Student Lecture Notes - 1971

SUPERNOVAE

D. E. Hogg

National Radio Astronomy Observatory
Green Bank, West Virginia

Amongst the various nonthermal radio sources found in the galaxy are a number having large angular (several minutes) diameter which have been identified as the remnants of supernova explosions. These have been of great interest because they can give information about this stage of stellar evolution, and because they may be the primary source of cosmic rays in the galaxy.

Good general summaries of the earlier work have been given by Shklovsky (1968) and Minkowski (1968).

I. SUPERNOVAE IN EXTERNAL GALAXIES

Because of the infrequency of supernovae in the galaxy, the properties of SN themselves must be determined by observation of events in external galaxies. Due principally to the work of Zwicky, we can identify at least five types of SN. (cf. Zwicky 1965).

Type I - Originally identified by light curve, now by color (relatively red, B-V 0.5 to 0.9) but especially by spectrum. The time near maximum is about 50 days, and the subsequent decay is exponential, with the 1/e time varying between 50 and 70 days. The difference in magnitude between the peak and the stellar remnant is between 15^m and 20^m. The maximum apparent photographic magnitude is -18. They appear with roughly equal frequency in all types of galaxies, suggesting that they are old stars of roughly solar mass.

A typical light curve is shown in Fig. 1.

Type II - The light curve shows great variations and cannot be used alone for type identification. If photometry is available, they can be distinguished by the ultraviolet excess. The best distinction is made by means of the spectrum. The maximum apparent photographic magnitude is -16^m, perhaps not significantly fainter than for Type I. They appear only in spiral or irregular galaxies, often actually within spiral arms.

Light curves for a number of these objects are also shown in Fig. 1.

Type III - Clearly different from Type II, although more like it than like Type I. The velocity is high, $\sim$ 12,000 km/s. The shell is very dense, since it remains opaque for several weeks, and the total mass ejected must be great.

Type IV - Only one object of this type is known. It is generally similar to Type I, but differs in detail.

Type V - Probably dwarf supernovae or massive novae. The energy release is smaller, the velocities are low, $\sim$ 2000 km/s.

Recently, H. van der Laan has reported the detection at 21 cm of radio emission from a SN in M101. Such observations will perhaps enable the determination of the variation of radio emission with time at the early stages of the expansion of the envelope.

II. GALACTIC SUPERNOVAE

There are four objects now well-established from both optical and radio evidence as being supernovae. These are SN 1006, SN 1054, SN 1572, and SN 1604. In addition, there are two or three objects that were observed visually, but with positions too inaccurate for identifications. These may ultimately be identified--for example, identifications of SN 1181 and of SN 1437 have recently been proposed. There was a supernova in Cas in AD 368, which might also be identified ultimately, since there are a number of peculiar objects in this region. Of these supernovae, SN 1054, SN 1572, and SN 1604 are all classed as Type I, on the basis of light curves, and, for SN 1572, because of its color. There is no information on SN 1006. However, I think that it is essentially meaningless to try to match types with light curves. As for SN 1572, the observation was that near maximum, it was whitish "like Venus", reddened with time, then became whiter again. Such color changes are not sufficient to distinguish the two types either. It seems then that perhaps the radio properties can be used for this distinction.

The object that does stand out by itself is the Crab Nebula SN 1054. It is a strong radio source, it has optical synchrotron radiation, acceleration of the expansion, and acceleration of particles, and thus it is unique. To lump it in with the rest of the remnants is to confuse matters, so it will be left to the end.

Let's look at one of the remnants in detail in order to show the type of observational material that can be obtained. As the prototype, we'll take Cas A, because it has the best data generally, since it is the brightest, and has been known the longest.

III. THE OBSERVED PROPERTIES OF CAS A -- RADIO

(a) The radiated power as a function of frequency, i.e., the spectrum. Over most of the range, the spectrum is a power law

$$S_\nu \; \alpha \; \nu^{-\alpha} \quad \text{with } \alpha - 0.75$$

where S_ν is the flux density at frequency ν

α is the spectral index. For most radio sources in the region of 10^3 MHz $\alpha > 0$. For an optically thin thermal source $\alpha = 0.1$.

Note that S_ν is usually measured in flux units.

$$1 \text{ flux unit} = 1 \times 10^{26} \text{ w m}^{-2} \text{ Hz}^{-1}$$
$$= 1 \times 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}.$$

There is, however, a "low-frequency" turnover at about 20 MHz. The power from Cas A in the radio spectrum:

The total flux is $\int S_\nu \, d\nu = 1.8 \times 10^{-10}$ erg s^{-1} cm^{-2} radiated between 10^7 and 10^{10} Hz. The total power for a distance of 3400 pc is

$$4\pi d^2 \int S_\nu \, d\nu = 2.5 \times 10^{35} \text{ erg s}^{-1}.$$

The spectrum of Cas A is shown in Fig. 2. The data are from Kellermann, Pauliny-Toth and Williams (1969), from Bridle and Purton (1968) and from Roger, Costain and Lacey (1969).

Recently, Gorenstein, Kellogg, and Gursky (1970) have shown that the remnant Cas A is a source of hard X-rays, in the range 2-9 kev. The X-ray intensity is such that it could be due to the same synchrotron radiation that is observed at radio wavelengths, but the spectral index is much steeper, having a value of 3.3.

(b) The radio brightness distribution. The source is about 5' in diameter so that little was known about it until recent measures at high frequency with single dishes, and with the aperture synthesis technique. Figure 3 shows brightness distribution of the small components at 11 cm obtained with NRAO tracking interferometer (Hogg et al. 1969). The contour interval is 1750° K, and the outermost contour is 5200° K. The size of the smallest features is not known -- they could certainly be optically thick at 20 MHz.

(c) Radio polarization. Again not much is yet known -- it was thought until recently that Cas A was unpolarized. Work by Mayer and Hollinger (1968) at 1.55 cm (beam 1!7) showed a degree of polarization of ∿ 5 percent, with orientation of the electric field very nearly circumferential, defining, under the synchrotron radiation hypothesis, a radial component of magnetic field associated with polarized radiation. The observed decrease of polarization radiation to zero at the center of the source may be a resolution effect, or it could be produced by a truly radial distribution in three dimensions of the magnetic field associated with the polarized radiation.

(d) Variation of radio flux with time. The idea that the flux density of a radio source should vary with time is now widely accepted, but in 1960, when Shklovsky first proposed that the flux from Cas should be decreasing, it was revolutionary. A number of groups have studied the problem, finding that

$$\frac{\Delta S}{S} \sim 1.1\% \text{ per year.}$$

(e) Distance from studies of the 21-cm absorption. This source, because of its strength, was one of the first to be used in H I absorption studies. There are three prominent absorption features -- one corresponding to the local gas concentration in the Orion Spur, or arm, and two more in the Perseus Arm, at a distance of 3 kpc. On the basis of a detailed study of the absorption, conclude that the distance is 3400 $\pm$ 400 pc.

IV. THE OBSERVED PROPERTIES OF CAS A - OPTICAL

The field was identified by Baade and Minkowski about 15 years ago. There are a large number of wisps, or filaments, perhaps up to 200. About 20 filaments are very red, show Hα and [N II], [O I], and [O III], with low radial velocities -30 km/s. The radial velocities are not a function of position within the nebula. The line width $\sim$400 km/s. The other filaments, numbering perhaps 200, are blue, and show no Hα or λ3727 [O II]. Lines of [O I], [O III] are present. Broad emission lines, many peaks within a given filament. The radial velocities are a function of angular distance from the center. Proper motions have also been measured and reach 0$''\!.$4/year at distances of 100" from the center.

From the proper motions, van der Bergh has deduced that the expansion began in AD 1667$\pm$8. The distance is 3400 pc. In a paper summarizing the most recent work (van den Bergh 1971), it is noted that the knots with high velocity show a velocity dispersion of up to 3000 km/s, suggesting that acceleration is still taking place, and that the "stationary" knots, about 30 in number, may well have been a pre-supernova circumstellar envelope that has been fragmented by the expanding supernova shell.

V. GENERAL PROPERTIES OF SUPERNOVA REMNANTS

There are now about 100 objects known to be or suggested to be SN remnants. With such a large number, it is possible to see what the characteristics of these objects are:

1. Optical Observations of Other Remnants

(a) SN 1572 (Tycho) - Observations of the light curve and color clearly suggest Type I supernova, although the evidence is certainly not very strong. The radio properties are in many ways similar to Cas A. The color question is badly confused by interstellar reddening.

The remnant is seen as two filaments and an arc which suffice to determine the center of expansion. The radial velocities are near zero, suggesting that the features are at the edge. However, even so there is a serious problem, since the nebula is young; how does such a rapid deceleration occur? If the whole shell is decelerated to 200 km/s in 400 years, then the linear dimension must be less than 10^{18} cm, and the distance $\sim$ 25 pc, clearly impossible.

(b) SN 1604 (Kepler) - Light curve similar to Tycho's. There are several filaments showing Hα, [N II], and [O I] in more or less normal intensity. The radial velocities are $\sim$ 200 km/s.

For both of these young remnants the low velocities are very puzzling. The most reasonable explanation is that the filaments are interstellar matter which has been swept up in a halo, like the stationary filaments in Cas A.

(c) Cygnus Loop - This is a famous object showing well-developed filamentary structure. In fact, part of it is so bright that it earned NGC numbers - NGC 6992/95.

There are more optical data about this remnant than any other, thanks to the work of R. Parker (1964). There is a wealth of detail, but the general picture is that the filaments are actually thin sheets of nebulosity seen edge-on. There is evidence for temperature stratification behind a shock front -- the presence of O III lines is best explained by a region of $> 5 \times 10^{4\circ}$ K, while the other lines, H, N, O, S arise in a region of temperature $2 \times 10^{4\circ}$ K. The abundances of these atoms are normal if stratification is assumed. The total mass of gas in NGC 6992/95 is $\sim 3\ M_{\odot}$, leading to a total mass for the whole complex of 5-10 $M_{\odot}$. Note that since up to 100 $M_{\odot}$ could have been originally contained in this volume, there may be now a lot of cool gas which is not seen.

From study of the proper motions and radial velocities, conclude that the age is 5×10^{4} years, and that the distance is 700 pc.

2. Radio Properties of the Supernova Remnants

Excellent summaries of the radio properties of SN remnants have been given by Milne (1970) and Downes (1971).

(a) Radio structure. There are now 35 objects which have been studied in detail with high-resolution radio telescopes, and most of these show a shell-structure, sometimes heavily fragmented, or with condensations. The Crab Nebula is of course an exception, and there are a few others as well. Figure 4, reproduced from the work of Milne, shows the brightness distributions over a large number of the remnants.

At this time theorists are still working on a simple shell model for SN remnants. The next stage of complexity will be to explain the presence of the condensations, or at least the apparent duplicity, which characterizes many remnants. One way is to require asymmetric explosions, while another is to have a highly variable distribution of interstellar clouds.

There has been a recent suggestion that the holes in the shell were preferentially aligned parallel to the galactic equator, implying perhaps an interaction between the shell and the general galactic field. However, I can see no alignment with the general magnetic field evident in the structure of these objects.

(b) <u>Radio spectrum</u>. The spectral indices vary from 0.8 to 0.15. There has been until recently a serious selection effect for SN with flat spectra (i.e., near the thermal index of 0.1), many of these objects have been confused with H II regions. Now, we can distinguish SN remnants from low-temperature H II regions by means of recombination lines. For high-temperature regions, where the recombination line intensity may be weak, this test is still not definitive.

One critical question is whether the index varies across the source. Three objects which have been extensively studied -- Cygnus Loop, IC 443, and HB 21 -- all show good evidence for a variation of spectral index with position in the source.

For the Cygnus Loop NGC 6992-95, the spectral index is ~ 0.1 in the region 40-200 MHz, and it steepens to 0.5 at 1000 MHz. Similar values obtain for IC 443. HB 21 in the north has a flat spectrum $\alpha = 0$, steepening to $\alpha = 0.4$ at higher frequencies. What can be the cause of this break in index?

(1) The distribution of particle energies is different in different parts of the nebula, due for example to a different acceleration process. Could the acceleration in the expanding shell be different if the shell runs into an interstellar cloud?

(2) The distribution of energies is different because the radiating particles are cosmic rays swept up by the shell. The spectrum of radiation should be that of the galactic background, shifted higher in frequency by the compression ratio. This might work in the Cygnus Loop, but certainly will not for HB 21.

(3) Thermal free-free absorption. This can just be made to work, within the large observational errors of the spectrum. If the observations improve even a little bit, it will be possible to decide if this mechanism operates.

(c) Polarization. SN 1604, 3C 58, and the Cygnus Loop all have some polarization data. Tycho's SN is very similar to Cas A, in that it shows a radial field. For the others the data are still fragmentary, and since they have been made at a low frequency, the positions of the electric vectors do not necessarily give the orientation of the magnetic field.

(d) Variation of flux density with time. Not observed for any supernova remnant other than Cas A.

3. Supernova Remnants as X-ray Sources

There are now six supernova remnants identified as X-ray sources. These are the Crab Nebula, Cas A, Tycho's Nova, The Cygnus Loop, Vela X and Puppis A. The first three emit a hard X-ray spectrum in comparison with the others. Little is known about the brightness distribution of X-ray emission, except for the Cygnus Loop, where high resolution studies (Gorenstein et al. 1971) have shown that the X-ray structure has the same angular size as the outermost boundaries of the optical filaments, and that the X-ray emission is more or less constant across the circular region of the sky defined by the filaments. This is in contrast to the radio emission which is confined closely to areas where the filaments are visible.

It appears that the nature of the X-ray radiation can be simply interpreted in terms of the emission process. The younger sources with the hard spectrum radiate predominately by synchrotron emission, whilst the older sources with the soft spectrum radiate by thermal emission.

VI. THE ORIGIN OF SUPERNOVAE

Theories of the origin of supernovae fall into two general classes, depending upon the mass and energy released at the time of the explosion. If it is believed that a Type II SN is associated with the evolution of a very massive star, of say 5-20 $M_{\odot}$, then the work of Hoyle and Fowler (1960) may apply. In an advanced evolutionary stage of a star, hydrogen is fused into successively heavier nuclei until the iron group elements are reached. Then nuclear-energy generation can cease and photo-disintegration set in. This rapidly produces an endothermic iron to helium-neutron phase change in the inner core, and a resultant implosion of the material. Then perhaps the energy necessary to disperse the star might come from burning of an outer shell of oxygen (Hoyle and Fowler) or by energy transfer to the mantle from the core by the emission and deposition of neutrinos (Colgate and

White 1966). In either case one might expect a remnant, presumably a neutron star. If the mass is much greater than 20 $M_{\odot}$ an envelope might be ejected, but the remnant would be a "collapsar"!

If the amount of material in the shell is small, and such may well be so even in Type II (Poveda and Woltjer 1968), then much less energy is required and the mechanism could be analogous to novae, i.e., an instability in a helium-burning shell could cause an explosion and subsequent ejection of material. This theory would predict a remnant (but not a neutron star) and as yet none have been found.

Finally, for stars of smaller mass there is some question as to whether they go through a supernovae stage. Some stars certainly pass through the less violent planetary nebula stage. One possibility for Type I SN is the theory of Hoyle and Fowler in which in advanced evolutionary stages of stars of 1.2-1.5 $M_{\odot}$, degenerate nuclear fuel such as C^{12}, O^{16}, N_e^{20} ignites, and for high enough central temperature, detonates.

One question not answered within the theory sketched above--if the Crab is the remnant of Type I, where did the neutron star come from?

VII. THE CRAB NEBULA

1. Details of the Observed Outburst

The outburst of 1054 was fully recorded in Chinese and Japanese chronicles, but not in the west. The principal values obtained from these observations are (i) the date of the SN, (ii) the position of the SN and (iii) a crude light curve. Thus it is noted that it was visible during the daylight (i.e., $m < -3.5$) for 23 days and visible all told for 650 days. Both of these suggest that at the peak m = -5. Although originally considered to be a Type I SN, more recently that classification has been questioned, and in fact Minkowsky does not now attempt a classification.

2. Distance of the Remnant

The definitive work is by V. Trimble (1968). It will be difficult to improve upon this.

In this work proper motions were measured for 250 of the emission-line filaments. Of these, about one-half also have measured radial velocities, so that given a distance a three-dimensional picture of the nebula can be derived. However, the nebula is obviously an ellipsoid, and the distance is critically dependent upon whether it is prolate or oblate. That is, in the center the radial velocity is observed to be V_r = 1450 km/s. Along the major axis the largest proper motions correspond to 0".22/year, and are fairly well-behaved, but along the minor axis not only are the expected values of 0".15/year found, but larger values, of up to 0".17/yr. The distance is, in pc,

$$D = \frac{V_r}{4.74\mu} \text{ with V in km/s, } \mu \text{ in "/yr}$$

from which

$$\begin{aligned} D &= 1.4 \text{ kpc} \qquad \mu = 0.22 \text{ oblate} \\ &= 2.0 \qquad\quad\;\; \mu = 0.15 \text{ prolate} \end{aligned}$$

The best estimate is that it is prolate spheroid, of distance 2 kpc.

Besides the distance, the proper motion studies show that the expansion has been accelerated since if the motions are assumed constant and extrapolated backward in time, they converge about 1140 AD.

3. The Physical Conditions in the Nebula

The best study even now is that by Woltjer (1958), using 200-inch plates from Baade. Trimble (1970) has summarized more recent observations. It appears that the ionization in the filaments can be maintained by the ultraviolet synchrotron radiation, although the distribution of N, O, and S amongst the various ionization states is not well understood. The temperature is 1.7×10^4, the density 10^3, and the total mass 1/20 $M_\odot$.

4. Observed Properties of the "Amorphous" Component

Within a central region outlined by the filaments is a bright continuum source, erroneously referred to as the amorphous mass. It was originally considered to be radiating by free-free and bound-free transitions in the strongly ionized gas. However, the great difficulties with this mechanism -- the large mass of ionized material, the absence of emission lines, the existence of "cold" filaments within the central region, the strong radio emission -- led Shklovsky to propose that the radiation was nonthermal, in fact synchrotron. The synchrotron theory seems to account for most of the radiation, but there are some anomalies as well.

(a) <u>In the frequency range 25-100 MHz</u>: The bulk of the observed radio emission comes from an elliptical region centered on the Crab and having orientation [150°] also about the same. It is definitely larger however, with size 5!5 x 3!5. Within this region, in fact at a position coinciding with the pulsar, is a strong point source with a peculiar spectrum. The source accounts for about 20% of the total flux at 38 MHz and about 10% at 81.5 MHz. Between these two frequencies, the spectral index is +1.2; at higher frequencies it must steepen, to about 1.8→2.0. Its size is uncertain, but scintillation measurements put it at $0\overset{''}{.}2 \pm 0.1$, implying that at 38 MHz $H < 2 \times 10^{-7}$ g, $E \sim 10^{50}$ erg in relativistic particles, if the source is radiating by synchrotron emission. This field is $\sim 10^{-3}$ that of the nebula which is a little difficult to imagine. An alternative is that they are plasma oscillations induced by currents of fast particles. Note that at this time it is a good assumption that this source is associated with the pulsar. An attempt has been made with a VLB, and the unpublished results show that the position of this source coincides with the pulsar.

(b) <u>In the frequency range 10^2-10^4 MHz</u>. The nebula has a straight spectrum with index 0.28. The general shape is still elliptical but the size decreases with increasing wavelength--on the order of $4\overset{'}{.}3 \times 3\overset{'}{.}0$ at 2-5 cm. However, there are also high resolution observations showing that there is much structure in the radiation as well, so that the exact dimensions cannot really be defined.

In this frequency range we see polarization in the radiation, especially at the high frequency end. In the region of 3 cm, the observed polarization amounts to 12%, and could be even higher if we observed with greater resolution. The source becomes depolarized at longer wavelengths, to $\sim$ 1% at 21 cm. The position angle of the observed polarization rotates as λ^2, showing Faraday rotation effects. It is difficult to obtain the observed depolarization on the basis of differential Faraday rotation, although the most recent high resolution maps of polarization may help considerably.

(c) Millimeter waves and infrared. There are a number of fluxes in the range 1-3 mm and 1-5μ. Considerable caution must be exercised in using these results -- often only the flux from the center is measured, and the total flux is guessed at. The observations of Ney and Stein (1968) are the best from this standpoint, but even so they probably have missed a part of the radiation by using too small a diaphragm.

(d) Optical wavelengths 3000 A-10,000 A. There is no doubt that between 10^{11} and 10^{13} Hz the spectrum breaks, but it is very difficult to tell by how much it breaks; the observations are not too bad, but the correction for interstellar reddening is all important. A review is given by Scargle (1969), but look elsewhere, e.g., Ney and Stein for the data. For a reddening of 1ᵐ5 which seems to be an acceptable value, the spectral index is $\alpha \sim 1$, although it might be as flat as 0.7.

(d) X-rays in the range 1 kev-100 kev, Gamma-rays in the range 100 kev-600 kev ($\nu = 10^{17}$-10^{20} Hz). The Crab Nebula was the first X-ray source to be identified. It is very strong, and thus has been quite well-studied. It is now known that the X-ray and visible light distributions have a common center, i.e., the pulsar to within the error of the position of the X-ray source (15"), and that the source has finite extent: The distribution of X-ray emission has not been determined -- it could be a more uniform distribution of diameter $\sim$ 100".

In summary, 63% of the radiated power appears in the ultraviolet and X-ray region (λ < 3000 A), 14% in the optical (3000-10,000 A), 23% in the infrared (1μ- 1 mm) and $\sim$ 1/2% in the radio (λ > 1 mm). The total power radiated for a distance of 2 kpc is 1 x 10^{38} erg.

REFERENCES

Van den Bergh, S. 1971, Ap. J., 165, 457.

Bridle, A. H., and Purton, C. R. 1968, A. J., 73, 717.

Colgate, S. A., and White, R. H. 1966, Ap. J., 143, 626.

Downes, D. 1971, A. J., 76, 305.

Gorenstein, P., Kellogg, E. M., and Gursky, H. 1970, Ap. J., 160, 199.

Gorenstein, P., Harris, B., Gursky, H., Giacconi, R., Novick, R., Vanden Bout, P. 1971, Science, 172, 369.

Hogg, D. E., Macdonald, G. H., Conway, R. G., and Wade, C. M. 1969, A. J., 74, 1206.

Hoyle, F., and Fowler, W. A. 1960, Ap. J., 132, 565.

Kellermann, K. I., Pualiny-Toth, I. I. K., and Williams, P. J. S. 1969, Ap. J., 157, 1.

Mayer, C. H., and Hollinger, J. P. 1968, Ap. J., 151, 53.

Milne, D. K. 1970, Aus. J. Phys., 23, 425.

Minkowski, R., 1968, in Nebulae and Interstellar Matter, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), p. 623.

Ney, E. P., and Stein, W. A. 1968, Ap. J. (Letters), 152, L21.

Parker, R. A. R. 1964, Ap. J., 139, 493.

Poveda, A., and Woltjer, L. 1968, A. J., 73, 65.

Roger, R., Costain, C., and Lacey, J. 1969, A. J., 74, 367.

Scargle, J. D. 1969, Ap. J., 156, 401.

Shklovsky, I. S. 1968, Supernovae (New York: Interscience)

Trimble, V. 1968, A. J., 73, 535.

Trimble, V. 1970, A. J., 75, 926.

Woltjer, L. 1958, B. A. N., 14, 39.

Zwicky, F. 1965, in Stars and Stellar Systems, ed. L. H. Aller and D. B. McLaughlin (Chicago: University of Chicago Press), p. 367.