RADIO SUPERNOVAE

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Three supernovae have so far been detected in the radio range shortly after their optical outbursts. All are Type IIs. A fourth supernova, a Type I, is being monitored for radio emission but, at an age of approximately one year, has not yet been detected. For two of the supernovae, extensive data are presented on their "light curves" and spectra and models which have been suggested in the literature are discussed.

I. INTRODUCTION

There are four examples which yield essentially all of our knowledge concerning the radio properties of supernovae. These are listed in Table 1. The first three (SN1970g, SN1979c, and SN1980k) were all Type II and are the only supernovae which have ever been detected in the radio range. The last, the Type I supernova in NGC4536, is recent and, although optically bright, has not yet been detected at 6 cm wavelength to a limit of less than 0.06 mJy (1σ) at an age of approximately one year. A lack of detection is, of course, never definitive so that a search for radio emission continues.

Table 1: Radio Supernovae

Object	Galaxy	SN Type	Optical Max.
SN1970g	M101	II	1 Aug. 1970
SN1979c	M100 (NGC 4321)	II	23 Apr. 1979
SN1980k	NGC 6946	II	3 Nov. 1980
SN1981b (undet.)	NGC 4536	I	5 Mar. 1981

In order to put the properties of radio supernovae in perspective, they are compared with several well known galactic supernova remnants in Table 2. The columns are self-explanatory except for, perhaps, column 8 which gives an example of how strong each source would be if it were placed at a standard distance of the galactic center (10 kpc). Examination of Table 2 shows that young Type II supernovae are likely to be intrinsically very bright and compact objects. From column 9 it is

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apparent that the detected radio supernovae are from one to more than two orders of magnitude stronger than the brightest supernova remnant known, Cassiopeia A.

Table 2: Comparisons

SOURCE	S^{6cm}_{Peak} Jy	DIST. kpc	S^{c}_{6cm} Jy	SIZE^{c} arcsec	SIZE^{c} pc	F Peak W Hz^{-1}	$S^{10kpc}_{6cm\ Peak}$ Jy	RATIO to Cas A
Cas A		2.8	900	300	4	$8*10^{17}$	71	1
3C10		5	30	600	14	$8*10^{16}$	8	0.1
Crab		2	660	360	3.5	$3*10^{17}$	26	0.4
3C58		8	29	480	18.5	$2*10^{17}$	19	0.3
SN1970g	$\approx$.005	$7*10^{3}$	undet	$3.6*10^{-3a}$	$1.2*10^{-1a}$	$3*10^{19}$	2,500	35
SN1979c	.008	$16*10^{3}$	.007	$4.1*10^{-4a}$	$3.2*10^{-2a}$	$2*10^{20}$	20,500	290
SN1980k	.003	$5*10^{3}$	.001	$6.2*10^{-4a}$	$1.5*10^{-2a}$	$8*10^{18}$	650	9
SN1981b	$\leq$.00006^{b}	$20*10^{3}$	undet	$1.1*10^{-4a}$	$1.1*10^{-2a}$	$\leq 3*10^{18}$	$\leq$240	$\leq$3

[a] Assumes an average expansion velocity of 10^{4} km s^{-1}
[b] One sigma
[c] In April 1982

SN1970g had only five significant detections (Marscher and Brown, 1978) so that little information is available on its radio light curve and spectrum and the Type I supernova in NGC4536 has not yet been detected. Thus, we will concentrate on the new results for SN1979c and SN1980k. A more detailed discussion of their general properties has recently been presented by Weiler et al. (1981, 1982).

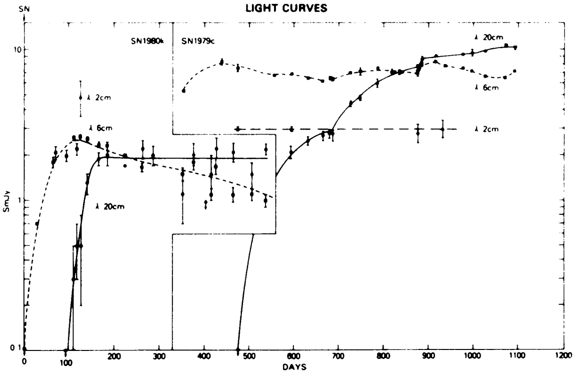

Figure 1: The radio "light curves" for SN1979c and SN1980k. All points are taken with the VLA. The "age" in days for both objects is counted from the date of maximum optical light.

II. RESULTS

The available information on the radio observations of SN1979c ($\alpha(1950) = 12^h 20^m 26.^s71$, $\delta(1950) = +16^\circ 04'29.''5$) and SN1980k ($\alpha(1950) = 20^h 34^m 26.^s68$, $\delta(1950) = +59^\circ 55'56.''5$) is shown in Figure 1. The observations at 20 cm (1.5 GHz), 6 cm (5 GHz) and 2 cm (15 GHz) are all taken with the VLA^1. Since their initial detections, both SN1979c and SN1980k have been monitored approximately once per month and additions to the light curves are still being observed.

The main features of the light curves are their extremely sharp turn-on, the delays between 6 and 20 cm, the differing delays before turn-on for SN1979c and SN1980k, and the irregular, "bumpy" form for the well determined light curve of SN1979c. It is also interesting to note that SN1979c shows higher peak flux densities at lower frequencies while SN1980k shows the reverse.

The radio spectra of both SN1979c and SN1980k are steepening with time as is seen in Figure 2. The rate of steepening, however, appears to be slowing for both sources and an asymptotic approach to a limit of $\alpha \sim -0.5$ - -0.7 appears possible.

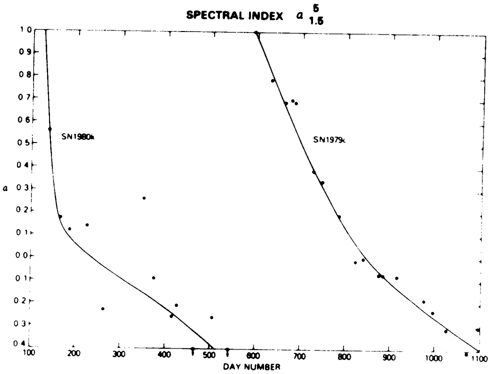

Figure 2: Spectral index ($S \propto \nu^{+\alpha}$) between 20 cm and 6 cm plotted as a function of time.

III. DISCUSSION

The sharp turn-on of the radio light curves and the time delay in the turn-on between 6 and 20cm can most easily be described by an optical depth effect. This has been discussed at greater length by Weiler et al. (1982).

Although a detailed discussion of models for the emission mechanism of radio supernovae will be deferred to a future paper, there are two general problems which must be addressed in any successful description:

1) how the relativistic synchrotron particles are generated, and
2) how the radio radiation escapes through the great amount of matter believed to be in the photosphere of a Type II supernova.

An older model, that of impulsive creation of relativistic electrons expanding adiabatically from a single outburst (van der Laan, 1966) is inconsistent with the data. The model predicts a slow turn-on at any frequency and significantly higher maxima at higher frequencies, neither of which are observed in SN1979c. The higher maxima at higher frequencies are observed in SN1980k, but the slow turn-on is not.

Three new models have recently been advanced which, although they lack the details necessary for a quantitative comparison, deserve further consideration. All three can permit the sharp turn-on of the radio radiation as an optical depth effect. However, they differ significantly in their generation and distribution mechanisms for relativistic particles.

1) The Shklovskii Model (Shklovskii, 1981) consists of a young plerion (a young Crab Nebula - Weiler and Panagia, 1980) which is formed by the pulsar remaining after the Type II supernova explosion. The pulsar's magnetic field and relativistic synchrotron particles "leak" through the filaments of the supernova shell to regions of sufficiently low optical depth to be visible at radio wavelengths. This situation is illustrated in Figure 3.

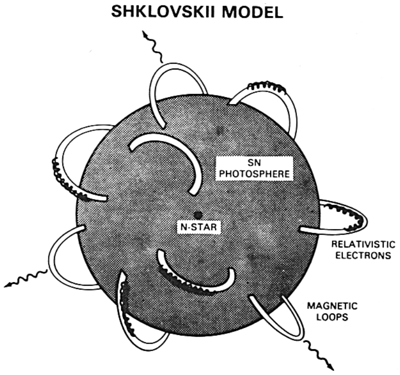

Figure 3: Author's (KWW) visualization of the Shklovskii Model.

2) The Pacini and Salvati Model (Pacini and Salvati, 1981; see also Pacini and Salvati, 1973 and Brown and Marscher, 1978) consists similarly of a young plerion formed by the remaining neutron star but this "mini-Crab" remains near the center of the supernova. With proper input parameters, the model can match the observed properties of the radio supernovae. However, the

problem remains of transporting the radiation through the expectably massive supernova shell. This can be solved if the shell quickly breaks into a net of dense filaments which provide low density paths to the central regions. This situation is illustrated in Figure 4.

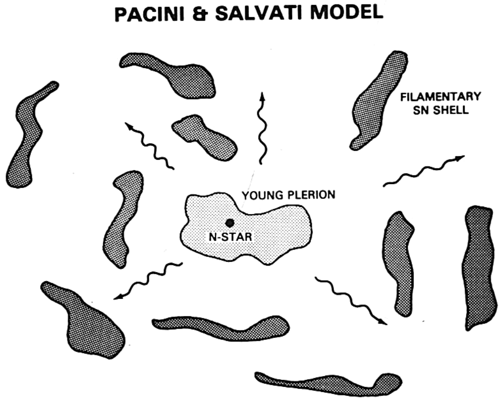

Figure 4: Author's (KWW) visualization of the Pacini and Salvati Model.

3) Whereas the previous two models are broadly related to plerionic supernova remnants, the Chevalier Model (1981) involves mechanisms resembling those of shell-type supernova remnants. The shock wave from the supernova explosion expands into the interstellar cocoon, formed by mass loss during the last stages of stellar evolution, and accelerates relativistic particles. This model can be made to fit the observed properties of SN1980k very well, but has difficulty describing the relatively constant level of radio emission still observed for SN1979c.

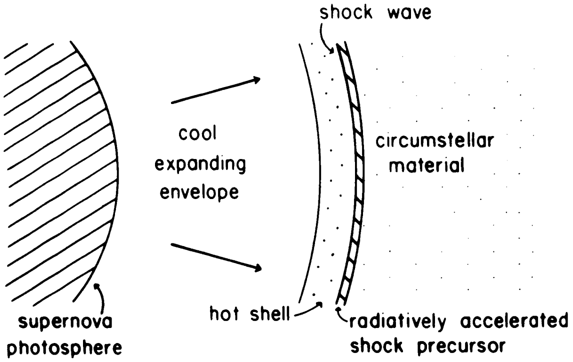

Figure 5: Chevalier Model (Chevalier, 1981)

M. Salvati (1983) has suggested that the flat light curve of SN1979c can be explained by a combination of Models 2 and 3. Initially, the shock wave in the circumstellar material predominated as in the Chevalier model, but more recently the central plerion has become visible through the cooling supernova shell as in the Pacini and Salvati model. The plerion emission is thus compensating for the expected decline in the shock-excited shell emission.

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