Observations of Circumstellar Media Around Supernovae

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Abstract

Some supernovae are visible for several years past explosion. The main energy source for this sustained emission is coming from the supernova shock interacting with the remnant of the stellar wind of the progenitor star. We review the available evidence for this picture and exclude other power sources on the basis of the radiated energies. We also discuss a group of supernovae which display narrow emission lines with high fluxes in their spectra and very slowly declining optical light curves. These observations can most readily be explained by interaction with a very dense medium close to the supernova.

1 Introduction

A variety of supernova interactions with circumstellar material (CSM) has been observed to date. The best, and most direct, example is the ring of emission around SN 1987A (Jakobsen et al. 1991). This material has been ionized by the UV and soft X-ray flash of the shock breakout at the surface of the supernova (Fransson et al. 1989, Lundqvist & Fransson 1989). The density enhancement in the ring is caused by the interaction of the fast blue supergiant wind colliding with the slow red supergiant wind of a previous epoch (Blondin & Lundqvist 1993). In the case of SN 1993J, the early detection of radio and X-ray emission, in combination with narrow emission lines in the UV and optical, are indicative of interaction with the CSM. Blue optical continua, X-ray detection at early phases, as well as the UV emission have been proposed as characteristics of a shock in the CSM around SN 1979C (Fransson 1984). Infrared light echos observed around SN 1979C and SN 1980K are indicators of cold CSM (Dwek 1983). The most frequently observed signatures of CSM around supernovae, however, are radio emission (Chevalier 1984, 1990) and optical detection several years past explosion. The structure of the stellar interior is exposed when the explosion becomes transparent and the circumstellar environment is excited by the supernova

To appear in Herstmonceux '34: *Circumstellar Media in Late Stages of Stellar Evolution*, eds. R. Clegg, P. Meikle, & I. Stevens (Cambridge University Press, Cambridge)

Table 1. *Supernovae interacting with circumstellar media*

SN	Type	radio	Ref.	optical (>3 years)	Ref.	X-rays	Ref.
1957D	?	$\surd$	1	$\surd$	22–24	–	–
1961V	II	$\surd$	2	$\surd$	25,2,26	–	–
1970G	II	$\surd$	3–7	$\surd$	27	–	–
1978K	?	$\surd$	8	$\surd$	8,28	$\surd$	8
1979C	II	$\surd$	9	$\surd$	29	–	–
1980K	II	$\surd$	10	$\surd$	30–32	$\surd$	39
1981K	?	$\surd$	6	–	–	–	–
1983N	Ib	$\surd$	6,11	$\circ$	22	–	–
1984L	Ib	$\surd$	6	–	–	–	–
1986J	II	$\surd$	12–15	$\surd$	31,32	$\surd$	40
1987A	II	($\surd$)	16,17	$\surd$	33,34	($\surd$)	41,42
1988Z	II	$\surd$	18	$\surd$	35,36	–	–
1989R	II	–	–	$\surd$	37	–	–
1990B	II	$\surd$	19	$\circ$	38	–	–
1993J	II	$\surd$	20,21	–	still young	$\surd$	43,44

References:
1 Cowan & Branch 1985; 2 Cowan et al. 1988; 3 Gottesman et al. 1972; 4 Allen et al. 1976; 5 Brown & Marscher 1978; 6 Weiler et al. 1986; 7 Cowan et al. 1991; 8 Ryder et al. 1992; 9 Weiler et al. 1991; 10 Weiler et al. 1992; 11 Panagia et al. 1986; 12 Rupen et al. 1987; 13 Weiler et al. 1990; 14 Sukumar & Allen 1989; 15 Bartel et al. 1991; 16 Turtle et al. 1987; 17 Staveley-Smith et al. 1992; 18 Sramek et al. 1990; 19 Van Dyk et al. 1993a; 20 Pooley & Green 1993; 21 Van Dyk et al. 1993b; 22 Long et al. 1989; 23 Long et al. 1992; 24 Turatto et al. 1989; 25 Fesen 1985; 26 Goodrich et al. 1993; 27 Fesen 1993; 28 Dopita & Ryder 1990; 29 Fesen & Matonick 1993; 30 Fesen & Becker 1990; 31 Leibundgut et al. 1991; 32 Uomoto 1991; 33 Bouchet et al. 1991; 34 Suntzeff et al. 1991; 35 Stathakis & Sadler 1991; 36 Turatto et al. 1993; 37 this contribution; 38 A. C. Porter, private communication; 39 Canizares et al. 1982; 40 Bregman & Pildis 1992; 41 Dotani et al. 1987; 42 Sunyaev et al. 1987 43 Zimmermann et al. 1993; 44 Tanaka et al. 1993

shock. Investigation of the stellar properties, however, has to await fading of the radiative display from the explosion. In a few cases the CSM is dense enough to dominate the emission from the explosion.

The list of supernovae (SNe) still optically observable several years after outburst includes now at least ten objects (Table 1). With one exception, SN 1989R which has not been observed, all these objects have been detected at radio wavelengths. Conversely, all SNe II with a radio detection have been recovered optically. All SNe Ib/c with radio observations faded in the optical a few (<3) years past their discovery. Two supernovae observed in the radio have no classification; SN 1957D has been recovered in the optical several decades after maximum, while SN 1981K has no optical detection so far. The radio light curve of SN 1987A is rather peculiar and is not necessarily due to strong interaction with the CSM (Staveley-Smith et al. 1992).

Five supernovae have also been detected in X-rays at different epochs in their evolutions. While SN 1980K and SN 1993J exhibited X-rays shortly after outbreak, SN 1978K and SN 1986J had observable X-ray fluxes several years past outburst. The X-ray flux of SN 1987A is probably due to comptonization of γ-rays and not necessarily related to CSM.

The optical evolution of SNe II can be separated into several phases (e.g. Leibundgut 1994). Interaction with CSM can influence the general evolution by different amounts for individual supernovae. The contribution from CSM interaction can dominate the optical emission from the start (e.g. SN 1988Z; Turatto et al. 1993), influence the evolution near peak (SN 1993J; Cumming et al., this conference), or drive the emission several years after explosion (Chugai 1990, 1992, Chevalier & Fransson 1993).

We will describe the evidence for shock interaction of a supernova with its CSM and present arguments that exclude other power sources. First we will review the available optical observations for supernovae older than a decade (§2). In section 3, we present the data on SNe II with strong and persistent narrow-line emission. The conclusions (§4) will try to justify the above distinction among SNe II.

2 Old Supernovae

The investigation of supernovae at very late phases has still a rather short history. The first supernova with an optical identification at an age >10 years has been SN 1961V (Fesen 1985, Cowan et al. 1988), but its classification as a supernova has been questioned (Goodrich et al. 1989, Bower et al. 1993). Three objects were discovered by a dedicated search program of Robert Fesen, who recovered SN 1980K (Fesen & Becker 1990), SN 1979C (Fesen & Matonick 1993), and SN 1970G (Fesen 1993). At the same time a search for supernova remnants in nearby galaxies disclosed SN 1957D more than two decades after explosion (Long et al. 1989). SN 1978K and SN 1981K have very little optical information and will not be discuss here.

2.1 SN 1957D in M83

This supernova in the southern sky has no spectral classification. Nonthermal radio emission was found by Cowan & Branch (1985). The same radio map also shows non-thermal sources near the sites of SN 1950B and SN 1983N, but neither has been recovered in the optical (Long et al. 1989). At optical wavelengths SN 1957D was first detected in the light of the [O III] ($\lambda\lambda$ 4959, 5007 Å) doublet lines in 1987. The narrow-band imaging was verified by spectra obtained a year later (Long et al. 1989, Turatto et al. 1989). Strong emission in [O III] but only weak lines of Hα and [O I] ($\lambda\lambda$ 6300, 6364 Å) were found.

A remarkable drop in optical luminosity occurred between 1987 and 1991, when the supernova faded by a factor of $\sim$5 (Long et al. 1992). This fading has been attributed to the supernova shock reaching the edge of the wind zone of the progenitor star. Another interpretation is that in 1987 an excited state was observed, when the shock ran into a condensation. In this case the emission would vary on time scales of years. Careful monitoring of SN 1957D is expected to provide further clues to the nature of this object.

2.2 SN 1970G in M101

The location of SN 1970G only 0.5 arcseconds away from a stellar-like source, which is probably part of the giant HII complex NGC 5455 in M101 (NGC 5457), makes observations of this object exceedingly difficult (Fesen 1993). SN 1970G has been clearly recovered in [O I] images and a spectrum has been secured. Broad emissions of [O I] and Hα are detected, with narrow lines superposed. The latter are most likely due to the nearby HII region.

The spectral identification of SN 1970G has profited greatly from comparison with SN 1980K, which shows similar line widths (Fesen 1993). While [O I] and Hα lines are observed, no [O III] emission is detected in SN 1970G, a remarkable distinction from all other supernovae at similar ages. Fesen (1993) points out that SN 1970G has shown a normal light curve and spectral evolution around maximum (Barbon et al. 1973, Kirshner et al. 1973) and does not constitute a peculiar case, which might be argued for SN 1979C and SN 1980K (see below).

2.3 SN 1979C in M100

This supernova in the Virgo cluster of galaxies is the most distant in the sample of decade-old SNe II. It has been exceptionally luminous at maximum (de Vaucouleurs et al. 1981, Branch et al. 1981) and its light curve did not display the characteristic plateau observed in many SNe II. The spectral evolution around maximum has also been peculiar exhibiting a narrow Hα emission at early times and little absorption in the P Cygni profile of Hα

(Branch et al. 1981). Interaction with CSM was inferred from the UV and blue spectral shape (Fransson 1984) and the strong radio emission, which turned on less than 13 months after explosion (Weiler et al. 1986).

This supernova is relatively luminous even at these very late phases (Fesen 1993). The optical emission of SN 1979C is again mostly in [O I] and Hα lines but also with a sizable [O III] emission (Fesen & Matonick 1993). In addition, [O II] or [Ca II] near λ 7300 Å is observed. The spectrum appears unchanged over the course of one year (Fesen & Matonick 1993). Narrow lines are probably due to a nearby HII region, which is situated less than 2 arcseconds from SN 1979C.

2.4 SN 1980K in NGC 6946

The most extensive data set is currently available for SN 1980K. It was recovered optically in 1987 (Fesen & Becker 1990) and has been monitored since (Leibundgut et al. 1991, 1993, Uomoto 1991, Fesen 1993). Around maximum this supernova is one of the best studied SN II. Its light curves declined steadily for the first 13 months (Barbon et al. 1982, Buta 1982). The spectral evolution was similar to SN 1979C (Barbon et al. 1982). It developed a nebular spectrum after about 8 months with strong Hα, [O I], and [O III] emissions (Uomoto & Kirshner 1986). Although the decline rate of Hα matched the half-life of ^{56}Co decays, Chugai (1990) showed that the emission had to be powered by an additional energy source. Note that this differs from the bolometric light curve (Schmidt et al. 1994), where the decline indeed reflects the characteristic lifetime of the radioactive source.

More than a decade after maximum SN 1980K is still emitting in the same lines. The decline, however, has stopped completely and all lines are emitting at a constant flux level (Fig. 1). Typical line widths are $\sim$5000 km s^{-1} (Fesen & Becker 1990, Leibundgut et al. 1991). Broad-band photometry established SN 1980K at V=22.8$\pm$0.2 mag. and R=21.9$\pm$0.1 mag. (Leibundgut et al. 1993).

The total luminosity in the BVRI wavelength range amounts to $1.2 \cdot 10^{-14}$ erg cm^{-2} s^{-1}. Given the distance to NGC 6946 the total emitted flux is then $8 \cdot 10^{37} \cdot (\frac{D}{7.5\ \mathrm{Mpc}})^2$ erg s^{-1}. Such high fluxes exclude long-lived radio isotopes as the power source, since an amount of 10^{-2} M$_\odot$ of ^{44}Ti would be needed in contradiction with nucleosynthesis yields in SNe II (Woosley et al. 1989). Because the line fluxes have not changed after recovery of SN 1980K, it is safe to integrate over this time span. The emitted energy is then $\sim 10^{46} \cdot (\frac{D}{7.5\ \mathrm{Mpc}})^2$ erg and, if the flux did not change since 1982 (the last observation of Uomoto & Kirshner), this number is doubled. This

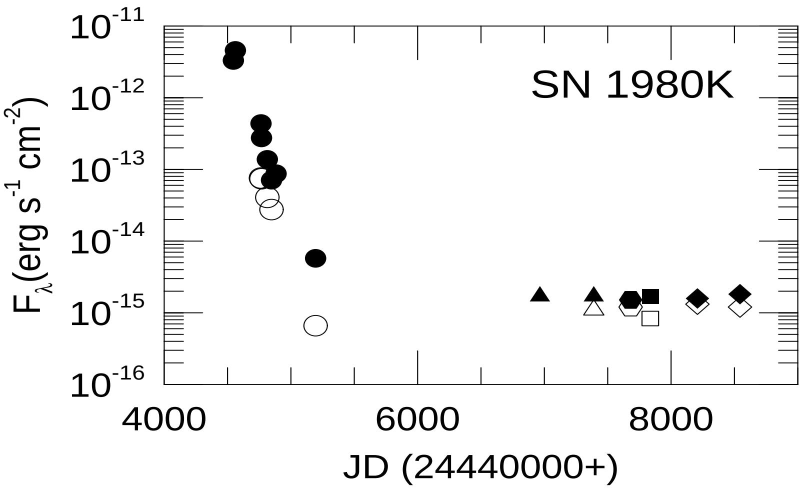

Fig. 1. Hα (filled symbols) and [O I] (open symbols) line fluxes for SN 1980K. The data are taking from the following references; Uomoto & Kirshner 1986 (○), Fesen & Becker 1990 (△), Uomoto 1991 (⬡), Leibundgut et al. 1991 (□), and this contribution (◇).

rules out a light echo from the shock breakout as the power source, since at least 10% of the UV flash would have had to be converted into optical emission and emitted over a period of >10 years. Because the flash ionizes the volume just once, the number of Hα photons ($3 \cdot 10^{57}$) requires >3 $M_\odot$ of hydrogen, assuming Case B recombination.

The flux in SN 1980K is remarkably close to what is expected from a powerful pulsar (like the Crab). Chevalier & Fransson (1992) have investigated the influences of powerful pulsars inside old SNe and young supernova remnants. They predict line velocities of a few hundred km s^{-1}, which is not observed in SN 1980K. The observed line widths of ~5000 km s^{-1} exclude this power source for SN 1980K.

Shock interaction with CSM taps the kinetic energy pool (~10^{51} erg) by converting a fraction of it into radiation. The forward shock ionizes the CSM and X-rays from the reverse shock produce emission from the ejecta (Chevalier & Fransson 1993). The observed energies and the line widths strongly favor circumstellar interaction. While the presence of the [O III] lines is probably due to ejecta heating, the [O I] and Hα emissions more likely arise from the CSM (Chevalier & Fransson 1993).

2.5 Summary

While only a few supernovae at very late epochs have been detected and their observations are still scarce, a trend seems to be emerging. All objects show emission lines of the same elements, namely hydrogen and oxygen with a possible contribution of calcium to the 7300 Å feature. This fits nicely with the CSM model presented by Chevalier & Fransson (1993). The ionizations differ among the individual SNe: SN 1957D shows mainly [O III] emission, while this is not detected in SN 1970G. The constant flux in SN 1980K, however, is not predicted by the models.

3 Strong Interactors

In recent years a few SNe II have been observed displaying some distinct properties. A first example was presented by Dopita et al. (1984) with observations of SN 1984E at maximum. This object had narrow lines of hydrogen and helium on top of strong P Cygni profiles. The narrow emissions were attributed to an extended, optically thick, outflow. For the derived density a very strong wind phase had to be invoked (Dopita et al. 1984).

Schlegel (1990) proposed a subclass for SNe II consisting of events with narrow emission lines. His list included a few objects which are clearly influenced by nearby HII regions and the class as a whole had no distinct characteristics apart from the narrow lines. We will discuss here three objects with narrow emission lines and particularly slow decline rates, which are not affected by contaminating light.

3.1 SN 1986J in NGC 891

The longest-observed supernova of this group, SN 1986J, was first discovered in the radio in 1986, but is found on radio maps and optical images as far back as 1984 (Rupen et al. 1987). Estimates of the explosion dates have large uncertainties, partly due to the peculiar nature of the supernova, but fall of 1982 seems generally accepted (Rupen et al. 1987, Weiler et al. 1990).

The optical spectrum of SN 1986J is remarkable for its narrow, unresolved (Δv<700 km s^{-1}) emission lines of H, He, N, and Fe, and broader (Δv$\approx$2000 km s^{-1}) lines of three ionization stages of oxygen (Leibundgut et al. 1991). The [O I] doublet lines did not display the usual optically thin ratio, but rather were of about equal strength. A detailed non-LTE investigation indicated high density material ($6 \cdot 10^8 < n_{O^0} < 2 \cdot 10^9$) at low temperatures ($3000 < T < 4000$ K). The line strengths of the narrow components decreased steadily, but at a rate much smaller than if powered by ^{56}Co decay. The oxygen lines, however, have remained roughly constant in absolute fluxes (Leibundgut et al. 1991). If the [N II] (λ5755 Å) line indeed comes from the CSM, as purported by the narrowness of the line, the wind is nitrogen-enriched like in SN 1987A (Fransson et al. 1989).

SN 1986J has also been observed at X-ray wavelengths (Bregman & Pildis 1992). This emission could be either from the reverse shock or from dense clumps in the circumstellar medium excited by the outer shock (Chugai 1993).

3.2 SN 1988Z in MCG 03-28-022

The photometric and spectroscopic appearance of this supernova has also been rather peculiar. Narrow lines dominated the spectrum, but broad and intermediate components of Hα could be resolved at early phases (Stathakis & Sadler 1992, Turatto et al. 1993, Filippenko 1991). The expansion deduced from the broad component was $\sim$40000 km s^{-1} and matches velocities in other SNe II. No P Cygni absorption was recorded for SN 1988Z in the photospheric phase. In addition to the narrow lines of H, He, N, and Fe, broad emission from Ca was detected (Turatto et al. 1993). A broad bump around 5300 Å observed half a year after discovery was attributed to smearing of many Fe II lines (Chugai, this conference).

The Hα luminosity evolution is also very slow with a peak about 400 days after discovery at around 10^{41} erg s^{-1} and a decline to $\sim 3 \cdot 10^{40}$ erg s^{-1} within 1200 days (Turatto et al. 1993). The shape of the L(Hα) curve and spectra at about 3-4 years after explosion (Leibundgut 1991) are rather similar for SN 1988Z and SN 1986J.

3.3 SN 1989R in UCG 2912

This is a new representative of SNe II with narrow lines and slowly decaying light curves. The first spectrum 2 days after discovery displays narrow emission lines (Kirshner et al. 1989) on a rather featureless continuum. There is only a hint of broad emission visible at Hα. Later observations show considerable reddening of the spectrum. The IR triplet of Ca II is possibly detected 2 years past discovery, but should be confirmed by a more careful analysis. The R light curve of SN 1989R has a break at around 250 days past discovery, when the slope changes from 0.025 ± 0.001 to $(1.9 \pm 0.2) \cdot 10^{-3}$ mag/day. The SN was still detectable 3 years after discovery.

3.4 Summary

We presented three cases of SNe with narrow emission lines of H, He, and N in their spectra and small decline rates in the R light curves. A detailed comparison of the spectrum of SN 1986J four years past explosion and SN 1988Z three years past discovery reveals a great similarity. The same set of lines is present in both SNe. They were also prolific radio emitters and are easily separated from the other radio supernovae (Van Dyk, this conference). SN 1989R is a new and fainter example of this group. Scaled to the distance of SN 1988Z it is $\sim$2.3 times (0.9 mag) fainter at discovery in R. Note that none of the SNe has been discovered on the rise. The light curve of SN 1988Z is decaying very slowly ($\sim$0.003 mag/day) and the SN has faded by $<$4 magnitudes in 3 years. SN 1986J and SN 1989R declined in a comparably slow manner.

All properties indicate an interaction of the supernova with dense CSM from the very onset of the explosion.

4 Conclusions

Circumstellar material around supernovae is evidenced in several ways. Light echos from the explosion can excite this matter and is observable as spatially resolved emission around SN 1987A, as narrow emission lines superposed on the supernova UV and optical spectrum (Fransson et al. 1989; Sonneborn, this conference, Cumming et al., this conference), or as an IR echo (Dwek 1983). Direct observations of X-rays and a blue continuum from down-scattered X-ray photons can indicate a shock in the CSM (Fransson 1984).

The most obvious signature of interaction with the CSM so far has been the radio emission (Van Dyk, this conference). All SNe with sustained optical radiation are radio supernovae.

The supernovae discussed here have been separated into two groups. To clarify the main distinction, we summarize the fluxes and energies emitted by all objects in Table 2. The measured fluxes are all rather small and constant for most old (t$>$10 years) SNe, while large but decreasing for the younger ones. All narrow-line SNe have been observed in rather distant galaxies (H_0=75 km s^{-1} Mpc^{-1} is assumed for SN 1988Z and SN 1989R; all other distances are either from cepheids or planetary nebulae luminosity functions). The luminosity in the Hα line is two to three orders of magnitudes larger in the narrow-line SNe. Note that we did not correct for extinction. An absorption of A_V=1.5 for SN 1986J (Leibundgut et al. 1991) increases the flux and luminosity of this object by a factor of $\sim$4. Thus, the narrow-line supernovae are much more luminous than regular old

Table 2. *Hα Luminosities of old supernovae*

SN	Galaxy	D (Mpc)	F(Hα)[a]	L(Hα)[b]	E(Hα)[c]	Period[d] (years)
1957D	M83	4	12–2[e]	20–4[e]	>1[e]	4
1970G	M101	7	1.8	>10	>10	22
1979C	M100	16	2.5	>80	>10	11
1980K	NGC 6946	7.5	1.7	>10	>10	10
1986J	NGC 891	10	100–10	$>10^3$–10^2	>100	5
1988Z	MCG +03-28-22	90	100–10	$>10^5$–10^4	>1000	2.3
1989R	UGC 2912	75	20–1	$>10^4$–10^3	>100	2

[a] in 10^{-15} erg s^{-1} cm^{-2}
[b] in 10^{36} erg s^{-1}
[c] in 10^{45} erg
[d] Period of integration for the total emitted energy
[e] Fluxes from the [O III] lines

SNe. This indicates a much stronger interaction with a very dense medium as was inferred for SN 1986J and SN 1988Z (Filippenko 1991, Turatto et al. 1993, Chugai & Danziger 1993), and is supported by the X-ray detection of SN 1986J (Bregman & Pildis 1992, Chugai 1993). The detection of [N II] indicates nitrogen-enriched CSM, possibly from the dredge up in the convection near the surface of a rather massive star.

The total energies emitted in Hα are remarkably uniform at $\geq 10^{46}$ erg (over a decade time span) for the old SNe II. The other group has energies of about one to two orders of magnitude higher over much shorter periods.

Other distinctions include the different radio luminosities and radio light curves shapes (Van Dyk, this conference) and decline rates of the optical light curves. A further distinction represent the widths of the emission lines. The narrow lines emerge from H, He, N, and Fe, while O appears in extended lines. For the old supernovae only broad O and Hα lines are observed. Narrow-line supernovae display all signatures of strong interaction with their circumstellar environment. The optical emission is dominated by the CSM at all times, while for regular supernovae the CSM interaction becomes visible only a few years past explosion.

Observations of CSM around supernovae have become available only recently and the sample is still small. Nevertheless, the shock interaction with the remnant of the stellar wind seems clearly confirmed in all cases. Although we are not yet able to derive detailed parameters of the CSM from these observations, they reinforce our picture of SNe II as core collapse in massive stars that suffered appreciable mass loss during their lives. Eventually, we should be able to map such mass loss histories as the supernova shock moves through the CSM. The variations in SN 1957D might be a hint of clumping in the wind or pulsations of the progenitor. Likewise, flux variations might disclose the presence of companion stars modulating the mass loss as proposed from radio data for SN 1979C (Weiler et al. 1992).

Acknowledgements

I would like to thank W. Vacca for helpful comments on the manuscript. Financial support by the Swiss National Science Foundation and through NSF Grant AST-9115174 are gratefully acknowledged.

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