Radio Studies of Extragalactic Supernovae

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Some exploding stars (supernovae) are powerful emitters of centimeter radio radiation. Detailed observations have shown that these supernovae quickly become detectable in the radio range, first at shorter wavelengths (higher frequencies) and later at progressively longer and longer wavelengths (lower frequencies). This part of the phenomenon appears to be well explained by a monotonic decrease in the amount of ionized material surrounding the radio-emitting regions as the shock from the explosion travels outward. The radio emission itself is of a nonthermal, synchrotron origin, as is the case in most bright cosmic radio sources. Once the absorption effects become negligible, the radio intensity declines with time until reaching the detection limit of the telescope. Models suggest that the absorbing material originates in a dense wind of matter lost by the supernova progenitor star, or by its companion if it is in a binary system, in the last stages of evolution before the explosion. The synchrotron radio emission can be generated either externally by the shock wave from the explosion propagating through this same high density stellar wind or internally by a rapidly rotating neutron star, which is the collapsed core of the exploded star. Present results appear to favor the former model for at least the first several years after the supernova explosion, although the latter model remains viable.

SEVERAL HUNDRED EXTRAGALACTIC SUPERNOVAE HAVE been discovered optically and catalogued since the first modern observation of a supernova (S Andromedae) in the nearby Andromeda Nebula (M31) by E. Hartwig at the Dorpat Observatory on 20 August 1885. However, for years radio searches at the positions of many tens of these objects yielded no detections to the limits of the largest and most sensitive radio telescopes available (*1–5*), with the single exception of the supernova SN1970g in M101 (*6*). (Supernovae are labeled by the year and order, letters a to z, of discovery.) This last supernova, showing itself as a weak increase in the integrated flux density from an area containing both the supernova and a radio-emitting, ionized hydrogen (HII) region, allowed the determination of a rough radio light curve (*7*). In the following decade, no further information about the radio emission from supernovae was obtained until April 1980, when SN1979c in M100 was found to be a powerful emitter of 6-cm radio emission (*4, 8*). Stimulated by this clear evidence that supernovae are significant sources of radio emission and that the study of these radio supernovae (RSN) provides important information on the properties of the progenitor stellar systems and their immediate circumstellar environments, the detection and study of additional events has progressed rapidly.

Here we summarize the observational data [essentially all of which have been obtained with the very large array (VLA) (*9*)] and theoretical knowledge presently available on RSN, with primary concentration on the newest examples for which the vast majority of information is available. [See (*10*) for a more detailed treatment of the subject.]

Radio Supernovae

A list of historical radio supernovae—those radio sources with which a modern optical supernova can be associated—along with their properties and those of their parent galaxies is given in Table 1. Two supernovae that have extensive data sets, SN1983n and SN1979c, are discussed in detail as representatives of the two main types of supernovae: Type I supernovae, which are thought to be the explosions of old, low mass stars containing no hydrogen, and Type II supernovae, which are thought to be the explosions of young, massive, hydrogen-rich stars.

SN1979c. SN1979c was discovered near maximum light on 19 April 1979, approximately 100 arc seconds southeast of the nucleus of the galaxy M100 (NGC4321) by the amateur astronomer G. E. Johnson (*11*) of Swanton, Maryland. It quickly became an object of intensive study in many wavelength ranges and has been firmly established as a Type II supernova of the linear (Type II_L) subclass (*4, 10–14*) (Table 1).

The radio information available about SN1979c is quite extensive (Fig. 1). Since the initial detection with the VLA of 6-cm radio emission on 6 April 1980, monitoring has been done at both 6- and 20-cm wavelengths at a rate of approximately once per month. The radio spectral index (α; flux density proportional to frequency to the power α) between 6 and 20 cm initially decreased rapidly with time as the source became optically thin, but it has now stabilized at a value of about -0.7, which is consistent with nonthermal synchrotron radiation.

SN1983n. SN1983n was discovered on 3 July 1983 in the spiral galaxy M83 (NGC5236) by the Australian amateur astronomer Robert Evans (*15*). The supernova reached maximum optical light on 17 July 1983. Subsequent observations determined it to be a peculiar, apparently subluminous Type I (designated Type I_{SL}) supernova (*16*). Radio observations were started quickly after the discovery, and on 6 July 1983, 11 days before maximum optical light, a detection at 6 cm with the VLA was obtained. Subsequent monitoring at 6 and 20 cm, at a rate of approximately once per month, established a rapidly declining radio light curve (*17, 18*) (Fig. 2).

Other RSN. With the excellent sensitivity of the VLA and with supernovae having been demonstrated to be significant emitters of

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centimeter radio radiation, strong interest in this area of study has resulted in an increasing number of new detections or very low upper limits. Because the number of candidates being examined is high, no absolutely complete list of known RSN can be given at any one time. However, in addition to the examples discussed in detail here, several other RSN have been detected and are being studied.

SN1957d was seen in December 1957 as a relatively faint optical supernova, possibly Type II, in M83. Using the VLA, Cowan and Branch (*19*) have shown it to be a radio source with flux density of approximately 2.6 millijanskys (mJy) at 20 cm and approximately 1.9 mJy at 6 cm. At an age of about 8500 days it has a radio spectral index α of about -0.3. More recent monitoring has revealed no significant change in the 6-cm flux density over a period of 3 years. In their continuing study of M83, the same authors have reported the detection of about 0.8 mJy at 20 cm and about 0.5 mJy at 6 cm, with spectral index α of approximately -0.4 probably associated with the optical supernova SN1950b.

SN1980k, discovered optically on 28 October 1980 (*20*), was found to be a Type II_L supernova similar to SN1979c. It was detected at 6 cm with the VLA only 35 days after optical maximum, and extensive measurements of its light curve were made at both 6 and 20 cm (*10*). It had a peak 6-cm flux density of about 3 mJy, an optically thin spectral index α of about -0.5, and a decline in flux density after maximum light β of -0.7 (β; flux density proportional to time after explosion to the power β) (*10*).

SN1981k was discovered in January 1982 by its radio emission (*21*) and was later identified with an optical supernova that had exploded sometime around 1 August 1981. It had a maximum detected radio flux density at 20 cm of about 5.5 mJy, a radio spectral index α of about -0.9, and a rate of decline of flux density β of about -0.7. These measurements suggest that it was probably a Type II supernova similar to SN1979c and SN1980k (*10*). The most recent supernova detection in the radio, SN1984l, was a Type I_{SL} supernova similar to SN1983n in both its optical (*22*) and radio (*23*) properties.

Four "normal" Type I supernovae—SN1980n, SN1981b, SN1983g, and SN1984a—have been examined at 6 cm with the VLA and remain undetected to low limits (<0.3 mJy; 3σ). This implies that their radio luminosities are significantly less than those of supernovae in the Type I_{SL} subclass (*10*).

Light Curves and Models

The radio light curves for SN1979c and SN1983n have been fitted by the relation

$$S\ (\text{mJy}) = K_1 \left(\frac{\nu}{5\ \text{GHz}}\right)^{\alpha} \left(\frac{t - t_0}{1\ \text{day}}\right)^{\beta} e^{-\tau} \qquad (1)$$

where

$$\tau = K_2 \left(\frac{\nu}{5\ \text{GHz}}\right)^{-2.1} \left(\frac{t - t_0}{1\ \text{day}}\right)^{\delta} \qquad (2)$$

This formulation assumes that the change of flux density S and of optical depth τ with time after the explosion date t_0 are described by power law functions of the supernova age $(t - t_0)$ with powers β and δ; that the change of τ with frequency ν is due to pure, external thermal absorption in an ionized medium with frequency dependence $\nu^{-2.1}$; and that the intrinsic radio emission is produced by the nonthermal synchrotron mechanism with an optically thin spectral index α. K_1 and K_2 are two scaling parameters for the units of choice: millijanskys, gigahertz, and days. The best-fit values for the parameters are as follows (*10*). SN1979c: $K_1 = 9.3 \times 10^2$, $\alpha = -0.72$, $\beta = -0.71$, $K_2 = 5.1 \times 10^7$, $\delta = -3.01$; SN1983n: $K_1 = 4.4 \times 10^3$, $\alpha = -1.03$, $\beta = -1.59$, $K_2 = 5.3 \times 10^2$, $\delta = -2.44$. The resulting curves are shown as the solid lines in Figs. 1 and 2.

The rising, optically thick part of the light curves is almost certaintly due to absorption by an ionized gas external to the radio-emitting regions. According to Chevalier (*24, 25*), the optical depth will decrease with time as $\tau \propto t^{-3m}$, where m is a model parameter ($0 < m < 1$) related to the time dependence of the radius R of the supernova shock wave ($R \propto t^m$) and dependent on the amount of deceleration experienced. Values are expected to lie mainly in the range $0.75 \leqslant m \leqslant 1.0$.

The most probable origin of this thermal, ionized, absorbing gas is mass loss from the presupernova system in a relatively high-density, low-velocity stellar wind. By adopting a reasonable velocity (10 km sec^{-1}) and temperature (10^4 K) for this wind and assuming that it is of normal chemical abundance and is fully ionized, it is possible to calculate the time dependence of the optical depth effects for comparison with the fitting parameter δ in Eq. 2. Further, the absolute radius of the supernova ejecta can be calculated from the velocity measured for optical emission lines during the early phase of the supernova explosion and its known evolution with time. All this information can then be combined to estimate the rate of mass loss from the presupernova stellar system (*10*). The values thus obtained from the fits to the data in the optically thick parts of the radio light curves are quite high, ranging from about 2×10^{-6} solar masses per year for SN1983n to about 5×10^{-5} solar masses per year for SN1979c. Such extreme mass loss rates (for example, the mass loss rate from the sun is less than 10^{-12} solar masses per year) can obviously be maintained only for a relatively short period near the end of a star's evolution.

The optically thin, nonthermal radio emission has two suggested mechanisms for accelerating the needed relativistic electrons or positrons (or both): (i) shock acceleration in a region external to the supernova photosphere and (ii) pulsar acceleration by the supernova stellar remnant. For simplicity, we have labeled these two relativistic particle acceleration mechanisms (i) minishell, from the resemblance of the shock model to shell-type supernova remnants such as Tycho (SN1572) and (ii) miniplerion, from the resemblance of the pulsar generation model to plerionic supernova remnants such as the Crab Nebula (SN1054).

The minishell model involves the external generation of relativistic particles and magnetic field by the shock wave of the supernova explosion interacting with a high-density gas envelope surrounding the supernova system. This high-density material is presumably the same as that which provided the initially observed absorption; that is, the mass lost from the stellar system in a wind preceding the supernova explosion. Since such a region of shock interaction is likely to be external to essentially all the mass ejected in the supernova explosion itself, the radio radiation would be able to escape after relatively modest absorption. This model has mainly been explored by Chevalier (*18, 24, 25*), who predicts an optically thin ($\tau = 0$) flux density dependence of

$$S \propto \nu^{\alpha} t^{\beta} = \nu^{(1-\gamma)/2} t^{-(\gamma+5-6m)/2}\ \text{(minishell)} \qquad (3)$$

where γ is the power-law dependence of the relativistic synchrotron electron injection spectrum.

The miniplerion models involve a central source of generation of the relativistic particles and magnetic fields, presumably by the remnant of the supernova progenitor star which has become something like a rapidly spinning pulsar or a black hole. This model has been explored by several investigators (*26–30*), with Pacini and Salvati (*26, 28*) predicting

$$S \propto \nu^{\alpha} t^{\beta} = \nu^{(1-\gamma)/2} t^{\alpha+3(1-\alpha)(1-m)/2}\ \text{(miniplerion; } \nu < \nu_b\text{)} \qquad (4)$$

Table 1. Radio supernovae.

Name	Optical type	Optical maximum: Date	Brightness m_B*	Brightness M_B†	Observed radio maximum at 6 cm: Age (years)	Peak (mJy)	Spectral luminosity (erg sec^{-1} Hz^{-1})	Parent galaxy: Name	Distance (Mpc)
SN1950b	II?	March 1950	$\lesssim$14.5	<-15.2	30	0.5	$\sim 3 \times 10^{25}$	NGC 5236 (M83)	~7
SN1957d	II?	December 1957	$\lesssim$15.0	<-15.7	23	1.9	$\sim 1 \times 10^{26}$	NGC 5236 (M83)	~7
SN1970g	II	1 August 1970	11.7	-18.2	1.4	~2.5	$\sim 1 \times 10^{26}$	NGC 5457 (M101)	~7
SN1979c	II_L	19 April 1979	11.6	-20.0	1.2	8.3	$\sim 2 \times 10^{27}$	NGC 4321 (M100)	~17
SN1980k	II_L	30 October 1980	11.6	-18.9	0.4	2.6	$\sim 1 \times 10^{26}$	NGC 6946	~7
SN1981k	II?	~15 August 1981	<16	<-14	0.5	~2	$\sim 1 \times 10^{26}$	NGC 4258	~7
SN1983n	I_{SL}	17 July 1983	11.8	-18.5	0.08	18.5	$\sim 1 \times 10^{27}$	NGC 5236 (M83)	~7
SN1984l	I_{SL}	30 August 1984	13.9	-18.5	0.14	0.7	$\sim 4 \times 10^{26}$	NGC 991	~24

*The apparent optical magnitude in blue light at the time of maximum observed brightness. †The estimated maximum absolute optical blue magnitude after correction for distance and extinction.

where ν_b is a discontinuity or critical break frequency at which adiabatic losses and synchrotron losses become equal.

There is one obvious difficulty common to the centrally driven miniplerion models. One expects from one to several solar masses of material to be in the ejecta of a supernova, and such a large amount of material, even if it were only partially ionized, would totally preclude the observation of radio emission from a centrally driven RSN for many decades. Two possibilities have been proposed to avoid this: (i) the matter in the supernova ejecta clumps very early into dense filaments that contain essentially all the mass but block very little of the view into the center of the supernova system, as occurs in the Crab Nebula (*29*); or (ii) the magnetic field and relativistic particles generated by the central energy source leak through the dense ejecta of the supernova and originate their radio radiation in an external region, surrounded only by the low-density wind material described earlier (*27*).

The correspondence between the light curve for the Type I_{SL} supernova SN1983n and the minishell model is quite satisfactory (*17, 18*). For $\alpha = -1.0$ and $m = 0.8$ ($S \propto \nu^{-1.0} t^{-1.6}$), the radio observations are fit in essentially all particulars (Fig. 2). Such a correspondence between a Type I supernova and a minishell model is also satisfying because it agrees, at least in principle, with the expectation that Type I supernovae leave no stellar remnants (*24, 25, 31, 32*) to act as the central energy source necessary for miniplerion models. This is not conclusive proof, however, because a miniplerion model with an accelerated outer boundary ($m = 1.2$) gives an identical prediction for the evolution of the nonthermal synchrotron emission, and the present data do not permit an unbiased choice to be made.

For the Type II_L supernova SN1979c, with its flatter radio spectrum and slower rate of decline after maximum, both classes of models have been applied [minishell (*24, 33*) and miniplerion (*26, 30*)]. However, neither model fits the data precisely, and one can be made to fit as well as the other (Fig. 1). In fact, SN1979c appears to

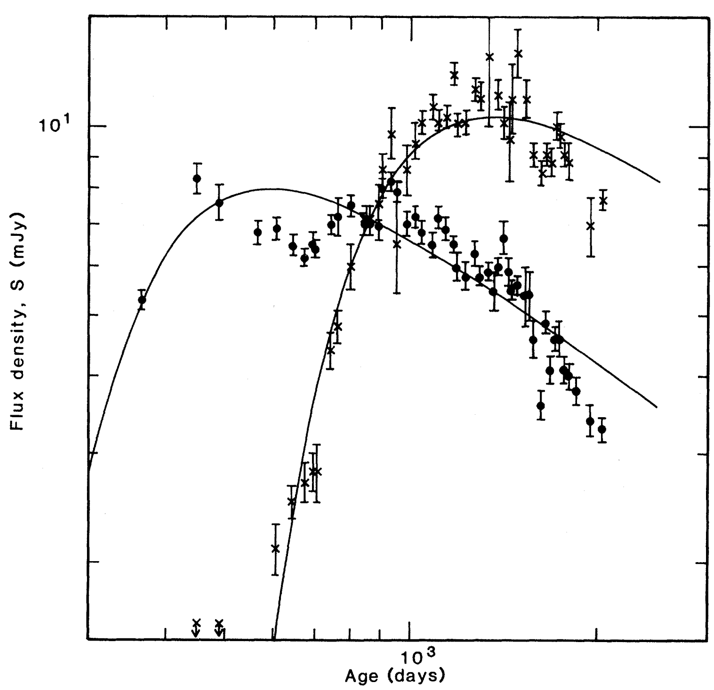

Fig. 1 (left). Radio light curves for the Type II_L supernova SN1979c in NGC4321 (M100). Symbols: (x) 20-cm wavelength, (●) 6-cm wavelength. The age of the supernova is measured in days from the estimated date of explosion on 4 April 1979, 15 days before the date of maximum optical light.

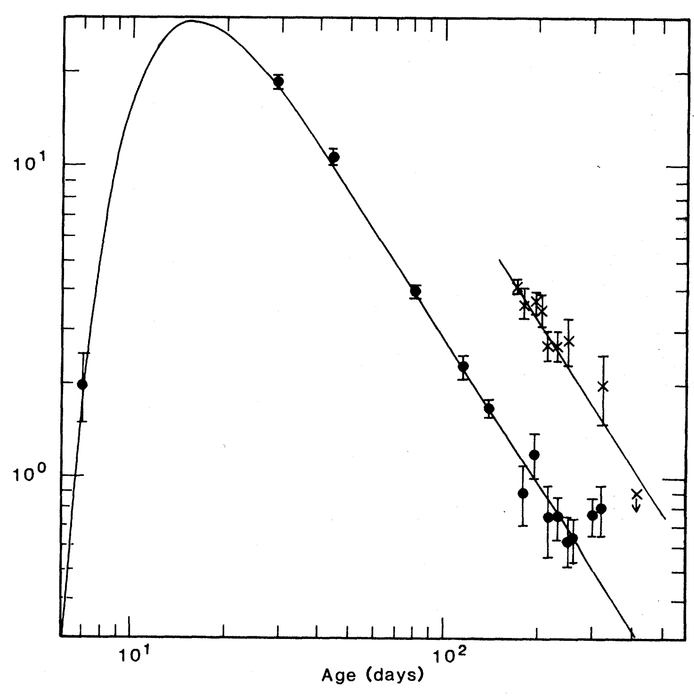

Fig. 2 (right). Radio light curves for the Type I_{SL} supernova SN1983n in NGC5236 (M83). Symbols: (x) 20-cm wavelength, (●) 6-cm wavelength. The age of the supernova is measured in days from estimated date of explosion on 29 June 1983, 18 days before the date of maximum optical light.

represent the degenerate case where the supernova outer boundary is moving with constant velocity, neither accelerated nor decelerated; in this case the two classes of models give identical predictions for the same observed parameters. However, SN1980k, one other Type II_L supernova that is not discussed in detail here, has measured parameters that are somewhat better described by the minishell model.

Thus, with the presently available data, a preference for the minishell model for describing the very early development of these young RSN, both of Type I and Type II, is indicated. The miniplerion model remains viable, however, and more observations are being taken to refine further our description of these exploding stars.

Obviously, the connection of young RSN such as SN1979c and SN1983n and middle-aged RSN such as SN1957d and SN1950b to the historical shell-type supernova remnants (Cassiopeia A, SN ~ 1670; Kepler's supernova, SN1604; Tycho's supernova, SN1572; and SN1006) and filled-center plerionic supernova remnants (3C58, SN1181; Crab Nebula, SN1054) is important but as yet relatively unexplored and poorly understood. An investigation of this connection is beyond the scope of the present work but has been described in more detail elsewhere (*10*).

Conclusions

Drawing very general conclusions from such a small sample of objects is hazardous. This is especially true because the broad classes of optical supernovae—Type I and Type II—are gradually, on the basis of more modern and accurate observations, being broken up into subclasses. Both SN1979c and SN1980k are members of the so-called linear, Type II_L subclass of supernovae, and SN1983n and SN1984l were subluminous Type I_{SL} supernovae (*10, 16, 22, 23*). However, with these limitations in mind, a preliminary summary may be made.

1) Type II supernovae show a consistently flatter, nonthermal radio spectral index ($\alpha \sim -0.6$) than Type I supernovae ($\alpha \sim -1.0$).

2) Type II supernovae show a slower decline of flux density with time ($\beta \sim -0.7$) than Type I supernovae ($\beta \sim -1.6$).

3) Type II supernovae turn on later in their radio emission than Type I supernovae, implying greater amounts of thermal matter or lower velocity shock waves (or both) in the former.

In further consideration of the third point, this great variation between the supernova types in their optically thick radio properties implies a great variation in supernova environments. However, the tendency for Type II supernovae to turn on later in the radio is generally consistent with a model where massive progenitors (greater than 8 solar masses) establish their own local environment through mass loss in the last stages of stellar evolution. A range of masses gives a variation in mass loss rates and a difference in thermal absorption effects, but all are relatively high. On the other hand, the progenitors for Type I supernovae are considered in some models to be white dwarf stars in mass-transfer binary systems. In such models, the companion star is insufficiently massive to become a Type II supernova (*34*) but is in its red supergiant phase and losing mass rapidly. Through this mass loss, it provides the mass both for accretion to its white dwarf companion, which triggers the white dwarf as a Type I supernova, and for the stellar wind environment where the radio emission takes place after the supernova explosion (*17*). However, some investigators feel that Type I_{SL} supernovae such as SN1983n and SN1984l may, in fact, have a different origin and arise from single, isolated, massive stars of 10 to 20 solar masses (*22, 23*).

The study of supernovae as opposed to the study of supernova remnants is a new one for radio astronomy, essentially opened up by the availability of the excellent resolution and sensitivity of the VLA. It has yielded detailed information about a number of objects and offers the fascinating possibility of being able to study the physical conditions in stellar systems undergoing violent supernova explosions. Also, through a method suggested by Bartel and his collaborators (*35*), very long baseline interferometry observations of RSN may lead to an independent means of determining the distance to other galaxies and perhaps to a new determination of the Hubble constant, the rate of expansion of the universe.

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