RADIO EMISSION FROM 16 POSSIBLE SUPERNOVA REMNANTS

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Summary

Sixteen radio sources, thought to be supernova remnants, have been observed at several frequencies between 408 and 2700 MHz. These data, together with previously published observations, have been used to derive spectra for these sources. The validity of the supernova remnant classification of certain of these sources is questioned.

I. Introduction

There are some 40 radio sources classified in the literature as remnants of galactic supernovae. The identification of these objects has generally followed the rules:

(1) The radio spectrum is nonthermal.

(2) The angular size is large enough to exclude identification as an external galaxy.

(3) The object should be a population I member (i.e. within 250 pc of the galactic plane).

(4) If the source is visible optically, then it should not be an HII region, and preferably should show some of the characteristic filamentary structure usually associated with supernova remnants.

(5) A radio brightness distribution indicating a shell structure.

To date the radio data available for these objects have been scant, particularly for certain of the southern sources. Within the range of the Parkes 210 ft radio telescope (declination $+27°$ to $-90°$) there are 24 radio sources classified as galactic supernova remnants. Some of these have been examined using the Parkes facilities (e.g. Gardner and Milne 1965; Hill 1967; Whiteoak and Gardner 1967; Milne 1968*a*) whilst for the other remnants often the only data available are from the low-resolution galactic surveys (e.g. Hill, Slee, and Mills 1958; Westerhout 1958; Wilson and Bolton 1960; Mathewson, Healey, and Rome 1962; Komesaroff 1966). It is these latter objects that are investigated in the present paper.

For most of the sources discussed we present information on structure, size, and radio flux density at frequencies of 635, 1410, and 2650 MHz. These data, together with the flux densities published by other workers, have been used to obtain the radio spectral index of each source. It has been necessary in certain cases to adjust published flux densities for angular extent using our angular size estimates for this purpose. With the improved data at our disposal we have then re-examined the validity of the supernova remnant classification of each of these objects. Preliminary observations on seven of the sources investigated here have been reported previously (Milne 1968*b*).

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II. Observations

Our primary aim was to obtain brightness distributions for each of these objects at frequencies of 635, 1410, and 2650 MHz. At these frequencies the ANRAO 210 ft radio telescope at Parkes has beamwidths of 31′, 15′, and 8′·4 arc respectively.* The regions containing each source were scanned, usually in declination, at drive rates such that at least six time constants were contained in each beamwidth. The scans were spaced at half-beamwidth intervals. Only one polarization was used in these surveys. Polarization data are not available for most of the sources investigated and no attempt has been made to allow for polarization in the brightness isotherms or in the estimated flux densities. The specification of errors allows for any effect that polarization might produce in these estimates.

Table 1

Details of receiving systems

Centre Frequency (MHz)	Receiver Details: Description	Receiver Details: Bandwidth (MHz)	Receiver Details: Noise Temp. (°K)	Antenna Beamwidth (min of arc)	Assumed Flux Densities of Calibrating Sources (f.u.): Hydra	19−46	3C 273
408	Crystal mixer	8	350	48	135	39	—
470	Crystal mixer	10	400	41	119	34	—
635	Non-degenerate parametric	8	180	31	90	26	—
1410	Degenerate parametric	10	120	15	42	12·5	39·6
1660	Crystal mixer	10	400	12·6	36	10·8	—
2650	Degenerate parametric	50	180	8·4	23·5	7·1	37·3
2700	Twin-channel correlation	400	100	8·1	23·0	6·9	—

The receiving system was calibrated nightly from scans in declination and right ascension through either of the two sources Hydra A or 19 −46. From these scans the flux density scale and the antenna beamwidth were determined. An argon discharge noise generator was used to interpolate equipment performance between these observations. The brightness temperature (°K) quoted in this paper was derived from the relationship

$$T_b = 10^{-26}\lambda^2 S/2k(1\cdot 13b^2)\,, \qquad (1)$$

where k is Boltzmann's constant ($1\cdot 38\times 10^{-23}$ J degK^{-1}), λ the wavelength (metres), b the half-power width (radians) of the antenna response to a point source, and S the flux density (f.u.†). This relationship is valid for a Gaussian antenna response, the beam solid angle being given by $1\cdot 13b^2$ under this condition. Table 1 gives details of the antenna and receiver performance at each frequency. The flux density adopted at each frequency for the calibration sources is also given in Table 1. The source 3C 273 was used only in conjunction with the observations on 13S6A.

* After these initial observations were made, the Mk II 2700 MHz receiver became available and three of the sources (S34, CTB 72, and 3C 3961) not discernible with the Mk I (2650 MHz) receiver were observed. In addition we have used measurements made at 408 MHz on 18−25, at 470 MHz on S34, and at 1660 MHz on W49B. We are indebted to Dr. F. F. Gardner for the latter result.

† 1 flux unit = 10^{-26} W m^{-2} Hz^{-1}.

III. Brightness Isotherms and Estimated Flux Densities

For most of the sources we have constructed maps of the brightness distribution over the region containing the source, at each of the frequencies used. This has not been necessary where the scans show the source to be a simple symmetrical object that is well separated from the background emission. In these cases we have fitted a Gaussian model to the observations and obtained the integrated flux from the relationship

$$S_{\text{int}} = S_{\text{peak}}(W_0/W_{\text{b}})^2, \tag{2}$$

where W_0 is the half-intensity width of the Gaussian fitted and W_{b} the antenna beamwidth. For the more complex sources, where isotherms were constructed, the integrated flux density was obtained from planimeter measures of isothermal areas substituted into the basic relationship

$$S_{\text{int}} = (2k/\lambda^2)\iint T_{\text{b}}\,\mathrm{d}\Omega\,. \tag{3}$$

In practice both methods were used whenever possible and the results compared.

The errors quoted in estimates of the flux density were determined mainly from the error introduced when a change was made in the baselevel over which the integration was carried out. The difficulty in properly determining this level is the largest source of error, particularly at the lowest frequency, where the galactic background is most troublesome. For the sources of fairly large extent this was found to introduce errors in the integrated flux density of about 20%. The probable error in determining the flux density of the smaller sources on a smooth background is estimated to be about 8%.

The brightness distributions presented here are isotherms of brightness temperature multiplied by a constant that varies from map to map (quoted in the legend for each). The flux density estimates made from each of these surveys are given in Tables 2–16. We also reproduce in these tables the flux densities estimated by other workers. In certain cases where these estimates are peak values or have been based on incorrect angular sizes, we have made corrections using our own size estimated for this purpose. We feel justified in doing this, for in all the sources examined there existed no previous measurements of resolution comparable with the one used in the present investigation. A discussion of the results obtained is given in the next section, the sources being taken in order of right ascension. We have plotted the isotherms obtained at each frequency where this information is of value.* The spectrum of each source is also reproduced in the figures.

IV. Discussion of Results

(a) *S34 (PKS 0607+17)*

The contour maps (Fig. 1) show this region resolved into three main sources: A at R.A. $06^{\text{h}}\,11^{\text{m}}$, Dec. $+18°$ (which we identify with a group of emission nebula numbers 254–258 in Sharpless 1953), B at $06^{\text{h}}\,07^{\text{m}}$, $+15°45'$ (clearly identified with the nebula S34), and C, a large source ($\sim 80'$ diameter) with its peak at $06^{\text{h}}\,07^{\text{m}}$, $+17°$.

* Copies of these maps (not reproduced here) may be obtained on application to: The Chief, Division of Radiophysics, CSIRO, P.O. Box 76, Epping, N.S.W. 2121, Australia.

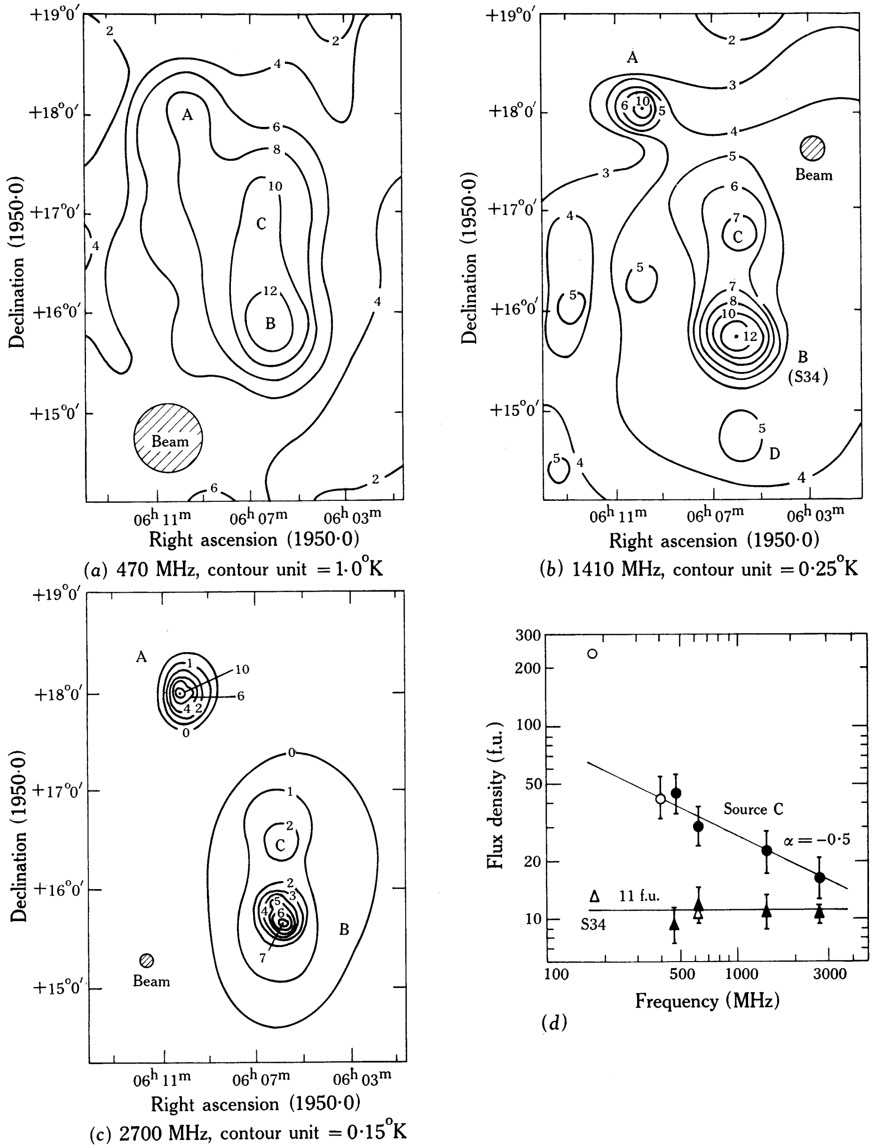


Fig. 1.—Contour maps of the region containing S34 at frequencies of (*a*) 470, (*b*) 1410, and (*c*) 2700 MHz. The contour units used in these and all subsequent maps are specified in full-beam brightness temperatures. Source B is the thermal source S34; source C is nonthermal and is possibly a supernova remnant. The spectra of these sources are shown in (*d*), where the full symbols represent the present data and the open symbols the data of other observers. This system is used in all subsequent spectra.

It would appear from the flux densities given in Table 2 that sources A and B are thermal sources that are optically thin over the frequency range observed. We have subtracted these and a weak source, D (R.A. $06^{h}05^{m}\cdot5$, Dec. $+14°45'$), from the integrated flux density for the whole region to obtain the values given in Table 2 for source C.

Comparing our results with those obtained by other observers (Table 2), we find good agreement between Bennett (1963), Dickel *et al.* (1967), and the present flux density estimates for S34, but the close fit to a power law spectrum ($\alpha = -0 \cdot 5$) for the nonthermal source C above 400 MHz suggests that Bennett (1963) may have overestimated the total flux from this region.

We accept the suggestion (Davies 1963) that this region contains a supernova remnant but we do not associate it with S34, nor is there any object of suitable size visible in this direction on the Palomar Sky Atlas. To avoid further confusion of this source with S34 we suggest that the nonthermal source C be referred to as PKS 0607+17 (following the Parkes catalogue notation).

TABLE 2

RADIO DATA FOR SOURCES IN S34 FIELD

Property	Ref.*	Source A	Source B (S34)	Source C (PKS 0607+17)	Source D	Total Flux
Position (1950·0)						
R.A.		$06^h 10^m$	$06^h 06^m$	$06^h 06^m$	$06^h 06^m$	
Dec.		+18°	+15°40′	+16°40′	+14°50′	
Angular Size						
(min of arc)		8	26	80	—	
Flux density (f.u.)						
178 MHz	1		13	240		
400	2			42 ±25%†		60 ±25%
470	Present		9·1±20%	44·5±25%†		62·5±25%
610	3		10·6			
635	Present	6 ±30%	11·6±20%	30 ±25%	1	48 ±25%
1410	Present	5 ±20%	10·8±20%	22 ±25%	2	40 ±25%
2700	Present	4·9±10%	10·5±10%	16 ±25%	2·3±25%	
Conclusion		5 f.u. Thermal	11 f.u. Thermal	Nonthermal $\alpha = -0 \cdot 5$	2 f.u. Thermal	

* References are: 1, Bennett (1963); 2, Davis, Gelato-Volders, and Westerhout (1965); 3, Dickel *et al.* (1967).

† These values for the flux of source C were not measured directly but were derived by subtracting the measured flux of components A, B, and D from the integrated flux.

(*b*) *The Monoceros Nebula*

It has been suggested (Davies 1963) that the Monoceros Nebula, a $3\frac{1}{2}°$ diameter ring centred on R.A. $06^h 37^m$, Dec. +6°, is a supernova remnant associated with a radio source found in a survey of this region at 237 MHz (Davies and Hazard 1962). We have mapped this object at 470 and 635 MHz (Figs 2(*a*) and 2(*b*)) and certain scans have been made at 1410 and 2700 MHz. (The emission was too weak at these two latter frequencies for a map to be constructed of this large object.)

Flux density estimates for this object are listed in Table 3. These estimates are of low accuracy; the object is very extended, of low brightness, and confused on the western side with the Rosette Nebula, NGC 2244. As a consequence we are not able to quote the spectral index with any great certainty. We have indicated a possible nonthermal spectral index of $\alpha = -0 \cdot 5$ in Figure 2(*c*); it is not intended

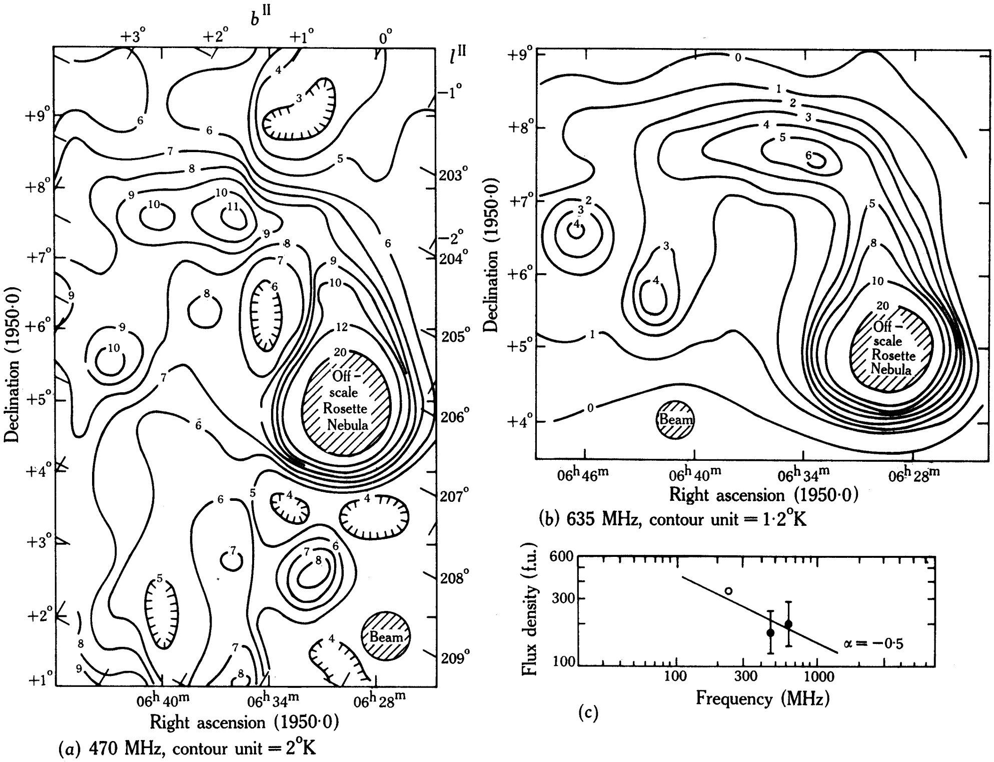


Fig. 2.—Showing (*a*) the 470 and (*b*) 635 MHz isotherms and (*c*) the spectrum of the Monoceros Nebula. Galactic coordinates are also given in (*a*) to permit easy comparison with the mosaic and charts of Raimond (1966) (see text).

Table 3

Radio Data for Monoceros Nebula

Property	Reference	Value
Position (1950·0)		R.A. $06^{h} 35^{m}$, Dec. $+16°30'$
Angular size		3°·5 diameter shell, thickness approx. 0°·5
Flux density (f.u.)		
237 MHz	Davies and Hazard (1962)	340
470	Present paper	176±30%
635	Present paper	200±30%
Conclusion	Possible supernova remnant	

that this be considered as the line of best fit. An index $\alpha = -0 \cdot 35$ is obtained, within the same low accuracy, by a comparison of the brightness temperature estimated at two points in this region over the frequency range 237–2700 MHz.

We have compared our isotherms (Fig. 2) with the Hα mosaic of Raimond (1966). The structural agreement is very good, leaving no doubt that the loop seen at radio frequencies is identified with the Monoceros Nebula. Furthermore, it seems most likely that the high velocity HI emission feature ($V = +38$ km sec^{-1}) in this

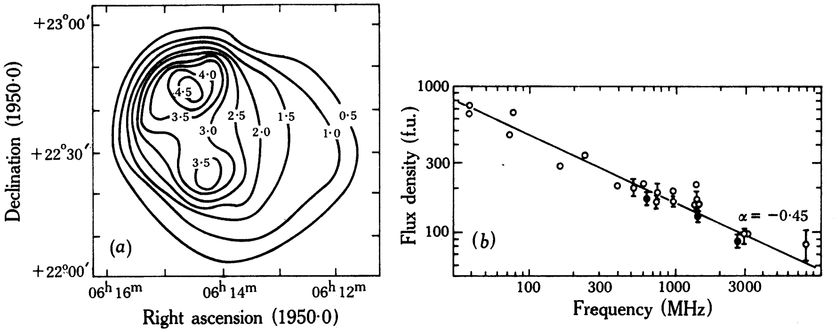


Fig. 3.—Showing (*a*) the 2700 MHz isotherms (contour unit = 1°K) and (*b*) the spectrum of IC 443.

TABLE 4

RADIO DATA FOR IC 443

Property	Ref.*	Value	Property	Ref.*	Value
		R.A. Dec.			
Position (1950·0)		$06^h 14^m 36^s$, +23°45′	Flux density (f.u.)		
2700 MHz, 2 peaks		$06^h 14^m 22^s$, +22°24′	635 MHz	Present	173±10%
Approx. centre		$06^h 14^m 00^s$, +22°30′	740	2	164±9%
Angular size		50′ with bright rim on	750	9	190±13%
		eastern side	960	8	195
Flux density (f.u.)			960	2	165±6%
38 MHz	1	650	1390	16	215
38	3	730	1400	15	159
81·5	14	470	1400	9	170±12%
85·5	13	660	1410	Present	131±10%
159	6	270	1420	7	160
237	4	340	2700	Present	88±10%
400	5	230	3000	9	100+5%
513	2	205±13%			−15%
600	12	220	3125	11	100
			8000	10	85±20%
			9400	17	16±25%
Conclusion		Nonthermal, $\alpha = -0{\cdot}45$, supernova remnant			

* References are: 1, Baldwin and Dewhirst (1954); 2, Bondar *et al.* (1965); 3, Blythe (1957); 4, Davies and Hazard (1962); 5, Davis, Gelato-Volders, and Westerhout (1965); 6, Edge, *et al.* (1958); 7, Hagen, Lilley, and McClain (1955); 8, Harris and Roberts (1960); 9, Hogg (1964); 10, Howard and Dickel (1963); 11, Kuzmin *et al.* (1960); 12, Piddington and Trent (1956); 13, Rishbeth (1956); 14, Shakeshaft *et al.* (1955); 15, Wanner (1961); 16, Westerhout (1958); 17, Yamashita and Watanabe (1968).

direction (Raimond 1966, feature i) is associated with the nebula and radio source. If this object is a supernova remnant then it is possible that there is a shell of neutral hydrogen moving away from (and behind) the expanding remnant. If this interpretation is correct then it is unlikely that the object is in the Perseus arm at 4 kpc from the Sun (Raimond 1966). It is possible that the object is in the association I Mon (Girnstein and Rohlfs 1964); it would then have a distance between 900 and 1300 pc, depending on whether an A_V/E_{B-V} of 5·7 or 3·9 is adopted. A further increase in A_V/E_{B-V}, as has been suggested lately, would reduce the distance to I Mon still further. For physical uniformity of this object with other supernova remnants a distance closer to 500 pc would be required. We conclude on the basis of spectra, appearance, and the possible association with the high velocity feature that the Monoceros Nebula is a supernova remnant.

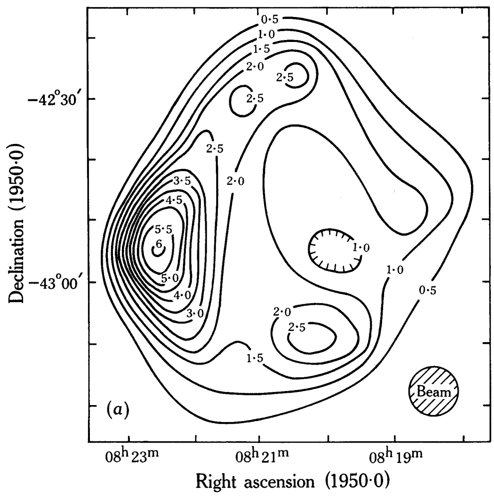


Fig. 4.—Showing for Puppis A:
(a) 2650 MHz isotherms (contour unit = 1°K),
(b) spectrum.

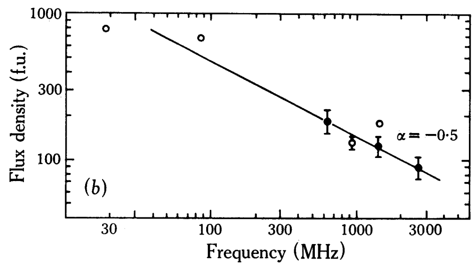


Table 5

RADIO DATA FOR PUPPIS A

Property	Reference	Value
Position (1950·0)		
Peak		R.A. $08^h 22^m 30^s$, Dec. −42°55′
Approximate centre		R.A. $08^h 20^m 30^s$, Dec. −42°50′
Angular size		55′; well-defined shell with bright rim on eastern side
Flux density (f.u.)		
19 MHz	Rishbeth (1958)	800
86	Mills, Slee, and Hill (1960)	690
635	Present paper	183±15%
960	Harris (1962)	132±10%
1410	Present paper	127±15%
1440	Mathewson, Healey, and Rome (1962)	180
2650	Present paper	90±15%
Conclusion	Nonthermal, $\alpha = -0\cdot5$, supernova remnant	

(c) *IC 443*

The emission nebula IC443, associated with the nonthermal radio source 06N2A, has long been identified as a supernova remnant. There is a marked correlation between our 2700 MHz brightness contours (Fig. 3(*a*)) and the form outlined by the nebula. The incomplete thick shell to the north-east is in close agreement with the stronger of the two sources into which this source is resolved by our 8′·4 beam. The weaker source has its optical counterpart in the fainter emission to the south-west.

In our 2700 MHz map we do not show the weak emission extending to the north-east which is so marked in Hogg's (1964) isotherms. This faint emission exists in our scans but we do not find it as bright as would be expected from Hogg's maps. We have neglected this emission in the construction of our isotherms and estimate of flux density. Our flux values generally are lower than those of other workers (Table 4); this may be due to the omission of this extended background from our estimates, although Hogg (1964), with whom we consistently differ, also specifically excluded it from his values.

The spectrum obtained from these data is illustrated in Figure 3(*b*); the spectral index shown is $\alpha = -0 \cdot 45$. We suggest a total angular size of 50′ arc for this object, with considerable concentration of the flux density into two extended sources forming a bright ridge around the eastern side.

(*d*) *Puppis A*

Puppis A, like IC443, is another object long identified as a supernova remnant. Our 2650 MHz contours (Fig. 4(*a*)) show a strong resemblance (at higher resolutions) to those we obtained on IC443, although in the case of Puppis A the shell is better defined. It is of interest to note here that our 8′·4 arc 2650 MHz survey is the first published investigation of this object with a resolution better than $\frac{3}{4}°$. The radio shell, although defined optically, is seen here at radio frequencies for the first time. In Table 5 we list flux densities obtained by us and other workers. The spectrum drawn from these data is shown in Figure 4(*b*); the spectral index that we obtain is $-0 \cdot 5$. An angular diameter of 55′ arc is indicated by the 2650 MHz contours.

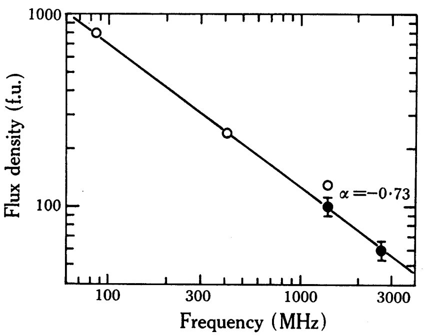


Fig. 5.—Spectrum of 13S6A.

(*e*) *13S6A* (*PKS 1343−60*)

The first suggestion that the source 13S6A was a supernova remnant was made by Shklovsky (1954), who had made a comparison of radio source positions with those of catastrophic events similar to those associated with supernovae and recorded in early Chinese astronomical chronicles. The low galactic latitude, the nonthermal radio spectrum, and the proximity of the source to the location of an event in the year 185 A.D. suggest a supernova remnant. Attempts to find optical remnants in the vicinity of the radio source position have not been successful, and identification with the 185 A.D. event has recently been disputed (see Hill 1967).

In Table 6 we list the flux densities obtained for this source. The spectrum (Fig. 5) drawn from these data is steeper than is usually found for a supernova remnant. Unpublished observation made at 5007 MHz (4′ beam) by one of us (D.K.M.) shows that 13S6A is a double source with a component separation of 8′ arc and diameters of 7′ and 4′·5. It is possible that this object is extragalactic.

TABLE 6

RADIO DATA FOR 13S6A (PKS 1343−60)

Property	Reference	Value
Position (1950·0)		R.A. $13^h 43^m 35^s$, Dec. −60°08′
Angular size		$5' \times 14'$ (major axis at position angle 45°)
Flux density (f.u.)		
85 MHz	Mills, Slee, and Hill (1960)	795
408	Komesaroff (1966)	242
1410	Present paper	102±10%
1440	Mathewson, Healey, and Rome (1962)	130
2650	Present paper	60±10%
Conclusion	Nonthermal, $\alpha = -0\cdot73$, but no definite evidence of supernova character	

(*f*) *CTB 35*

Braes and Hovenier (1966) suggested that this source was associated with the supernova of 1203 A.D. Their proposal was based mainly on a nonthermal spectral index ($\alpha = -0\cdot7$) derived from the flux densities given in the General Catalogue of Radio Sources (Howard and Maran 1965). The dominating feature of this spectrum is the low 3200 MHz flux, unfortunately a peak value uncorrected for the considerable extent of this object.

In Figure 6 we have overlaid a photograph of the region with the 2650 MHz contours; clearly we resolve the source into three components well identified with three nebulae in this direction, presumably HII regions. Table 7 gives details of the flux density obtained for each of these sources in the two higher resolution surveys (1410 and 2650 MHz), together with the total flux densities estimated by us and by other workers. The flux densities quoted by Komesaroff (1966), Mathewson, Healey, and Rome (1962), and Haddock, Mayer, and Sloanaker (1954) are peak values only and have been corrected in Table 7 for the angular extent of the complex. The spectrum (Fig. 7(*c*)) of the three sources combined is that of an optically thin thermal region as is the spectrum of each source taken over the limited frequency range 1410–2650 MHz. Furthermore, the centroid position of the three sources at 2650 MHz was computed and found to lie only 1′·2 from the 635 MHz centroid, indicating that the spectral index must have much the same value for each component source.

CTB 35 is not listed in the Mills, Slee, and Hill (1960) 86 MHz catalogue; an inspection of the 86 MHz contours (Hill, Slee, and Mills 1958) shows possible absorption in the position of this soucre, a confirmation of its thermal spectrum. We cannot agree with the suggestion of Howard and Maran (1965) that MSH 16−4*11* is CTB 35, since this source (16−4*11*) is also seen in the Parkes 1410 MHz galactic survey (Hill 1968).

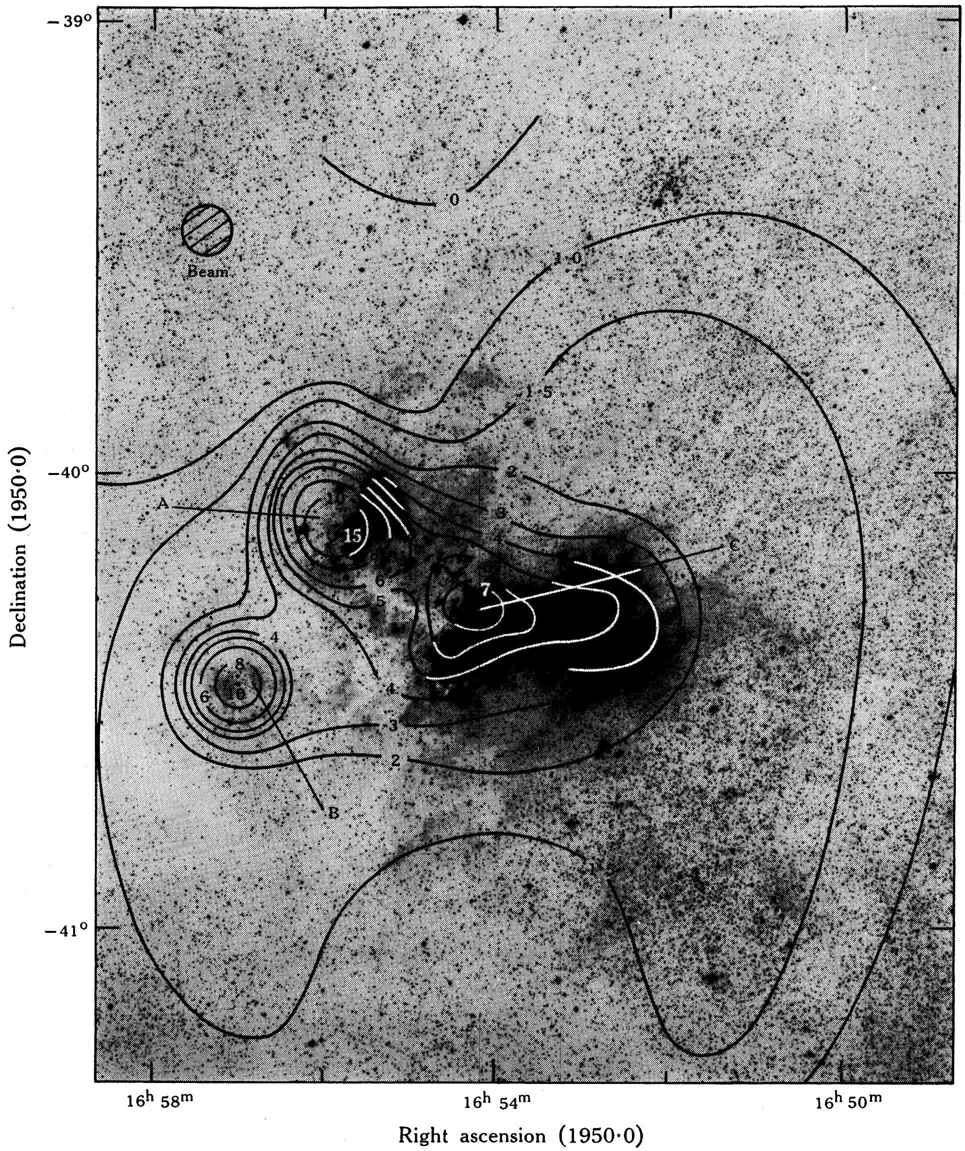


Fig. 6.—Showing the 2650 MHz isotherms (contour unit = 1°K) of the three thermal sources comprising CTB 35 compared with the optical features in this direction. The photograph has been reproduced from a 48 in. Schmidt plate in the Whiteoak Atlas (California Institute of Technology).

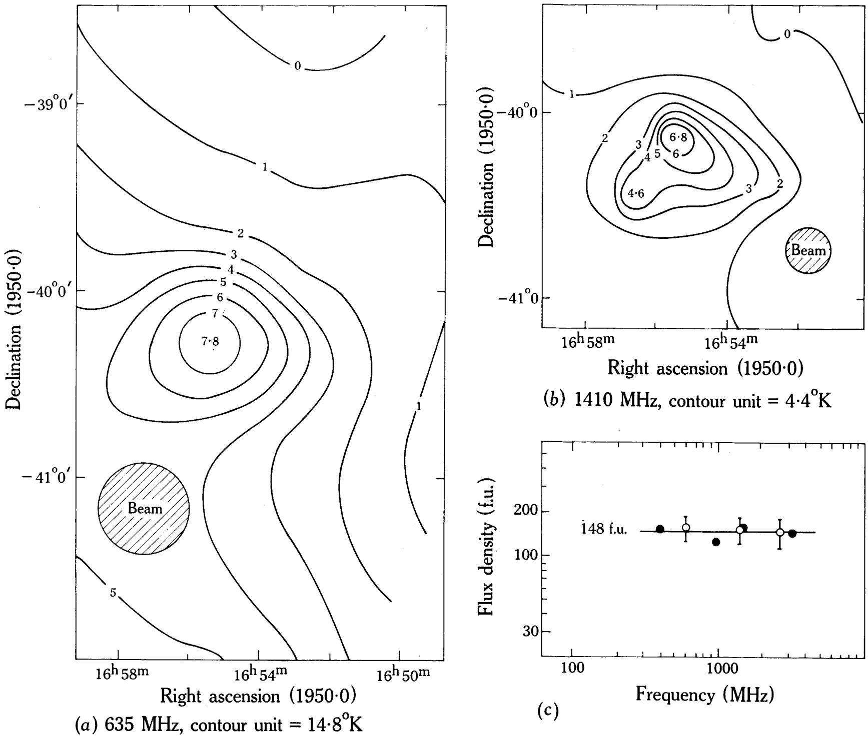


Fig. 7.—Showing (*a*) the 635 and (*b*) 1410 MHz isotherms and (*c*) the spectrum of CTB 35.

TABLE 7

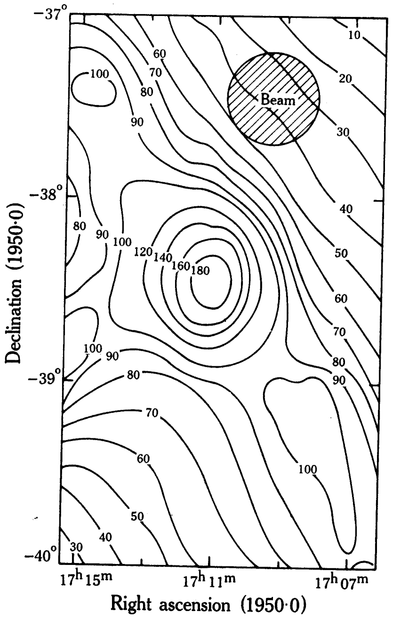
RADIO DATA FOR CTB 35

Property	Ref.*	Component A	B	C	A+B+C
Position (1950·0)					
R.A.		$16^h 55^m 50^s$	$16^h 57^m 00^s$	$16^h 54^m 20^s$	
Dec.		−40°07′	−40°35′	−40°17′	
Angular size (min of arc)		$10 \cdot 0 \times 7 \cdot 5$	8×8	37×18	$40 \cdot 7 \times 25 \cdot 7$ (at 635 MHz)
Flux density (f.u.)					
408 MHz	2				154 (106 peak)†
635	Present				$158 \pm 20\%$
960	4				134
1410	Present	$43 \pm 20\%$	$21 \pm 20\%$	$87 \pm 30\%$	$151 \pm 20\%$
1440	3				156 (106 peak)†
2650	Present	$41 \pm 10\%$	$20 \cdot 5 \pm 10\%$	$84 \pm 20\%$	$145 \pm 25\%$
3200	1				143 (55 peak)†
Conclusion		HII region	HII region	HII region	

* References are: 1, Haddock, Mayer, and Sloanaker (1954); 2, Komesaroff (1966); 3, Mathewson, Healey, and Rome (1962); 4, Wilson (1963).

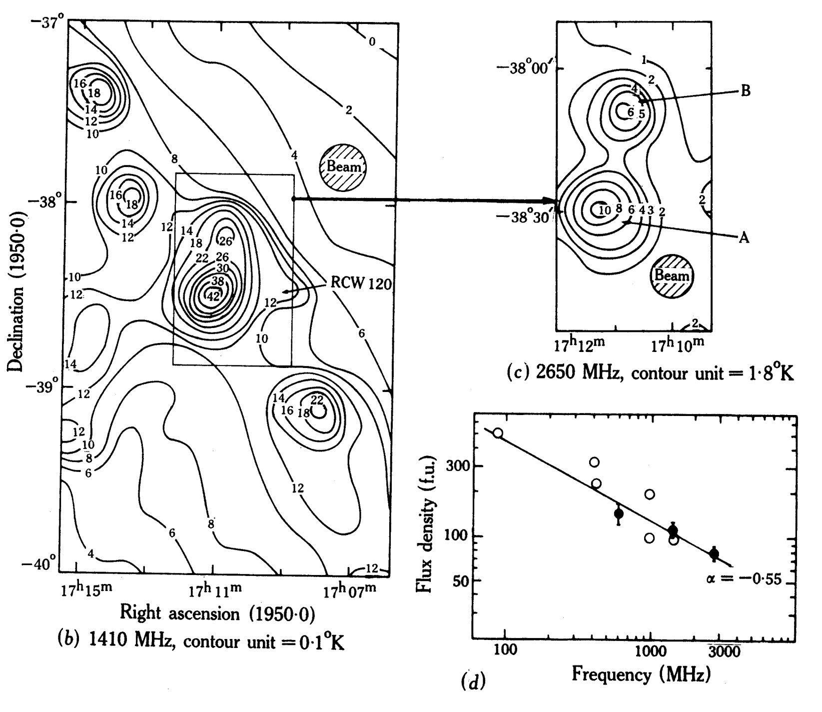
† Peak values have been corrected for angular extent.

Summarizing then, it would appear that CTB 35 is a thermal complex well identified with emission nebulae in this direction. Its interpretation as a supernova remnant does not seem justified.



(*a*) 635 MHz, contour unit = 0·1°K

Fig. 8.—Showing for CTB 37:
(*a*) 635 MHz isotherms,
(*b*) 1410 MHz isotherms,
(*c*) 2650 MHz isotherms,
(*d*) spectrum.



(*b*) 1410 MHz, contour unit = 0·1°K

(*c*) 2650 MHz, contour unit = 1·8°K

(*d*)

(*g*) *CTB 37*

The source CTB 37, proposed by Xi Ze-Zong and Bo Shu-Ren (1965) to be the remnant of the 1203 A.D. supernova, appears with our resolution as a pair of non-thermal sources about 9′ east of the small bright emission nebula RCW 120 (seen in Fig. 8 as a weak extension west of CTB 37A). The Palomar Sky Atlas shows obscuration at the position of CTB 37.

TABLE 8

RADIO DATA FOR CTB 37

Property	Ref.*	Component A	Component B	Component A+B
Position (1950·0)				
R.A.		$17^{h} 11^{m} 15^{s}$	$17^{h} 10^{m} 50^{s}$	$17^{h} 11^{m} 07^{s}$ (2650 MHz
Dec.		$-38°28'·0$	$-38°08'·4$	$-38°21'·0$ centroid)
Angular size				
(min of arc)		$9·2\times8·2$	$6·1\times9·2$	7×24 (at 635 MHz)
Flux density (f.u.)				
86 MHz	4			500
400	2			330
408	1			235 (196 peak)†
635	Present			$143\pm15\%$
960	6			100 (86 peak)
960	5			195 (86 peak)
1410	Present	$74\pm10\%$	$39\pm10\%$	$113\pm10\%$
1440	3			100
2650	Present	$51\pm10\%$	$28\pm10\%$	$79\pm10\%$
Conclusion		Nonthermal, $\alpha = -0·55$	Nonthermal, $\alpha = -0·55$	Nonthermal. Possible physical double, extragalactic

* References are: 1, Komesaroff (1966); 2, McGee, Slee, and Stanley (1955); 3, Mathewson, Healey, and Rome (1962); 4, Mills, Slee, and Hill (1960); 5, Wilson (1963); 6, Wilson and Bolton (1960).

† Komesaroff's peak flux density has been corrected for angular extent.

Whether the two components of CTB 37 are related is not established. They have the same angular size (8′ diameter), the same spectral index (−0·55), a flux ratio of about 2·1, and an angular separation of 20′ (Table 8). It is possible that this source is an extragalactic object of the Fornax A type.

(*h*) *Kepler's Nova*

The supernova of 1604 A.D. has been identified with the radio source MSH 17−*211* for many years. This radio source is only 2′·2 in diameter, so no structure is seen with the resolution available to us. Our measurements therefore consist of estimates of the peak and integrated flux densities, angular size, and position at frequencies of 635, 1410, and 2650 MHz. These results are given in Table 9, together with the flux densities estimated by other observers. We rather feel that Wilson (1963) and Lequeux (1962) may have underestimated the flux density. All the other values lie very close to a power law spectrum with $\alpha = -0·55$ (Fig. 9).

(*i*) *W28*

The nonthermal source W28 is confused at low resolution with the thermal source M20 15′ to the north-east. In our 2650 MHz contours (Fig. 10(*a*)) W28 appears to form the north-eastern edge of a shell source of which the weak source to the south-west (R.A. $17^h 57^m$, Dec. $-28°45'$ (1950)) may be part. A comparison of the radio isotherms with the Palomar Sky Atlas shows that this proposed shell encircles a nebula about 30′ in diameter, having a mottled appearance and with a few filamentary wisps visible. The 2650 MHz peak of W28 is coincident with the most northern of these wisps, and the orientation of this wisp and the extension of the radio source are similar.

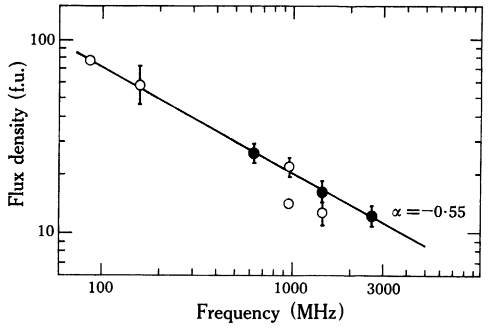


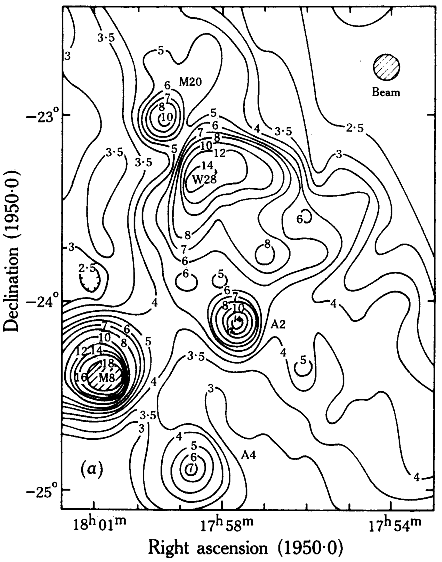
Fig. 9.—Spectrum of Kepler's Nova.

TABLE 9

RADIO DATA FOR KEPLER'S NOVA

Property	Reference	Value
Position (1950·0)		R.A. $17^h 27^m 44^s$, Dec. $-21°27'\cdot 4$
Angular size		$2'\cdot 2$
Flux density (f.u.)		
86 MHz	Mills, Slee, and Hill (1960)	77
159	Edge *et al.* (1958)	$58 \pm 20\%$
635	Present paper	$26 \pm 10\%$ (26 peak)
960	Harris (1962)	$22 \pm 10\%$
960	Wilson (1963)	14 (14 peak)
1410	Present paper	$16 \pm 10\%$ (15·7 peak)
1420	Lequeux (1962)	$12\cdot 7 \pm 12\%$
2650	Present paper	$12\cdot 2 \pm 10\%$ (10·9 peak)
Conclusion	Nonthermal, $\alpha = -0\cdot 55$, supernova remnant	

Until the present investigation, the highest resolution with which this region had been surveyed was 21′ arc at 1410 MHz (Rieu 1963) and we have adopted Rieu's catalogue numbers A2 and A4 for two of the sources. With the improved resolution of our survey it is necessary to modify the angular sizes and hence the integrated flux densities that Rieu gives for each of the thermal sources M20, A2, and A4. The flux densities we so obtain are given in Table 10, together with our measurements. These corrected flux densities agree closely with our estimates, and the thermal nature of these sources is established. We then subtracted the flux density of M20



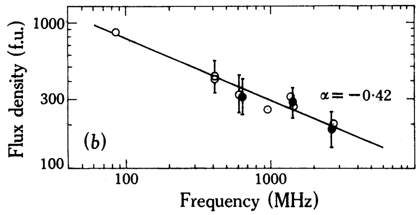


Fig. 10.—Showing for W28:
(*a*) 2650 MHz isotherms (contour unit = 1·0°K),
(*b*) spectrum.

TABLE 10

RADIO DATA FOR SOURCES IN W28 FIELD

Property	Ref.*	W28	M20	A2	A4
Position (1950·0)					
Centroid R.A.		$17^h 57^m 30^s$	$17^h 59^m 20^s$	$17^h 57^m 40^s$	$17^h 58^m 44^s$
Dec.		−23°25′	−23°02′	−24°07′	−24°54′
Peak R.A.		$17^h 58^m 30^s$			
Dec.		−23°20′			
Angular size					
(min of arc)		30 with bright rim on NE. side	5·5×7·5	8·4×7·0	13×18
Flux density (f.u.)					
86 MHz	4	855 (900)†			
408	3	405 (450)†			
408	2	430±20% (475)†			
510	5	325±25% (370)†			
635	Present	315±25% (360)†			40 ±10%
960	8	255 (300)†			
1390	7	315 (360)†			
1410	Present	286±20%	15·8±20%	30·3±20%	34 ±10%
1430	6	270	13 [27]‡	31 [58]‡	35 [38]‡
2650	Present	187±25%	15·6±10%	28·7±10%	32·3±10%
2700	1	206 (251)†			
Conclusion		Nonthermal, $\alpha = -0{\cdot}42$, supernova remnant	HII region		

* References are: 1, Altenhoff *et al.* (1960); 2, Davis, Gelato-Volders, and Westerhout (1965); 3, Large, Mathewson, and Haslam (1961); 4, Mills, Slee, and Hill (1960); 5, Moran (1965); 6, Rieu (1963); 7, Westerhout (1958); 8, Wilson (1963).

† The flux densities given in parentheses include the thermal sources M20 and A2. The total flux of M20 and A2 was estimated from the 1410 and 2650 MHz surveys to be 45 f.u. This was therefore subtracted from each of the published values.

‡ The flux density values published by Rieu (given in square brackets) have been corrected for the source angular extent measured at 2650 MHz.

and A2 from our 635 MHz integrated flux and from the published estimates in which W28 was not resolved from M20 and A2. These results appear in Table 10 and are used to obtain the spectrum of W28 in Figure 10(*b*).

With a spectral index of $-0 \cdot 42$ (Fig. 10(*b*)), a radio structure similar to that of other remnants, and a positive optical identification with a filamentary nebula, W28 is, it would seem, indeed a supernova remnant.

(*j*) *W33*

The source W33 was classified as a supernova remnant by Aizu and Tabara (1967), but our measurements do not confirm the nonthermal spectrum ($\alpha = -0 \cdot 83$) that they derive. The source lies in an observationally difficult position in the galactic plane. It was difficult to separate W33 from the general galactic emission at 635 MHz and we have not drawn isotherms at that frequency. In our 1410 MHz contours, W33 appears as a prominent source connected by a ridge to the emission nebula IC 4701 to the north. At our highest resolution (Fig. 11) this ridge breaks up into several isolated sources and does not confirm the identification of W33 with IC 4701 (Westerhout 1958).

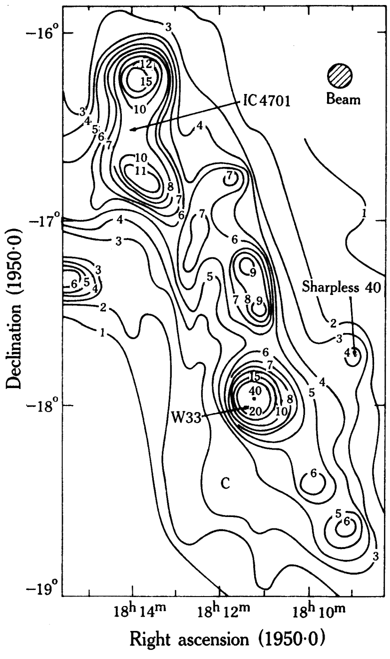


Fig. 11.—Isotherms at 2650 MHz of W33 (contour unit = $0 \cdot 6$°K). The source labelled W33 here is only part of the original Westerhout source, which included the objects to the north-east as far as and including IC 4701.

Because of the high degree of confusion in this region, it has not been possible to compare our estimated flux densities with those obtained by other authors. We feel that the much higher flux densities estimated by these observers are due to their inclusion of varying amounts of the nearby field. This is apparent also in their large estimated diameters for W33. Using our results (Table 11) we suggest that this source is an isolated thermal source having a diameter of 8′ arc and an optically thin flux density of 64 f.u. The Palomar Sky Atlas shows heavy absorption in the direction of W33, and it seems unlikely that W33 is associated with any of the visible features nearby. The discovery of recombination lines in this source (Dieter 1967) supports its classification as an HII region.

Table 11

radio data for W33

Property	Reference	Value
Position (1950·0)		R.A. $18^h 11^m 12^s$, Dec. $-17°57'$
Angular size		$8'$
Flux Density (f.u.)		
635 MHz	Present paper	$66 \pm 30\%$
1410	Present paper	$64 \pm 15\%$
2650	Present paper	$62 \pm 10\%$
Conclusion	HII region	

(*k*) *MSH 18−25*

Pskovskii (1963) proposed MSH 18−25 as the radio remnant of the nova "Sagittarii 1928", which he considered might be a supernova. Our observations (Table 12) show a $25'$ error in the radio position on which this identification was based. The spectrum of this source (Fig. 12) remains nonthermal, but not as steep as Pskovskii deduced from the Mills, Slee, and Hill (1960) and Kellermann and Harris (1960) flux;

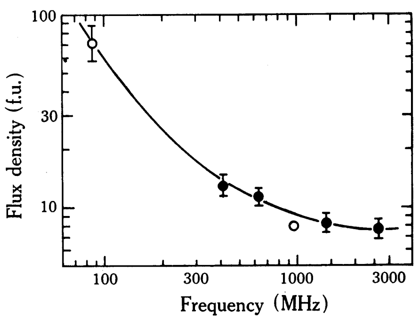


Fig. 12.—Spectrum of MSH 18−25. This is a small angular size nonthermal source together with an extended thermal object.

this latter flux must be corrected for position and extent. The spectrum displays a negative curvature that would be consistent with a thermal source of about 6 f.u. (optically thin at centimetric wavelengths) superimposed on a nonthermal source of steep spectral index ($\alpha \simeq -1\cdot2$); this nonthermal spectrum depends entirely on the 86 MHz flux density. Our surveys indicate that 18−25 has a displaced peak and an angular size that varies with frequency, consistent with the behaviour expected if the object is a nonthermal point source combined with a $15'$ diameter thermal source. We do not consider this object to be a supernova remnant.

(*l*) *CTB 63* (*PKS 1855+16*)

The source CTB 63 was a difficult one to observe; it is of low surface brightness, located on a steep galactic background, and confused with nearby sources. In our 1410 and 635 MHz maps (Figs 13(*a*) and 13(*b*)) we have removed this background and what we think are non-associated field sources. The dominant source in the region has a structure at 1410 MHz resembling some supernova remnants. At 635 MHz this structure is smoothed out considerably, suggesting that if the resolution

TABLE 12

RADIO DATA FOR MSH 18−25

Property	Reference	Value
Position (1950·0)		
2650 MHz, Peak R.A.		$18^h 13^m 49^s$
Dec.		−24°07′
Centroid R.A.		$18^h 14^m 11^s$
Dec.		−24°04′·8
Angular size* (min of arc)		
2650 MHz		19·3×14·5
1410		15·0×14·8
635		2·5×4·6
Flux Density (f.u.)		
86 MHz	Mills, Slee, and Hill (1960)	71 ±20%
408	Present paper	13 ±12%
635	Present paper	11·3±10%
960	Kellermann and Harris (1960)	8†
1410	Present paper	8·35±10%
2650	Present paper	7·75±10%
Conclusion	Composite source, nonthermal point source, together with HII region	

* The angular size was difficult to measure at 408 MHz; the source lies on a steep galactic background at this frequency. It was thought, however, that the 408 MHz beam was unbroadened.

† This value has been corrected for positional error and angular size.

were further reduced an apparent source diameter of 1° would be obtained. The source was not found at 2650 MHz. Its disappearance at this frequency is to be expected from an extrapolation of the 1410 MHz brightness temperatures even with a thermal spectral index.

Comparison of our results with previously published data (Table 13) is extremely difficult. The integrated flux densities at 400 MHz (Davis, Gelato-Volders, and Westerhout 1965) and 960 MHz (Wilson 1963) are both a factor of 10 higher than would be expected from our measurements. These flux densities could be reduced to within a factor of 3 of our results if an angular diameter of 1° is adopted as a correction to the published peak flux densities. This diameter is much smaller than that obtained by Wilson (1963) or Davis, Gelato-Volders, and Westerhout (1965).

It may be that we have neglected part of CTB 63; there is a weak extended source centred on $19^h 04^m$, +15°30′ (1967·0) visible in our 635 MHz scans but it is well separated from the source shown in Figure 13(*a*). Furthermore, there are also several weak small-diameter sources nearby that would be included in the large diameters quoted above. Inclusion of these sources could increase our flux density by only a small factor. Because of the possibility that CTB 63 includes more than just the dominant feature in this region, we propose that the object described here and shown in Figure 13 be referred to as PKS 1855+16.

We are not prepared on the evidence presented to say whether this source is nonthermal or whether it might be, as Aizu and Tabara (1967) suggest, a supernova remnant. We must point out, however, that there is no justification for the spectral index (—0·34) estimated by Aizu and Tabara from the published 400 and 960 MHz flux densities.

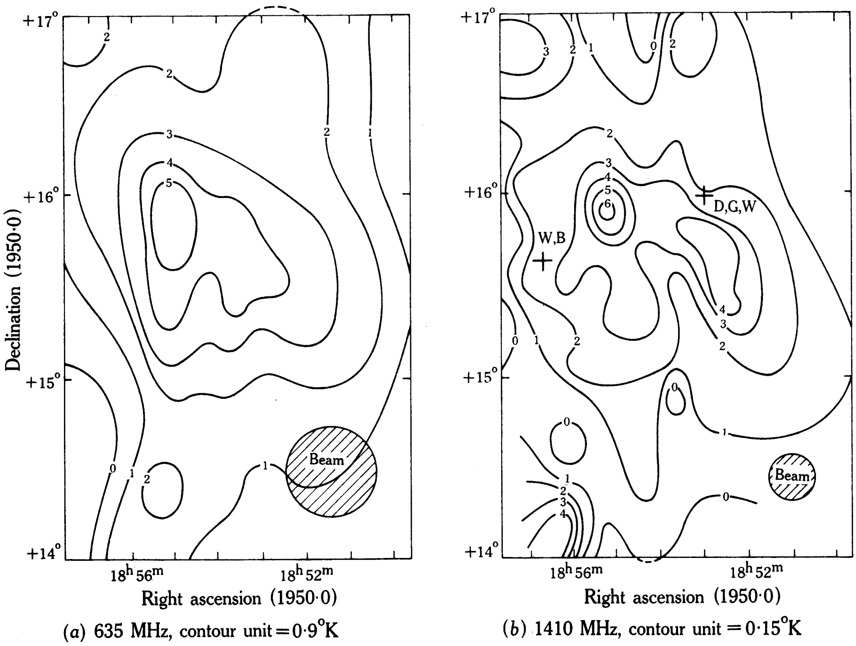


Fig. 13.—Isotherms of CTB 63 (PKS 1855+16) at (a) 635 and (b) 1410 MHz. In (b) are indicated the positions given for CTB 63 by Wilson and Bolton (1960) and Davis, Gelato-Volders, and Westerhout (1965).

TABLE 13
RADIO DATA FOR CTB 63 (PKS 1855+16)
N.A. = not applicable

Freq. (MHz)	Ref.*		Position (1950·0) R.A. h	m	s	Dec. °	′	Angular Size (deg.)	Flux Density (f.u.) Peak	Integ.	Integ. Flux if Angular Size = 1°
400	1		18	52	48	+16	00	3×4	55±30%	170	68
635	Present		18	54		+15	45	1	4·7	14±30%	N.A.
960	3		18	56	24	+15	37	1·5	14	60	37
960	2		18	56	24	+15	37	2·5	14	150	37
1410	Present	Peak	18	55	05	+15	54	—	1·2	11·5	N.A.
		Centroid	18	54		+15	45				

* References are: 1, Davis, Gelato-Volders, and Westerhout (1965); 2, Wilson (1963); 3, Wilson and Bolton (1960).

(m) *3C 396·1*

The source 3C 396·1, which Aizu and Tabara (1967) classify as a type II supernova remnant, lies on a fairly steep galactic background slope in a region confused with nearby sources at 635 MHz. We have not constructed any isotherms of this source nor could we find any evidence of it at 2650 MHz with the Mk I receiver.

However, we have obtained a peak deflection of 0·16 f.u. with the Mk II 2700 MHz receiver. The angular size determined from a Gaussian fit is 51′ by 81′ at 635 MHz and 61′ by 73′ at 1410 MHz. These values are self-consistent, and agree with the

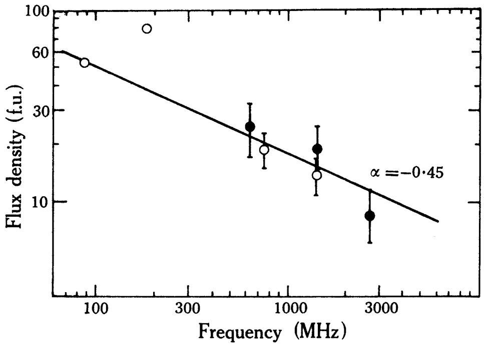


Fig. 14.—Spectrum of 3C 396·1.

2700 MHz estimate, but are much higher than have been obtained by Bennett (1963) (35′×10′) and Pauliny-Toth, Wade, and Heeschen (1966) (48′). Influenced by these lower values, but still biased towards our own, we have adopted an angular diameter of 60′±15′ for 3C 396·1. This is also the diameter implied by the correction for extent in the MSH catalogue (Mills, Slee, and Hill 1960). The flux densities in Table 14 have been corrected, where necessary, for an angular diameter of 60′.

Table 14

RADIO DATA FOR 3C 396·1

Freq. (MHz)	Ref.*	Position (1950·0) R.A. h m s	Dec. ° ′	Angular Size (min of arc)	Flux Density (f.u.) Peak	Integ.	Integ. Flux if Angular Size = 60′
86	2	19 04 12	−03 06	60	34	53	53
178	1	19 04 30	−03 12	35		30±8%	80
635	Present			51×81	6·6		25±30%
750	3					12·6±25%	19±25%
1400	3	19 04 18	−03 06	48		9·2±25%	14±25%
1410	Present	19 04 32	−03 06·5	61×73	1·18		19±30%
2700	Present			60	0·16		8·6±30%
Conclusion		Nonthermal, α = −0·4, probable supernova remnant					

* References are: 1, Bennett (1963); 2, Mills, Slee, and Hill (1958); 3, Pauliny-Toth, Wade, and Heeschen (1966).

With an angular size of 60′ and a spectral index of −0·45 (Fig. 14) (or even more negative if the angular size is reduced), the supernova origin of this source is fairly certain. There is high optical absorption in this direction.

(*n*) *W49B*

Much has been written lately about the nonthermal source W49B and its nearby thermal companion W49A. With a separation of 13′ and angular diameters of 5′·5 and 3′·0 for both sources they are just resolved in our 2650 MHz beam. The positions obtained at this frequency are very close to those measured by the authors

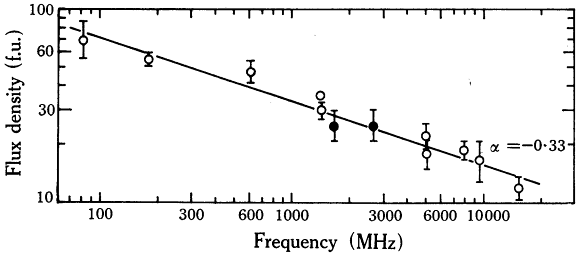


Fig. 15.—Spectrum of W49B.

TABLE 15

RADIO DATA FOR W49

Property	Ref.*	Component A	Component B	A+B
Position (1950·0)				
2650 MHz, R.A.		$19^h 07^m 46^s$	$19^h 08^m 39^s$	
Dec.		$+09°00'·6$	$+09°00'·5$	
Angular size (min of arc)		$5·4\times3·5$	$5·4\times3·0$	
Flux density (f.u.)				
81·5 MHz	6		69 ±20%†	69 ±20%†
178	1		55 ±6%†	55 ±6%†
611	4	39 ±10%	48 ±13%	87 ±12%
635	Present			97·5±10%
1400	5	51‡	36‡	87·6±5%
1410	Present			85 ±10%
1414	4	44 ±10%	30 ±10%	74 ±10%
1660	Present	52 ±20%§	25 ±20%§	77·3±10%
2650	Present	54 ±10%	25 ±20%	79 ±15%
5007	3	57·7±12%	22·1±14%	79·8±13%
5007	4	59·8±10%	17·9±17%	77·7±10%
7830	2	64·5±9%	18·9±9%	83·4±9%
9400	7	71 ±20%	16 ±25%	87 ±20%
15375	4	59 ±7%	12 ±14%	71 ±8%
Conclusion		Thermal HII region	Nonthermal, $\alpha = -0·33$, probable supernova remnant	

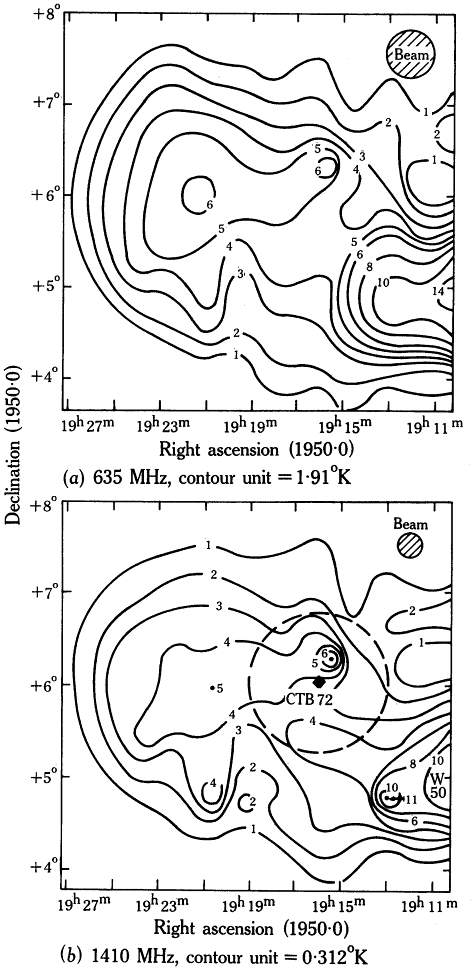
* References are: 1, Bennett (1962); 2, Burke and Wilson (1967); 3, Mezger and Henderson (1967); 4, Mezger, Schraml, and Terzian (1967); 5, Pauliny-Toth, Wade, and Heeschen (1966); 6, Shakeshaft *et al.* (1955); 7, Yamashita and Watanabe (1968).

† The source would be entirely nonthermal at these frequencies.

‡ The published peak flux densities have been corrected for angular size.

§ These values are derived from a two-component model based on the 2650 MHz positions and angular sizes.

quoted in Table 15, and we have used our positions and angular sizes to fit a two-source model to the 1660 MHz scans. The flux densities for each component arrived at in this way are given in Table 15. In this table we quote only our measurements and those published flux densities for W49 where the two components have been separated. The spectrum of W49B deduced from these data is shown in Figure 15;



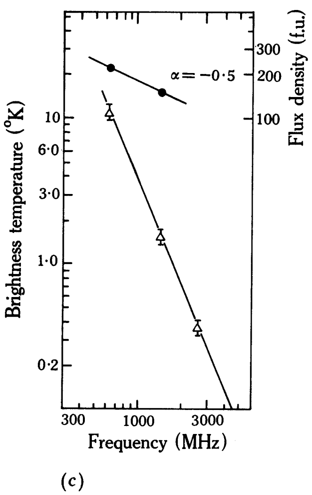


Fig. 16.—Showing for CTB 72 (PKS 1920+06):

(a) 635 MHz isotherms,

(b) 1410 MHz isotherms,

(c) spectrum in both integrated flux and brightness temperature.

The position and size originally given for this object (Wilson 1963) are indicated in (b).

a power law spectrum of $\alpha = -0\cdot33$ is indicated. From these data we see no apparent justification for the departure from a simple power law spectrum as was suggested by Mezger, Schraml, and Terzian (1967).

At the suggested distance of 14 kpc (Sato, Akabane, and Kerr 1967) and with an angular size of $5'\cdot4$ by $3'\cdot0$, W49B would have a physical size 23 by 14 pc, which is acceptable for a supernova remnant. The spectral index is typical of these objects and is not as steeply nonthermal as is usual for an extragalactic source. There is heavy optical obscuration in this direction. We accept W49B as a probable supernova remnant.

(o) *CTB 72* (*PKS 1920+06*)

It would appear from our contours (Figs 16(a) and 16(b)) that CTB 72 is only the western extremity of a much larger object. The Caltech result was probably influenced by a small diameter (4′) source located near the CTB position. It is therefore difficult to relate our flux estimates to the CTB value (Wilson and Bolton 1960; Wilson 1963). The contour maps at 635 and 1410 MHz (Figs 16(*a*) and 16(*b*)) have been drawn with the galactic background removed. The integrated flux densities (Table 16) include the sources at R.A. $19^{h}20^{m}40^{s}$, Dec. $+04°50'$ and $19^{h}15^{m}30^{s}$, $+16°10'$. The flux of this latter source is also given separately in Table 16; its spectrum is steeply nonthermal with $\alpha = -1\cdot0$. Only a few scans through this region were made at 2700 MHz (Mk II receiver), and the integrated flux could not be reliably estimated. The peak brightness temperature at 2700 MHz was $0\cdot365°$K; using this value, together with the temperatures given by the isotherms of Figures 16(*a*) and 16(*b*), we derive an average brightness spectral index of $-2\cdot4$ (Fig. 16(*c*)). This is consistent with the flux spectral index ($\alpha = -0\cdot5$) indicated in the same figure. There are no optical features visible in this direction; the Palomar Sky Atlas shows considerable absorption here.

Table 16
Radio data for CTB 72 (PKS 1920+06)

Property	Reference	Small Diam. Component (PKS 1915+06)	Large Diam. Component (PKS 1920+06)
Position (1950·0)			
R.A.		$19^{h}15^{m}30^{s}$	$19^{h}20^{m}$
Dec.		$+06°10'$	$+06°$
Angular size (min of arc)		4×4	150×100
Flux density (f.u.)			
635 MHz	Present paper	$4\cdot8\ \pm15\%$	$225\pm25\%$
960	Wilson (1963)		80
1410	Present paper	$2\cdot15\pm10\%$	$150\pm25\%$
2700	Present paper	$1\cdot06\pm15\%$	$83\pm40\%$
Conclusion		Nonthermal, $\alpha = -0\cdot5$	Probable supernova remnant

The large angular size of this object (150′ by 100′) and its nonthermal spectrum admit it to the supernova remnant classification. We must remark, however, on the vague premise on which the source was originally classified (Aizu and Tabara 1967) and we suggest, with the discrepancies between this source and CTB 72, that the source that we classify as a remnant be known as PKS 1920+06.

V. Conclusions

We have now examined 16 sources, each of which has been suggested to be a supernova remnant. Of these 16 we agree that IC 443, Puppis A, Kepler's Nova, and W28 are supernova remnants, and that W49B, 3C 396·1, CTB 72, the Monoceros Nebula, and a nonthermal source near S34 are probable supernova remnants. Three sources (CTB 35, W33, and S34) were found to have thermal spectra and are consequently unlikely to be supernova remnants. The nonthermal spectra of CTB 37, 13S6A, and 18−25 are confirmed, but we feel that they are extragalactic objects.

Of CTB 63 (PKS 1920+06) we are uncertain; the object mapped by us has a structure similar to that of supernova remnants but the spectrum is not sufficiently well established to justify its inclusion as a supernova remnant at this stage.

This investigation was undertaken primarily to improve the data available for some of the suggested supernova remnants. It is hoped that with improved data it will be possible to derive a distance indicator along the lines suggested by Shklovsky (1960), Harris (1962), Aizu and Tabara (1967), or more recently by Poveda and Woltjer (1968).

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