# SUPERNOVA REMNANTS AS RADIO SOURCES

By M. J. L. Kesteven*

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*Summary*

The results of a survey with the 1 mile Molonglo cross-type radio telescope of nonthermal galactic sources are discussed in terms of supernova remnant theories. The contour maps obtained indicate that most sources are consistent with a portion of a shell of emission. The results suggest that a remnant's spectral index is independent of its age. A supernova remnant evolutionary path is also derived, and compared with the path predicted by the various theories.

## I. Introduction

Surveys of the galactic plane at radio frequencies reveal sources of two types, the basis for classification being the spectral index. On various grounds, the sources with a nonthermal index are generally thought to be remnants of supernova outbursts. For example, sources have been found at the sites of three observed supernovae: Taurus A, Tycho's nova, and Kepler's nova. Further, gas filaments consistent with a supernova outburst have been found at the positions of some radio sources: Cassiopeia A, Cygnus Loop, IC 443 (Minkowski 1959), and RCW 86 (Westerlund and Mathewson 1966). Several theories have been proposed relating a radio source to the gaseous remnant (Shklovskii 1960*a*; Van der Laan 1962). There have been few opportunities, however, for testing these theories: the most direct tests require that the distance to the source be known. This is so for a small number of sources only. Statistical tests have been of little use as each of the low resolution surveys available contained too few sources, and the ensemble of surveys failed to form a statistically homogeneous sample. It was hoped that the catalogue described in a previous paper (Kesteven 1968) would permit a fresh approach to the problem. Four questions are tackled in the present paper. The first relates to the type of supernova; it will be shown that the distribution of the sources is similar to the distribution of population I objects, suggesting that the sources are remnants of type II supernovae. Secondly, the morphology of the sources is examined; it will be shown that few sources have the circularly symmetric structure characteristic of the complete shell of emission assumed by the theories. The majority of the sources are consistent, however, with a fraction of a shell. Thirdly, the evolution of the radiation spectral index is examined. Analyses of the loss mechanisms that affect the radiation spectrum indicate that the spectral index should be independent of the age of the source. The present results confirm this, in contrast to the findings of Harris (1962) and Pskovskii (1963). Finally, the evolution of the radiated power is examined. This could be a sensitive test of the various theories, but the errors associated with the present set of observations are too large for the conclusions to be of great significance.

* Cornell–Sydney University Astronomy Centre, School of Physics, University of Sydney, N.S.W. 2006.

## II. Galactic Distribution of the Sources

The galactic distribution of the sources of the catalogue indicates that they are associated with population I objects; both the thermal and nonthermal sources lie close to the galactic plane. The mean absolute latitude of $0°\cdot 8$ is consistent with the value noted by other observers: Large, Mathewson, and Haslam (1961), for example, found $|b^{\mathrm{II}}| = 0°\cdot 3$. The distribution in longitude is equally consistent with a population I distribution, as the sources show a "bunching" suggesting a spiral arm structure. The number of sources is too small to determine the location of the arms with precision, but the peaks in the source distribution agree with the "tangential points" noted by other observers (Mills 1959; Elsasser and Haug 1960; Kerr 1962; Mathewson, Healey, and Rome 1962). The source distribution is shown in Figure 1 along with the tangential points of Mills.

It appears then that the nonthermal sources are remnants of type II supernovae (if indeed they are supernova remnants).

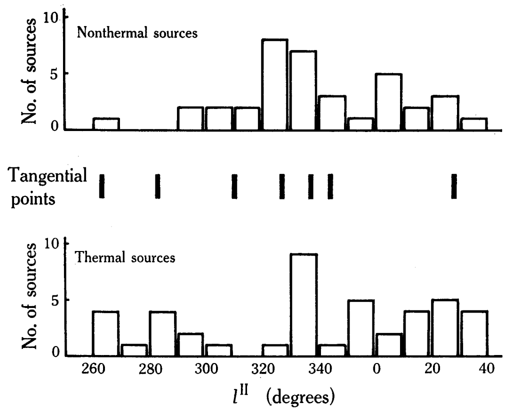
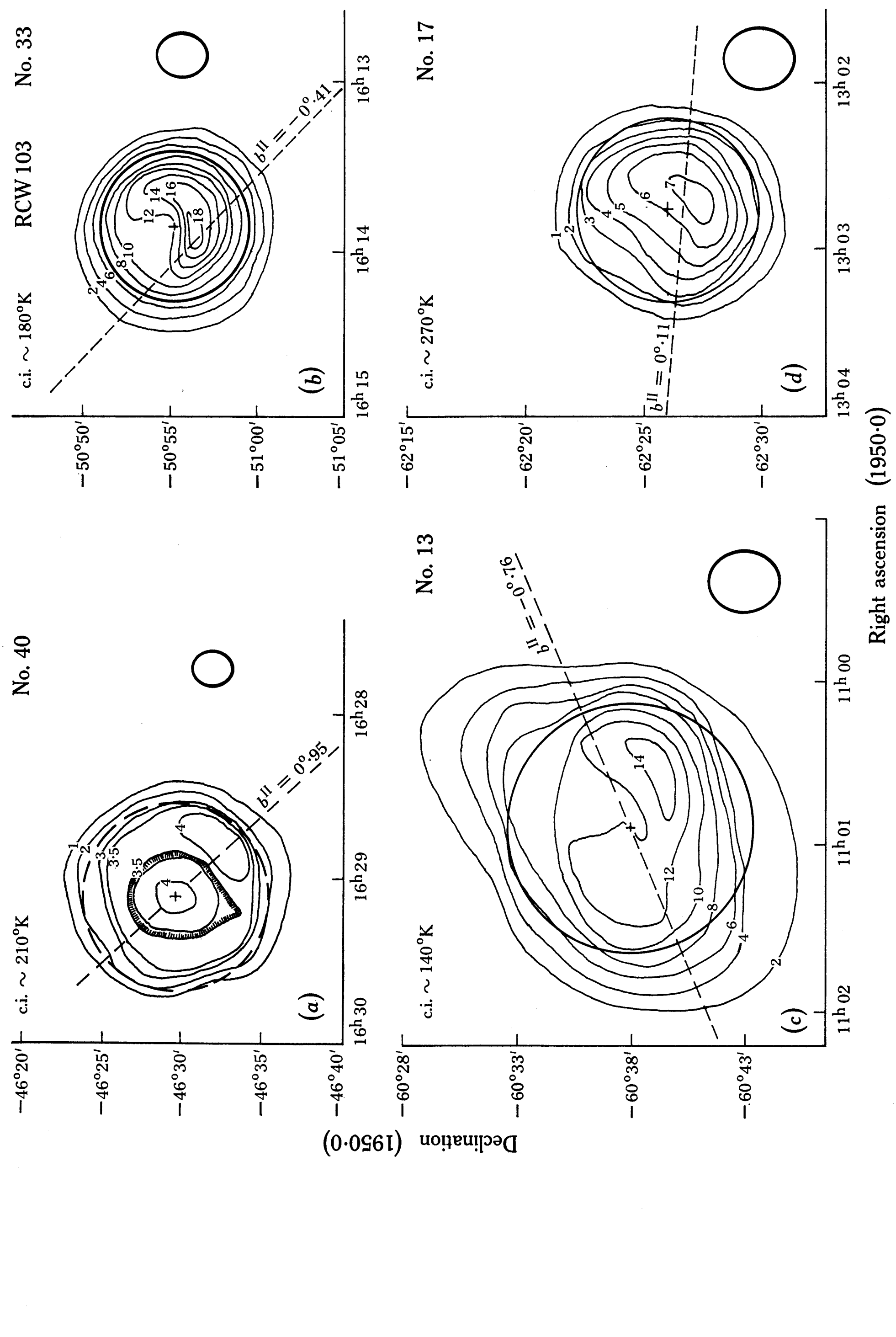



Fig. 1.—Distribution in galactic longitude $l^{\mathrm{II}}$ of the sources of the catalogue.

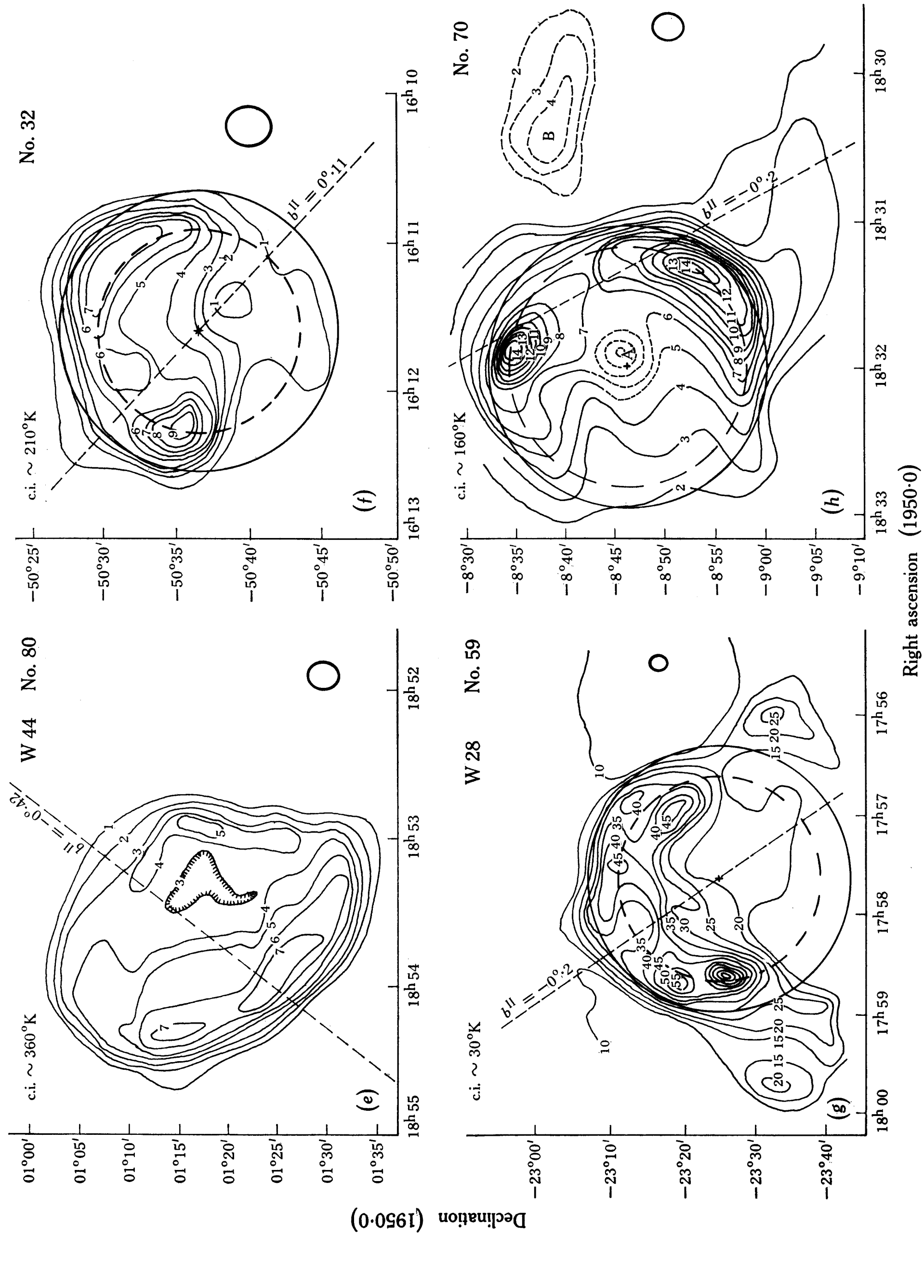
## III. Source Contour Diagrams

Both theories of the supernova remnant assume the radio source to be associated with an expanding shell of plasma ejected by the outburst. In Shklovskii's theory the source is embedded in the shell; in Van der Laan's theory the source is situated in the region between the shell and the associated shock front. In addition, both theories assume the shell to be complete. Nineteen of the nonthermal sources are large enough to be resolved by the pencil beam of the cross-type telescope of the Molonglo Observatory. It could be hoped that an examination of the contours might decide between these two theories. Further, it should be possible to determine from the contours the nature of the shell, in the manner described by Hill (1967).

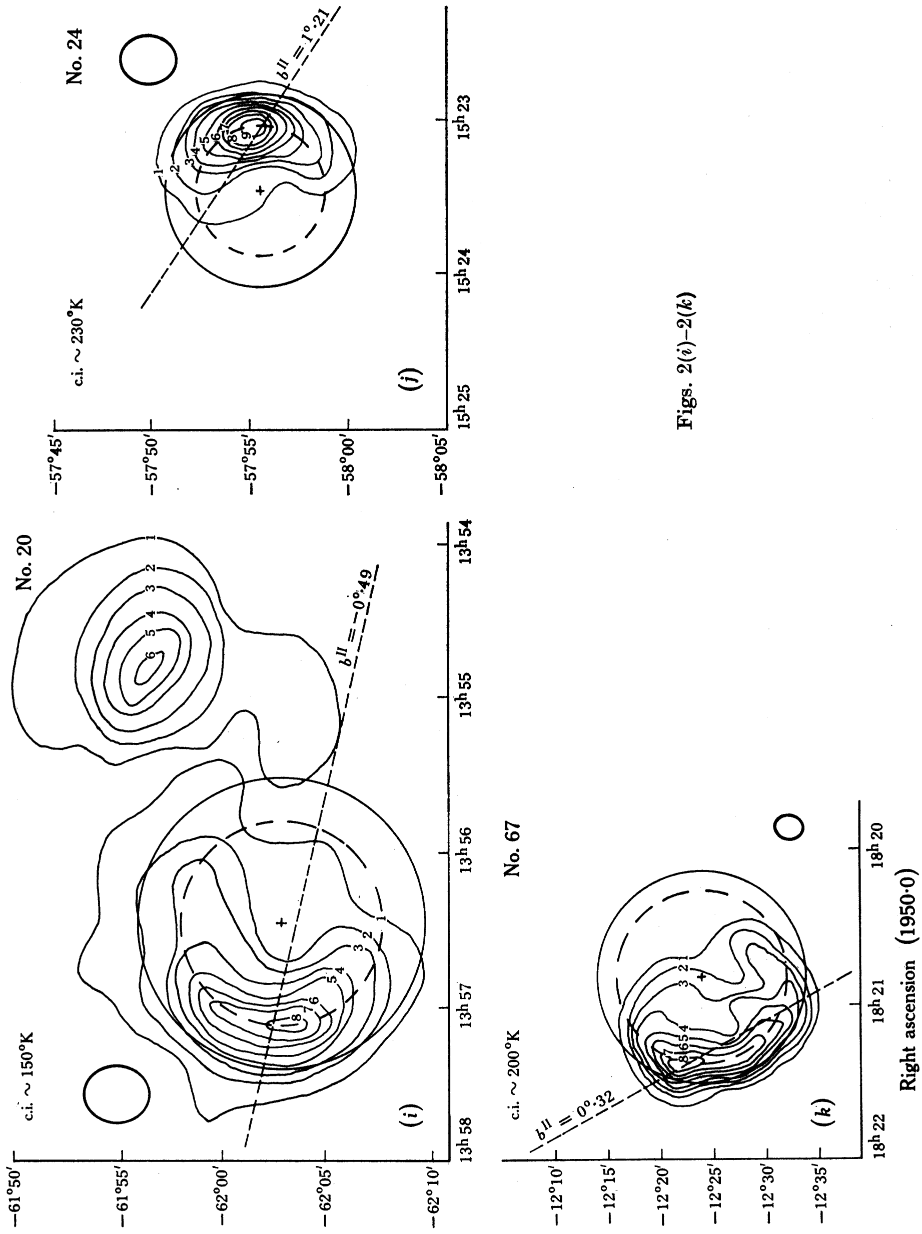
Figs. 2(*a*)–2(*r*).—The 408 MHz isophotes of the 19 largest nonthermal sources of the catalogue. In each figure the contour interval (c.i.) is shown and the solid circle is an estimate of the outer radius of the supernova shell.


(a)
c.i. ~ 210°K
No. 40
$b^{II} = 0°.95$
−46°20′
−46°25′
−46°30′
−46°35′
−46°40′
16h30
16h29
16h28
(b)
c.i. ~ 180°K
RCW 103
No. 33
$b^{II} = -0°.41$
−50°50′
−50°55′
−51°00′
−51°05′
16h15
16h14
16h13
(c)
c.i. ~ 140°K
No. 13
$b^{II} = -0°.76$
−60°28′
−60°33′
−60°38′
−60°43′
11h02
11h01
11h00
(d)
c.i. ~ 270°K
No. 17
$b^{II} = 0°.11$
−62°15′
−62°20′
−62°25′
−62°30′
13h04
13h03
13h02
Declination (1950·0)
Right ascension (1950·0)

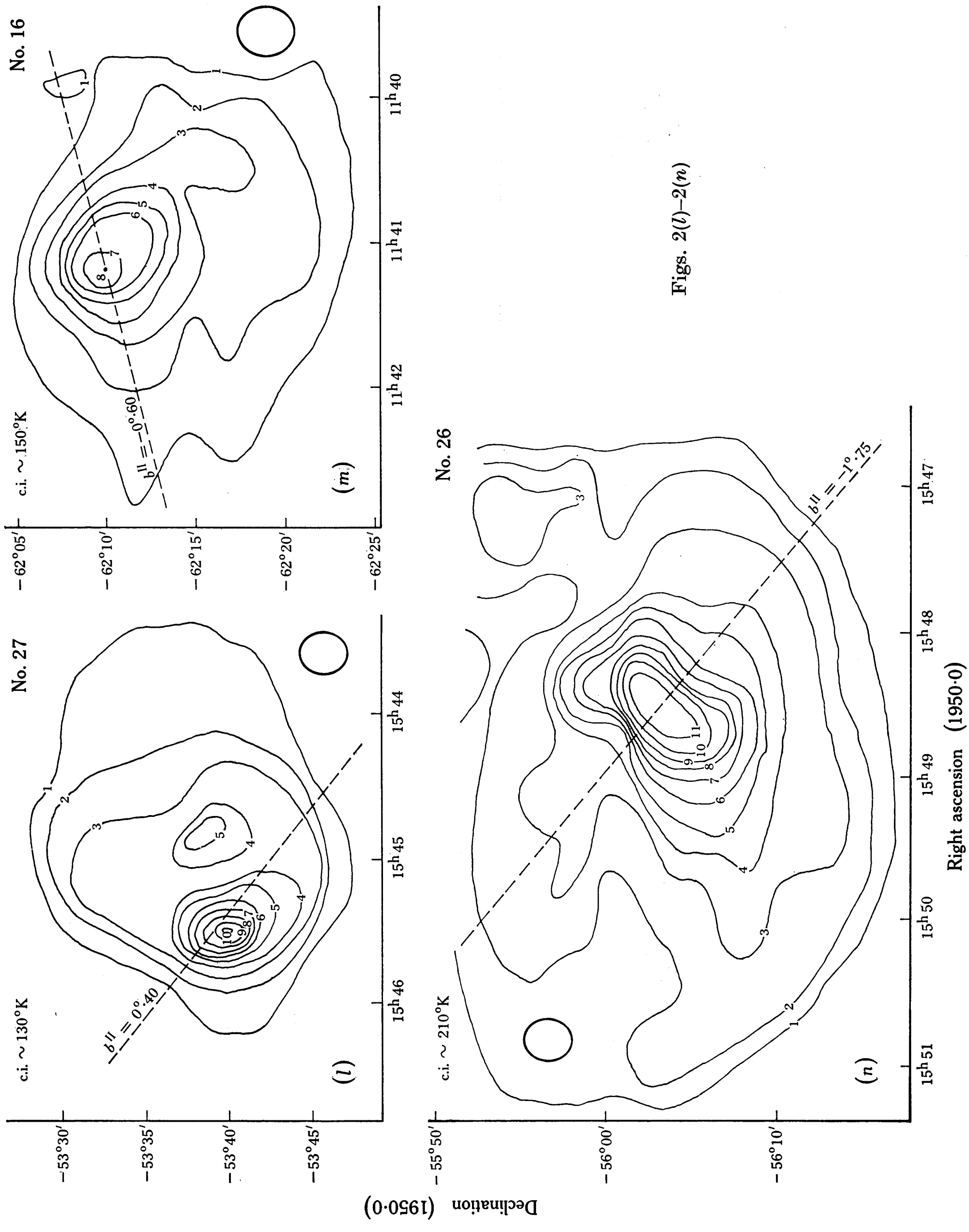
Figs. 2(a)–2(d)


W 44 No. 80
c.i. ~ 360°K
(e)
No. 32
c.i. ~ 210°K
(f)
W 28 No. 59
c.i. ~ 30°K
(g)
No. 70
c.i. ~ 160°K
(h)
Right ascension (1950·0)
Declination (1950·0)

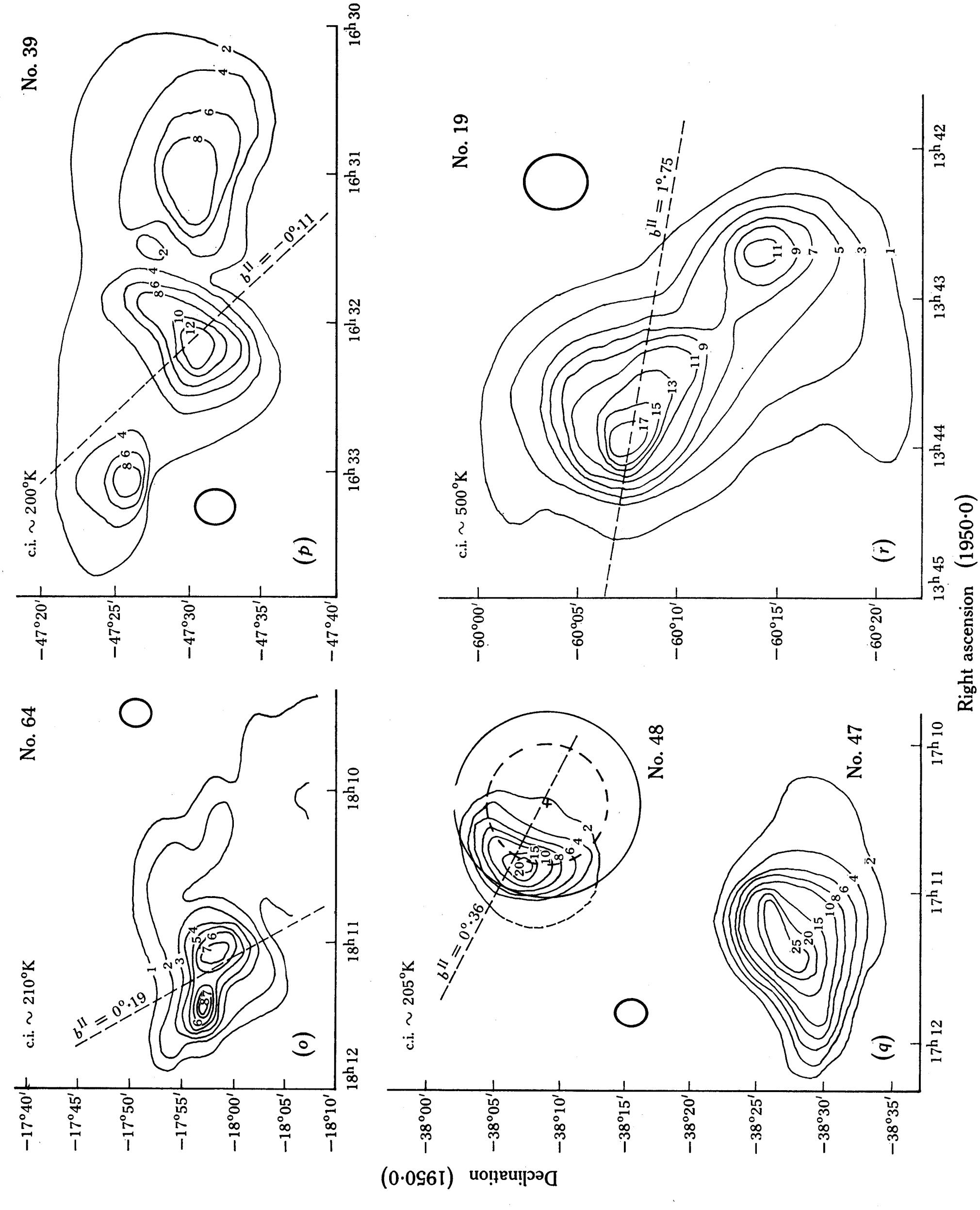
Figs. 2(e)–2(h)


No. 20
c.i. ~ 150°K
(i)
$b^{II} = -0°.49$
No. 24
c.i. ~ 230°K
(j)
$b^{II} = 1°.21$
No. 67
c.i. ~ 200°K
(k)
$b^{II} = 0°.32$
Declination (1950·0)
Right ascension (1950·0)
−61°50′
−61°55′
−62°00′
−62°05′
−62°10′
13h 58
13h 57
13h 56
13h 55
13h 54
−57°45′
−57°50′
−57°55′
−58°00′
−58°05′
15h 25
15h 24
15h 23
−12°10′
−12°15′
−12°20′
−12°25′
−12°30′
−12°35′
18h 22
18h 21
18h 20

Figs. 2(i)–2(k)


No. 27
c.i. ~ 130°K
(l)
$b^{II} = 0°.40$
No. 16
c.i. ~ 150°K
(m)
$b^{II} = -0°.60$
No. 26
c.i. ~ 210°K
(n)
$b^{II} = -1°.75$
Declination (1950·0)
Right ascension (1950·0)

Figs. 2(l)–2(n)


No. 64
c.i. ~ 210°K
(o)
No. 39
c.i. ~ 200°K
(p)
No. 48
No. 47
c.i. ~ 205°K
(q)
No. 19
c.i. ~ 500°K
(r)
Right ascension (1950·0)
Declination (1950·0)

Figs. 2(o)–2(r)

The contours are shown in Figures 2(*a*)–2(*r*). It is clear that few sources can be described as shells of emission. Two classes of sources can be distinguished:

(*a*) The sources of this group (Figs. 2(*a*)–2(*k*)) are consistent with a shell of emission, or at least a fraction of a shell.

(*b*) The sources of this group (Figs. 2(*l*)–2(*r*)) are amorphous masses, about which little can be said.

### *Class* (*a*) *Sources*

Since the majority of the sources of this group show only a fraction of a shell, it is pertinent to enquire whether this is an evolutionary effect. Although there is no way, at present, of measuring the age of a source, it appears (on the basis of the two theories) that the brightness is a reasonable measure.

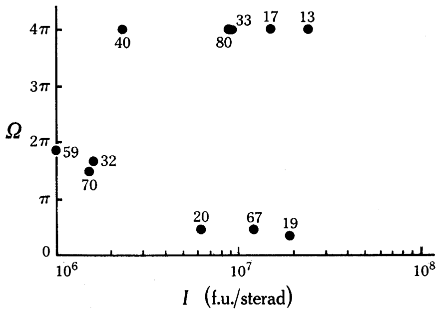
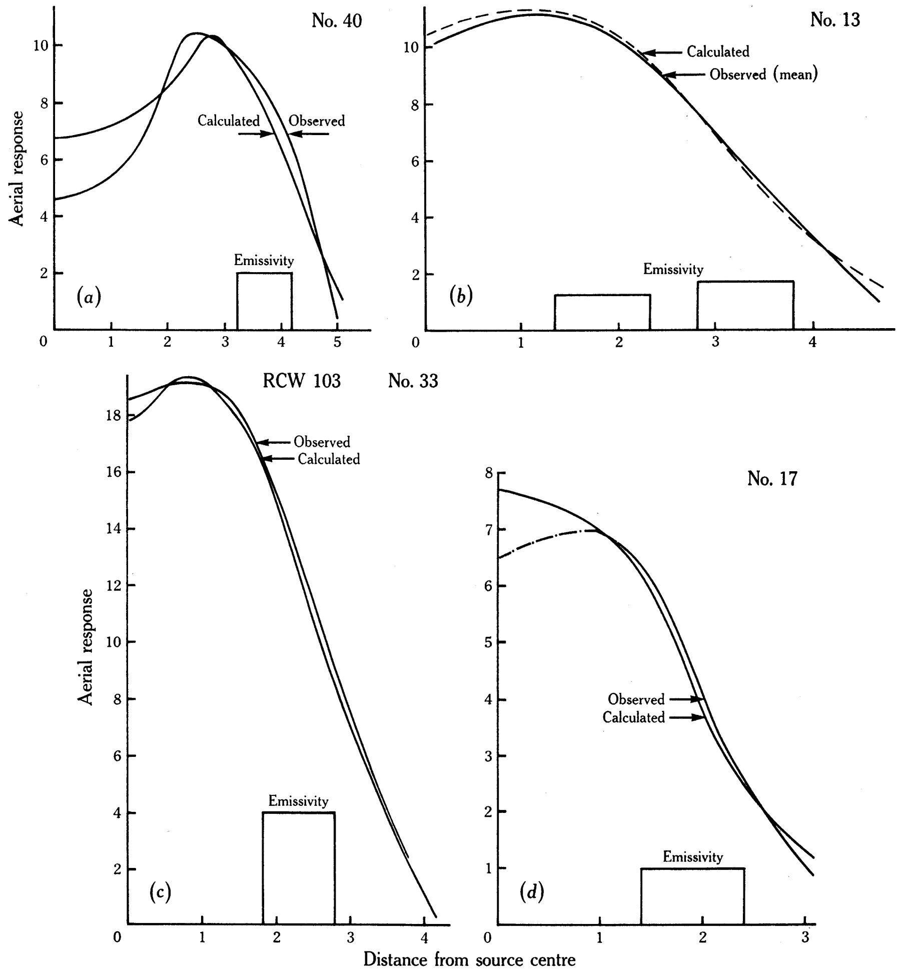



Fig. 3.—Plot of the class (*a*) sources of the catalogue, showing source brightness $I$ versus the solid angle $\Omega$ subtended (at the site of the outburst) by the region of emission.

An estimate was made of the degree to which the shell is filled. A circle was drawn approximately concentric with the ridge of emission. The centre of the circle was taken as the site of the outburst. The solid angle subtended by the shell at the centre was then calculated, on the assumption that the shell was symmetrically disposed about a line, perpendicular to the line of sight, joining the centre of the circle to the centroid of the emission. In Figure 3 the solid angle for each source has been plotted as a function of its brightness. It is clear that no evolutionary trend is present, which suggests that the degree of completeness of the shell is determined by the outburst and not by the subsequent interaction with the interstellar medium.

This conclusion is supported by the observation that, of the previously reported complete shell sources, one, Cassiopeia A, exceeds in brightness all the sources of the catalogue, whilst three others, HB 21, PKS 1439—62, and PKS 0902—38, are weaker in brightness.

Four sources were analysed with the aid of the table prepared by Hill (1967) to determine the shell parameters; the aerial response measured along a radius was compared with the predicted response of the aerial to a shell of emission. The sources analysed are numbers 40, 33, 13, and 17 of the catalogue (Figs. 2(*a*)–2(*d*)). The results are shown in Figure 4. In each case there is reasonable agreement between the predicted and the observed responses. The analysis indicates that for source number 13 the emission occurs in two shells; but since the observed response is in fact an average taken around the source, the particular values for the emissivity should be treated with caution. This source could have been analysed as an ellipsoid, in the manner described by Crowther (1966), but it is doubtful whether a significantly better fit to the observations would have been achieved.




Figs. 4(*a*)–4(*d*).—Calculated radial response of the aerial to a shell of emission compared with the observed response. The unit of distance is half the half-power beamwidth. The radial dependence of the volume emissivity is also shown.

It will be noted that in the case of number 40, the central response is substantially less than the predicted value. (The analysis was in terms of shells of emission whose thicknesses were half the half-power beamwidth; analysis with shells of smaller thickness will not significantly alter this result.) Since this source has a fair degree of circular symmetry, it is pertinent to enquire whether an explanation for the low central value can be found which is independent of the line of sight. Absorption in the interior of the source would give a low central value, but this is unlikely to be the explanation for No. 40; the temperature of the gas ejected by the outburst would have to be less than $10^3$ °K, the brightness temperature of the radiation. A low central value would result if the radiation were emitted preferentially tangentially to the surface of the shell. On the assumption that the radiation is due to the synchrotron mechanism, this would indicate a radial magnetic field, which implies a magnetic monopole. In this context, however, it is of interest to note that Mayer and Hollinger (1967) found polarization in Cassiopeia A that is consistent with a radial field. However, the magnitude of the polarization is small ($\sim 4 \cdot 5\%$) and would be inadequate to explain the observations of number 40. High resolution polarization observations would clearly be of great value in elucidating this source. It appears, however, that the symmetry requirements will have to be relaxed.

A partial shell symmetrically disposed about the line of sight would give a low central value. In view of the relatively large number of partial shells observed, this seems the most likely explanation.

W44 is clearly consistent with a shell emission, but no analysis was attempted in view of the large east–west asymmetry. For similar reasons of asymmetry, no analysis was made on the remaining sources of group (*a*). However, by analogy with the analysis presented, an estimate was made of the outer radius of the shell. This radius is indicated in Figures 2(*a*)–2(*k*).

### *Class* (*b*) *Sources*

These sources show little evidence of a shell structure; the general appearance is one of a peak embedded in a broad region of low brightness. The question arises as to whether perhaps some of these sources are extragalactic. An extrapolation of source counts from high latitude surveys indicates that 3 extragalactic sources should be found by chance in the present set of 19 sources. Three sources are particularly noteworthy: number 19 (MSH 13−6*2*) and numbers 47 and 48 (MSH 17−6*3*).

*Number 19* (Fig. 2(*r*)).—In appearance this source is strongly suggestive of an extragalactic source. In addition, neutral hydrogen-line absorption measurements suggest that this source lies beyond the solar distance from the galactic centre (Radhakrishnan, personal communication).

*Numbers 47 and 48* (Fig. 2(*q*)).—Individually, each source could be a supernova remnant, but the close proximity of the two brightest sources of the catalogue must suggest that the sources are in some way associated, and that they also are components of an extragalactic source.

### *Search for Optical Features*

A search was made of the optical fields of the 19 sources. Only in 1 case were optical features found. As indicated by Beard (1966) number 33 is in good agreement with the object RCW 103. The field, from an enlargement of an Uppsala Schmidt plate provided by Dr. G. Lynga, is shown in Figure 5. It will be noted that the filaments are in good agreement with the projection of the shell determined from the isophotes.

In addition to a search for gas filaments, a particular effort was made in the case of the sources 19, 47, and 48. A search along the major axis failed to reveal, in either case, any object of note. In particular, there was no evidence of a galaxy in the field. This was not unexpected, however, in view of the obscuration in the plane of the galactic disk.

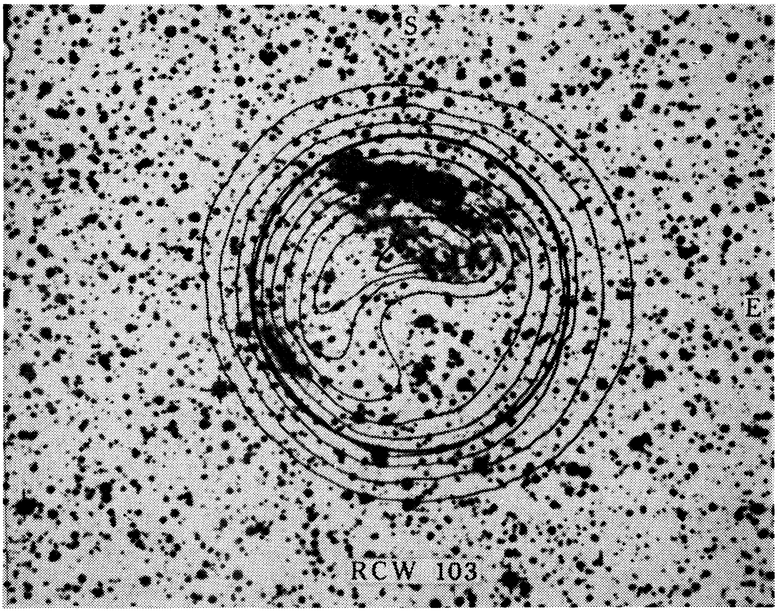



Fig. 5.—Field of the source RCW 103 (number 33 of the catalogue). The radio isophotes are also shown.

## IV. Evolution of Spectral Index

Analyses by Kardashev (1963) and by de la Beaujardière (1966) of the loss mechanisms likely to be present in a supernova remnant indicate that the spectral index of the radiation is unlikely to evolve. Under some extreme conditions, however, the spectral index could steepen, in the sense of becoming more nonthermal. This result is in direct contrast to the findings of Harris (1962) and Pskovskii (1963), which indicate that the index flattens as the source ages. If this latter result were confirmed, it would indicate that either the conditions in the remnant differ substantially from the current estimates, or that the sources are not supernova remnants. In view of these consequences, the question was re-examined.

Estimates of the spectral index are available for 30 nonthermal sources of the catalogue. In addition, data have been published on a further 28. In Figure 6 the indices have been plotted as a function of the source brightness. There is little indication of an evolutionary trend. The mean of the low brightness sources is $-0 \cdot 44 \pm 0 \cdot 04$, and that of the high brightness sources is $-0 \cdot 52 \pm 0 \cdot 05$. The means lie just within their standard deviations, suggesting that the evolutionary trend, if present, is very slight. The spectral indices are centred on a value of $-0 \cdot 5$ with an r.m.s. scatter of about $0 \cdot 3$.

## V. Evolution of Radiated Power

The two theories that have received most attention in the literature are due to Shklovskii (1960*a*) and Van der Laan (1962). According to Shklovskii's hypothesis, both the field and the particles are generated by the outburst and are situated within the expanding plasma shell. The assumption is then made that the expansion of the shell is adiabatic; a relation can then be determined between the source radius and the radiated flux. This can be expressed in the form

$$P \propto R^{-2\gamma}, \tag{1}$$

where $P$ is the power per unit bandwidth radiated over all directions at the observing

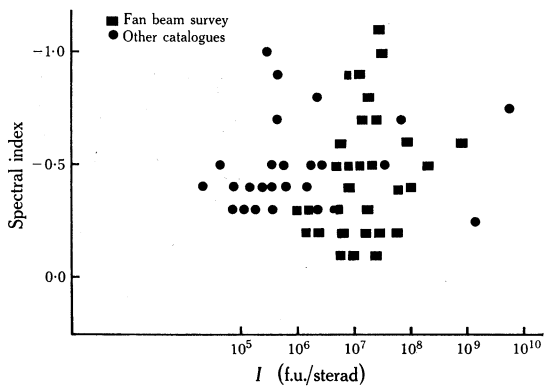



Fig. 6.—Plot of the distribution of the source spectral index as a function of its brightness $I$.

frequency, $R$ the shell radius, and $\gamma$ the exponent of the relativistic electron energy spectrum:

$$N(E)\,\mathrm{d}E = KE^{-\gamma}\,\mathrm{d}E\,.$$

Here $\gamma$ is related to the radiation spectral index $\alpha$ by the expression

$$\alpha = -\tfrac{1}{2}(\gamma-1)\,.$$

Equation (1) was derived on the assumption that the source was a spherical mass rather than a shell. The same expression is obtained if the source is a shell whose thickness is a constant fraction of the radius.

The rate at which the shell thickness increases is determined by the gas and the magnetic pressures. (Essentially, the problem is that of expansion into a vacuum.) Thus, if the magnetic field is weak, the ratio of the shell thickness to the shell radius may decrease during the initial stages of the remnant's evolution. The limiting case is where the shell thickness is constant, and the evolution equation becomes

$$P \propto R^{-\frac{1}{2}(3\gamma-1)}\,. \tag{2}$$

Van der Laan's theory assumes the relativistic particles to be generated by the outburst, and to be trapped in the region between the expanding shell and the shock generated by the expansion. The magnetic field is due to a compression of the galactic medium. The evolution in this model, once the mass of the interstellar gas swept up by the shell exceeds the mass of the shell, is given approximately by the form

$$P \propto R^{-3\gamma}. \tag{3}$$

There are few ways in which these theories can be tested. There is no clear evidence to indicate whether the radio source lies within the expanding plasma shell or in the shocked region. This is because of the small number of cases where optical filaments have been found at the site of a radio source, the difficulty in defining the position of the plasma shell, and the insufficient resolution of the radio observations. The lack of evolution in the spectral index indicates that the current estimates of the conditions within the shell are plausible, without deciding between the two theories. However, the differences between the models in the predicted evolution of the radiated power are substantial and should provide a reasonable basis for testing.

The secular decrease in the flux density can be calculated if the expansion rate of the shell is known. This is the basis of the prediction made in 1960 by Shklovskii (1960*b*) for Cassiopeia A. The observed value of $\sim 2\%$ is consistent with equations (1) and (2). The value from equation (3) seems rather higher than can be accounted for with the observational errors.

An evolutionary path can be reconstructed if the distances are known to a number of sources which are assumed to have similar evolutionary paths. There are five sources at known distances: Cassiopeia A and the Cygnus Loop in the Milky Way (Minkowski 1959) and N49, N63A, and N132D in the Large Magellanic Cloud (Westerlund and Mathewson 1966). The possible evolutionary paths are shown in Figure 7, along with the points corresponding to the five sources. It is clear from equations (1), (2), and (3) that an allowance ought to be made for the different spectral indices. Such correction is not warranted (at present) in view of the uncertainties in the observed parameters. The models are based on a spectral index of $-0\cdot5$, the mean of all the nonthermal sources.

Each model is of the form

$$P = AR^{-g}.$$

The constant $A$ was determined from the curve of index $-g$ which best fits the data.

Equation (2) seems the best fit, although the observations cannot exclude the other two models.

Since the distance is not known for the sources of the catalogue, a statistical method was tried. Let the frequency of occurrence of the supernova outbursts be $f$, and assume (for the moment) that all supernova remnants of given brightness are detected. The number of remnants brighter than a given value $I$ is

$$N(\geqslant I) = f_0\, t(I), \tag{4}$$

where $t(I)$ is the age of a remnant whose brightness is $I$ and $f_0$ is the frequency of supernovae outbursts in the longitude range $180° < l^{\mathrm{II}} < 40°$. On the assumption that the outbursts all occur within 10 kpc of the galactic centre, $f_0$ can be related to the frequency $f$ for the whole galaxy by

$$f \sim 1 \cdot 2 f_0 .$$

Equations (1), (2), and (3) can be reformulated in terms of brightness $I$,

$$I = S/\Omega = P/4\pi^2 R^2 = (A/4\pi^2) R^{-g-2},$$

where $S$ is the integrated flux density and $\Omega$ the solid angle subtended by the source (derived from the observed half-power dimensions).

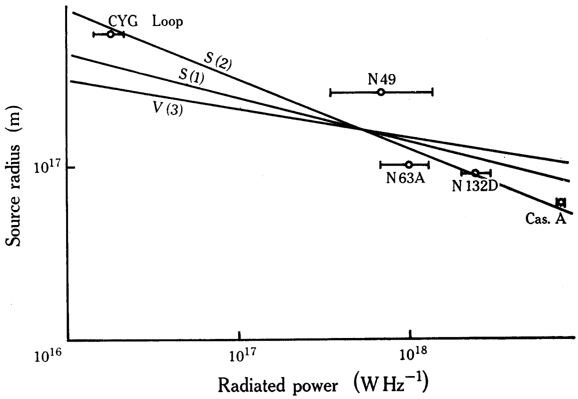



Fig. 7.—Evolutionary relation between the radius of a remnant and its radiated power, calculated on the basis of the three models of a supernova remnant: S(1), Shklovskii (equation (1)); S(2), Shklovskii (equation (2)); V(3), Van der Laan (equation (3)). Points corresponding to the five sources are also plotted.

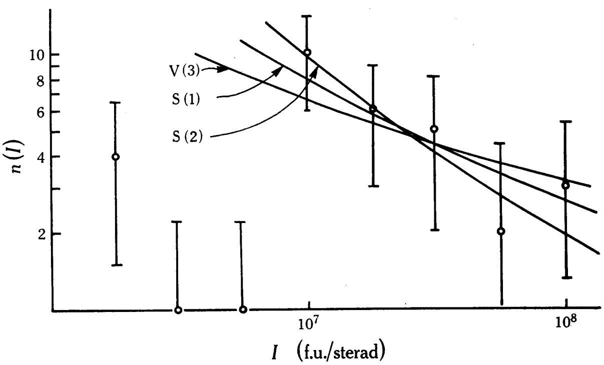



Fig. 8.—Differential number brightness distribution $n(I)$ calculated for the three models, $n(I) = N(\geqslant 0 \cdot 56 I) - N(\geqslant I)$.

An analysis of the expansion of the plasma shell yields a relation between the shell radius and its age:

$$t = \frac{R}{V_0}\left(1 + \frac{\pi\rho}{3M_0}(\alpha R)^3\right), \tag{5}$$

where $\rho$ is the density of the interstellar medium ($\sim 0 \cdot 5$ hydrogen atom/cm), $M_0$ the mass of the shell ($\sim 10\ M_{\odot}$), and $V_0$ the initial velocity of the shell ($\sim 7000$ km/sec). This expression is derived on the assumption that there is no energy input after the initial explosion, and no interaction between different parts of the shell. The constant

$\alpha$ ($\sim 1$) accounts for the difference between the radius of the shell and the radius of the shock front. The precise value is of little importance, in view of the uncertainty in $\rho$ and $M_0$. Thus

$$t(I) = \left(\frac{A}{4\pi^2 I}\right)^{1/(g+2)} \frac{1}{V_0}\left\{1+\frac{\pi\rho\alpha^3}{3M_0}\left(\frac{A}{4\pi^2 I}\right)^{3/(g+2)}\right\}. \tag{6}$$

In Figure 8 the function $n(I) = N(\geqslant 0\cdot 56\,I) - N(\geqslant I)$ has been plotted. This function, rather than $N(\geqslant I)$, was chosen in order to minimize the contaminating effect of the class II sources included by chance in the catalogue. The 32 sources in

Table 1

FREQUENCY OF SUPERNOVA OUTBURSTS

| Technique | $\tau = 1/f$ (yr) | Reference |
|---|---|---|
| Supernova remnants | $50 \pm 30\%$ | Present paper (equation (1)) |
| | 90 | Present paper (equation (2)) |
| | 40 | Aizu and Tabara (1967) |
| | 30–60 | Shklovskii (1955) |
| | 50 | Minkowski (1964) |
| Search for supernovae in external galaxies | 450 | Zwicky (1965) |
| | 60 | Bertaud (1961) |
| Cosmic ray density* | 100 | Kaplon and Skadron (1966) |
| | $10^{2\pm0\cdot5}$ | Rosen and Milford (1966) |
| | 50 | Ginzburg and Syrovatskii (1964) |

* In this method the supernova outbursts are assumed to be the sites of cosmic ray production. Subject then to the assumed efficiency of the generation process, an estimate can be made of the frequency of the outbursts from the cosmic ray density.

this figure are drawn from the catalogue and refer to the longitude range $180° < l^{\mathrm{II}} < 40°$. A number of these sources are small relative to the aerial beam-width and no contours have been produced. No estimate of the spectral index is available for some of the sources; they are therefore not included in Figure 2. Also shown in Figure 8 are the functions $n(I)$ calculated from equations (1), (2), and (3). The scale factor of the calculated functions is the frequency of occurrence $f$. Since this is not known, the curves have been drawn in the position of best fit. The frequency corresponding to these curves is given in Table 1. The values are in good agreement with estimates made by other observers.

Because of the nature of the instrument used in the primary survey, the limiting condition governing the inclusion of a source in the catalogue is a complex function of the integrated flux density and the angular size. The function $n(I)$ is therefore affected in the low brightness region. No attempt has been made to calculate $n(I)$ in this region, as the function depends critically on the distribution of supernovae in the Galaxy. The brightness corresponding to the maximum of $n(I)$ has been estimated, on the assumption that the distribution is uniform out to 10 kpc. The maximum occurs in the interval $10^7 < I < 1\cdot 8 \times 10^7$, which is reasonably consistent with Figure 8.

These various tests suggest that Van der Laan's theory is a poor fit to the data, and that either variant of Shklovskii's theory is plausible. The present statistical method indicates that the remnants do have a common evolutionary path but, due to the uncertainties of the technique, this path is not yet well defined. It is likely that the evolutionary path could be recovered if the distance were known to a number of sources. The neutral hydrogen absorption measurements may be of particular value in this context, even though the errors in their results may be large.

## VI. Acknowledgments

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