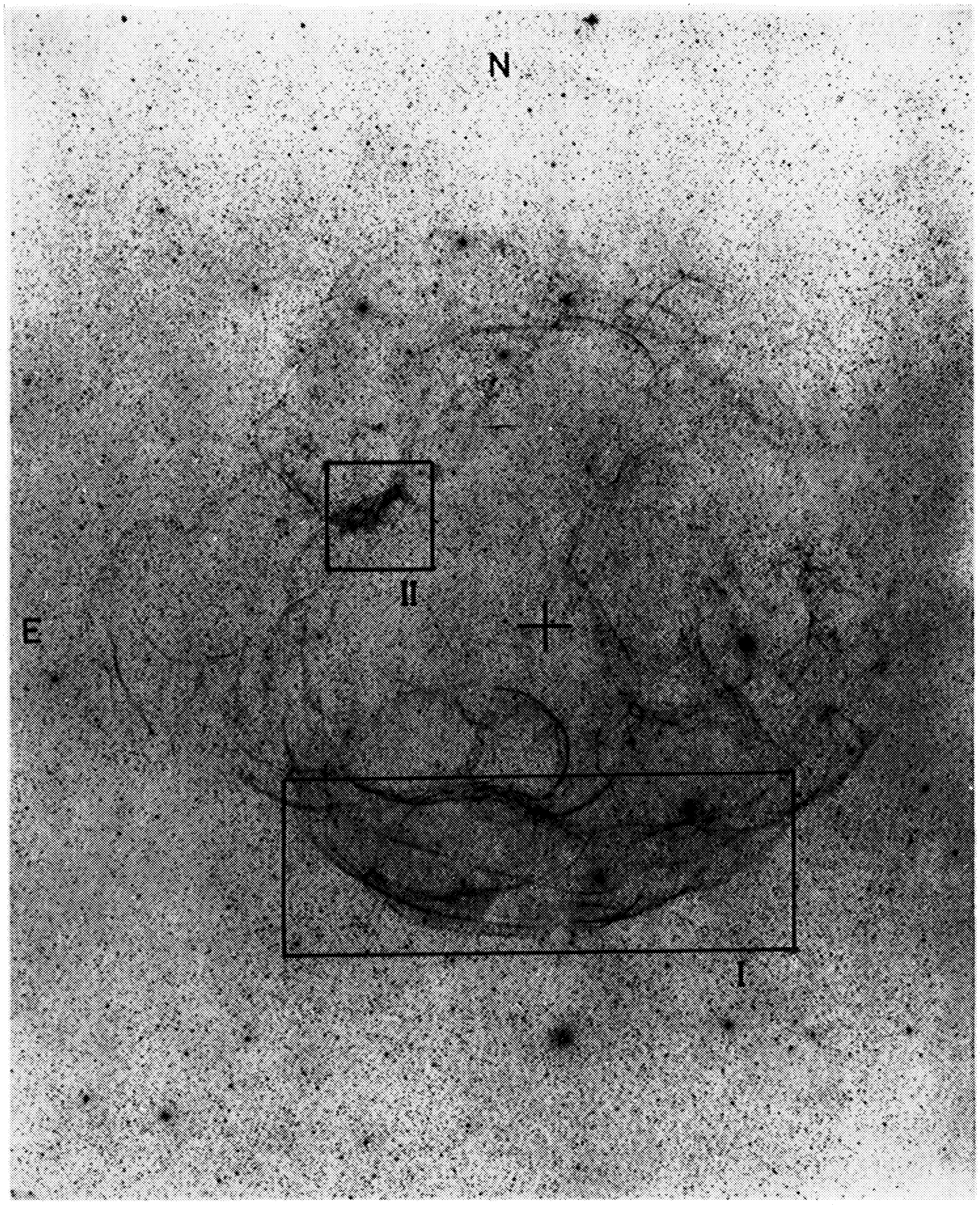

Fig. 1. Optical photograph of the SNR S 147 (van den Bergh et al. 1973: copyright © American Astronomical Society). Squared regions I and II have been observed in the radio continuum at 6 cm and the contour maps are shown in figures 2 and 3. The geometrical center of the radio shell as determined by the present observations is marked with a cross (see the text).

Such a difference in the radio-to-optical brightness ratio may be due to a difference in gaseous temperatures and magnetic field strengths in the filaments; the straight one being associated with a stronger shock wave with stronger magnetic fields and a higher gaseous temperature at which the Hα emission is rather weak, although it should probably appear brighter in the emission-lines represent-

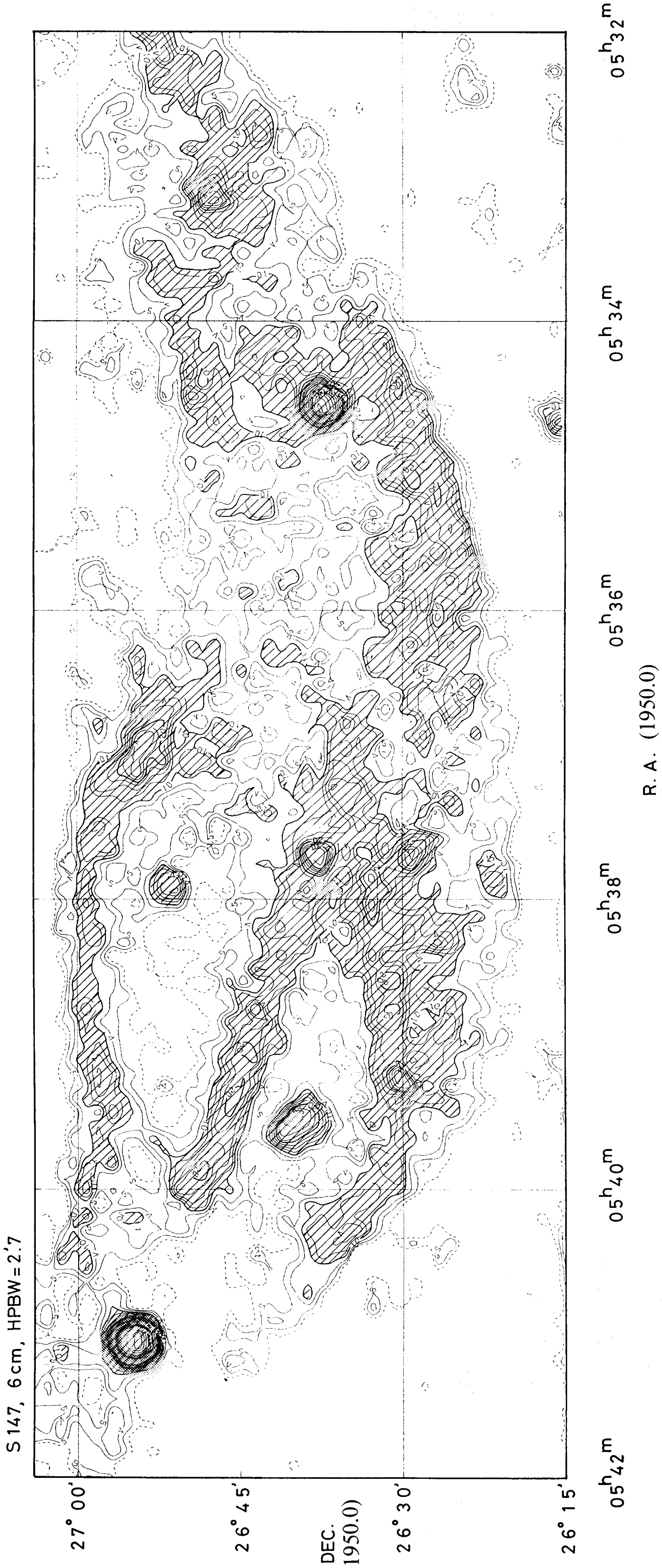

Fig. 2. 6-cm contour map of the southernmost region I of S 147. Contour values are total main-beam brightness temperatures in millikelvins. Areas brighter than T_b=10 mK are hatched. Arrows on contours point down the local gradient.

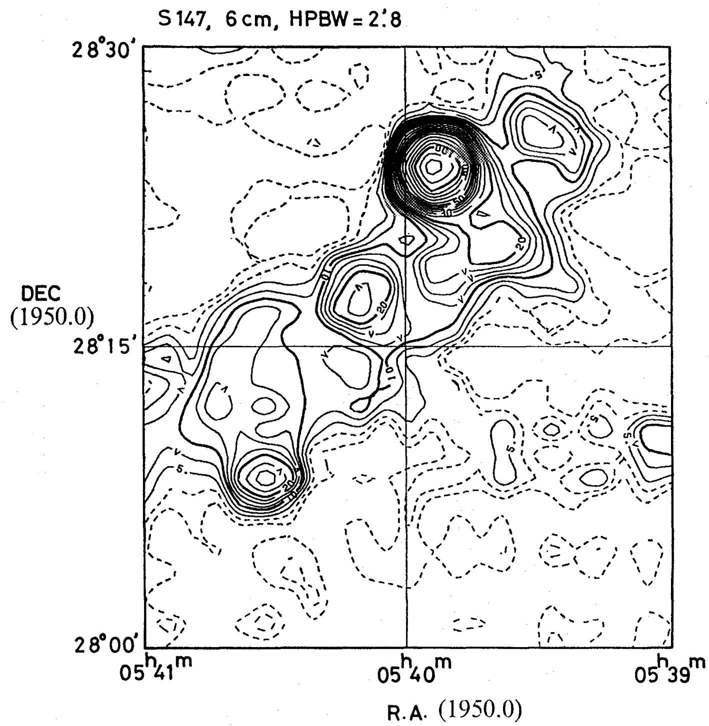

Fig. 3. The same as figure 2 but the north-eastern complex region II of S147.

ing higher excitations. Alternatively the relatively high radio-to-optical brightness ratio at the straight filament could be caused by material which has already cooled through the emission-line stage to become neutral. Then, to maintain a pressure balance against the ambient ionized gas, the filament is highly condensed and has a high magnetic field strength and relativistic particle density to produce the strong radio emission.

A spectral index distribution in region I was obtained by a comparison with a map by at 11-cm wavelength (Angerhofer et al. 1978). After smoothing the 6-cm map by the 11-cm beam (4'.6) we find that most of the extended structures reveal nonthermal spectra with temperature spectral indices between $\beta=2.5$ and 3 with β defined as $T_b \propto f^{-\beta}$. A few bright point sources with steep spectral indices of $\alpha \geqq 0.7$ have been found in the SNR, where α is defined as $S \propto f^{-\alpha}$ with S the flux density. The two brightest point sources of steep spectra will be referred to as A and B (table 2).

Region II has a complex association composed of bright optical filaments and patches (figure 1), which is thought to be formed through a focusing of the SNR shock front interacting with a dense interstellar cloud (Sofue 1978). The radio map of the region in figure 3 reveals an extended radio ridge running from (RA, Dec)=($05^h39.5^m$, 28°25') to (05^h41^m, 28°10') in good positional coincidence with the optical complex. Also seen on the radio map are a number of compact, high-emission regions unresolved by the full resolution HPBW of 2'.6. Five compact sources can be found in region II. The brightest source (referred to as C in table 2) is not accompanied by any significant optical counterpart, but is located slightly outside of the optical complex to NE with respect to the SNR center given below.

3. *Diameter, Distance, Age, and Energy of S 147*

Figure 2 shows a well-defined circular boundary of the southernmost shell of S 147. By fitting a circular arc to this boundary, we determine the geometrical center of the shell as $(\mathrm{RA}, \mathrm{Dec})_{1950}=(05^{\mathrm{h}}36^{\mathrm{m}}.9\pm0^{\mathrm{m}}.2,\ 27°43'\pm3')$, and the corresponding angular diameter is $\theta=166'\pm5'$. The integrated flux density of the remnant is unknown because of the lack of observations of the northern half. However, we can determine the mean brightness temperature $\overline{T}_{\mathrm{b}}$ averaged over the area enclosed by the shell in figure 2. We obtain $\overline{T}_{\mathrm{b}}=10.3\pm0.5\,\mathrm{mK}$. We can derive immediately the surface brightness Σ in region I at 5 GHz as

$$\Sigma_{5\,\mathrm{GHz}}=(7.9\pm0.8)\times10^{-23}\ \mathrm{W\,m^{-2}\,str^{-1}\,Hz^{-1}}\,, \tag{1}$$

where we use the relation $\Sigma=2kT_{\mathrm{b}}/\lambda^2$ with λ the wavelength and k the Boltzmann constant.

The total flux density of the remnant derived from the above diameter and the mean surface brightness is approximately 14.5±5 Jy. Here the large error of ±5 Jy (±30%) is because of the extrapolation of the mean surface brightness derived from the restricted area in figure 2 to the whole area of the remnant with an uncertain filling factor. In figure 4 we show the spectrum of the remnant between 178 MHz and 5 GHz, where the total flux densities below 1420 MHz are from the literature. The spectrum may be either fitted by a straight line of

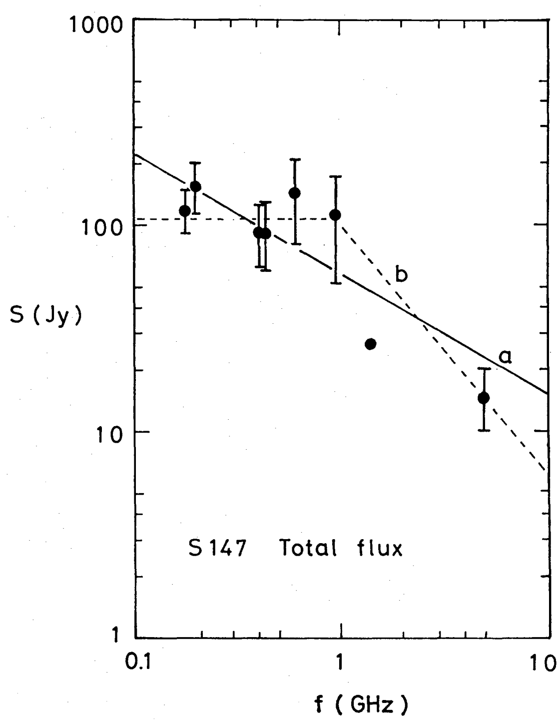

Fig. 4. Spectrum of the total flux density of S 147. The data are from Bennett (1963; 178 MHz), DeNoyer (1974; 195 and 430 MHz), Haslam and Salter (1971; 408 MHz), Dickel and McKinley (1969; 610.5 MHz), Harris (1962; 960 MHz), Galt and Kennedy (1968; 1420 MHz), and the present work (5 GHz). Line a is the least-squares fit to all the data with a straight spectrum of mean spectral index $\alpha=0.57$. Line b fits the data by two components of flat ($\alpha=0$ at $f\lesssim1$ GHz) and steep ($\alpha=1.2$ at $f>1$ GHz) spectra.

index $\alpha=0.57\pm0.1$ (line a; the least-squares fit to all data in figure 4 with equal weight), or divided into two parts of flat ($\alpha\approx0$ below 1 GHz) and steep ($\alpha\approx1.2$ above 1 GHz) components (line b). To discriminate between these two possibilities further observations between 1 and 5 GHz, and beyond 5 GHz, would be necessary. For a later convenience when applying the Σ–D (surface brightness–diameter) relation, we estimate Σ at 1 GHz, adopting the mean spectral index $\alpha=0.57$ as represented by line a in figure 4:

$$\Sigma_{1\,\mathrm{GHz}}=(3.0\pm0.2)\times10^{-22}\ \mathrm{W\,m^{-2}\,str^{-1}\,Hz^{-1}}\ . \tag{2}$$

The $\Sigma-D$ relation is assumed to have the form:

$$\Sigma=pD^{-q} \quad \text{or} \quad D=(\Sigma/p)^{-1/q}\ . \tag{3}$$

Empirical values of p and q have been derived by various authors at 408 MHz, 1 GHz, and 5 GHz. The Σ–D relation at 5 GHz derived by Clark and Caswell (1976) gives $D=56\pm10$ pc for the linear diameter of S 147 as derived from region I. The most recent Σ–D relation at 1 GHz corrected for variation in height z (in parsecs) above the galactic plane derived by Milne (1979) is expressed in the form

$$D=4.12\times10^{-4}\Sigma^{-0.25}\exp(-|z|/214)\ \mathrm{pc}\ . \tag{4}$$

The iterative solution of equation (4) for S 147 using equation (2) yields $D=79\pm15$ pc. The distance of this SNR is then $d=D/\tan\theta=1.6\pm0.3$ kpc and the height of its center above the galactic plane is $z=-48\pm5$ pc. However, the recent paper by Caswell and Lerche (1979) yields $D\approx114$ pc and a distance $d\approx2.4$ kpc, which are far beyond the results of the other authors. Here we take a distance of 1.6 ± 0.3 kpc corresponding to $D=79$ pc as a more reliable one. This distance would support the possible association with the pulsar PSR0525+21 at a distance of 1.9 kpc (Manchester and Taylor 1977; Morris et al. 1978). For the quantities derived below the values according to Caswell and Lerche (1979) are added in parentheses.

Table 1. Parameters for S 147 as derived from the 6-cm observations of the southern region I.

Center of the radio shell	RA $=05^{\mathrm{h}}36^{\mathrm{m}}.9\pm0^{\mathrm{m}}.2$ (1950)
	Dec. $=27°43'\pm3'$ (1950)
	$l=180°23'\pm3'$
	$b=-1°42'\pm3'$
Angular diameter	$\theta=166'\pm5'$
Average brightness temperature at 5 GHz	$\bar{T}_{\mathrm{b}}=10.3\pm0.5$ mK
Average surface brightness	$\Sigma_{5\,\mathrm{GHz}}=(7.9\pm0.8)\times10^{-23}\ \mathrm{W\,m^{-2}\,str^{-1}\,Hz^{-1}}$ (region I)
	$\Sigma_{1\,\mathrm{GHz}}=(3.0\pm0.4)\times10^{-22}\ \mathrm{W\,m^{-2}\,str^{-1}\,Hz^{-1}}$ (line a in figure 4)
Linear diameter	$D=79\pm15$ pc
Distance	$d=1.6\pm0.3$ kpc
Expansion velocity	$v=80\ \mathrm{km\,s^{-1}}$ (Kirshner and Arnold 1979)
Age	$t=2.0\times10^{5}$ yr
Total energy	$E=5.5\times10^{50}$ erg for $n_0=1\ \mathrm{cm^{-3}}$
	$=5.5\times10^{49}$ erg for $n_0=0.1\ \mathrm{cm^{-3}}$

The Sedov (1959) similarity solution is well known for a point explosion in a uniform medium, which relates the total explosion energy E, radius r of the spherical shock front, ambient density ρ_0, expansion velocity of the shell v, and age t as follows:

$$r=(2E/\rho_0)^{1/5}t^{2/5}\ , \tag{5}$$

$$t=\frac{2}{5}\frac{r}{v}\ , \tag{6}$$

and

$$E=3.1\rho_0 r^3 v^2\ . \tag{7}$$

Optical measurements of the systematic expansion velocity have been undertaken by Lozinskaya (1978) (v=25–100 km s^{-1} with a mean of 50 km s^{-1}) and by Kirshner and Arnold (1979) (v=80 km s^{-1}). Combining the value of 80 km s^{-1} with our estimate of the radius $r=D/2=39$ pc, we obtain an age of $t=2.0\times10^5$ yr (3×10^5 yr, if D=114 pc), and a total energy of $E=5.5\times10^{50}$ erg (2×10^{51} erg) for an ambient number density of $n_0=1$ cm^{-3} and $E=5.5\times10^{49}$ erg (2×10^{50} erg) for $n_0=0.1$ cm^{-3}. The derived quantities for S 147 are summarized in table 1.

5. *Discussion*

Many compact radio sources unresolved by the present observations can be seen in figures 2 and 3. Table 2 lists major compact sources in S 147, where their temporary numbers, positions, flux densities, and spectral indices between 6 and 11 cm, if available, are given. The 11-cm flux densities were read from the map by Angerhofer et al. (1978). The strongest sources, A, B, and C have steep spectra with $\alpha\geqq0.7$, which indicates that they are of nonthermal nature. These compact sources are not associated with optical counterparts, and are characteristic of the radio maps alone.

According to a source count at 5 GHz in a selected area near the north galactic pole (Wall and Cooke 1975), approximately ten extragalactic radio sources

Table 2. Compact radio sources in S 147 at 6 cm.

Region	No.	RA (1950)	Dec (1950)	$S_{6\,\mathrm{cm}}$ (mJy)	$S_{11\,\mathrm{cm}}$ (mJy)	α_{11}^{6} ($S\propto f^{-\alpha}$)	Special designation
I	1	$05^h33^m09\overset{s}{.}7$	26°47′13″	11			
	2	34 34.4	37 22	33	105	1.7	A
	3	37 41.0	28 53	10			
	4	37 41.7	37 37	16			
	5	37 54.5	51 23	8			
	6	39 12.8	30 29	10			
	7	05 41 02.4	26 54 34	55	81	0.8	B
II	1	05 39 29.2	28 25 34	8			
	2	39 38.1	20 05	9			
	3	39 53.8	23 54	75	115	0.7	C
	4	40 10.7	17 18	10			
	5	05 40 31.6	28 08 20	15			

of $S \geqq 10$ mJy are expected to fall in the area enclosed by the shell of S 147 in region I (figure 2) and roughly two such sources in region II (figure 3). These numbers are comparable to those counted in table 2. Therefore, it is uncertain whether any of these sources is connected with the SNR: some of them may be extragalactic. However, it should be remembered that the number density of the compact sources in a restricted area coinciding with the optical complex in region II is clearly higher than that expected for the background sources. Recently Ryle et al. (1978) have discussed the possible correlation between compact sources and supernova remnants, while Kirshner and Chevalier (1978) demonstrated a superposition of an extragalactic radio source on the galactic SNR G 127.1±0.5 [see also Shaffer et al. (1978)]. In the following we assume that the sources A, B, and C are related to the SNR S 147 and discuss briefly the physical nature of these sources.

Since the observed extents of these compact sources are not significantly different from the antenna beam width, we may estimate their angular sizes to be less than 20 percent of the HPBW, i.e., less than $0\overset{\prime}{.}5$. Adopting the distance of 1.6 kpc their linear sizes would turn out to be less than 0.23 pc. If we assume an equipartition between magnetic and cosmic-ray electron energy densities in the sources, the field strength in the compact sources is estimated to be $\gtrsim 10^{-4}$ G and the number density of high energy electrons $\gtrsim 10^{-5}$ cm^{-3}, for a flux density of $S=55$ mJy. This magnetic field strength is $\sim 10^2$ times the ambient interstellar value. If the sources are formed by a contraction or compression of interstellar medium with frozen-in magnetic fields, then the gas density in the source will be $\gtrsim 300$ cm^{-3}, if $n_0 = 1$ cm^{-3}. Such high-density compact regions could originate through the Rayleigh–Taylor instability during strong braking of a dense, shocked shell by the interstellar medium (Chevalier 1977; Gull 1975). The origin might possibly be common to compact radio sources in some SNRs like Cas A (Bell et al. 1975; Rosenberg 1970), IC 443 (Duin and van der Laan 1975), Cygnus Loop (Keen et al. 1973), and G 65.2+5.7 (Reich et al. 1978).

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