Supernovae

To appear in Frontiers of Space and Ground-Based Astronomy, *eds. W. Wamsteker, M. Longair, and Y. Kondo, Kluwer Academic Publ., 1994*

Claes Fransson
Stockholm Observatory, S-133 36 Saltsjöbaden, Sweden

and

George Sonneborn
Laboratory for Astronomy and Solar Physics, NASA/GSFC, Greenbelt, MD 20771, USA

Abstract. The IUE observations of SN 1987A are reviewed, and the implications for the nature of the progenitor and the supernova are discussed. Radio, UV and X-ray observations of the recent SN 1993J also provide ample evidence for a dense circumstellar medium. In particular, the strong N V emission seen by IUE provides important information about the state high energy radiation from the shocks and outbreak of the supernova shock wave. We discuss how radio, UV, and X-ray observations can be combined into a consistent scenario, involving the interaction of the supernova with the circumstellar medium.

Key words: Supernovae, Circumstellar matter, SN 1987A, SN 1993J

1 Introduction

SN 1987A and the recent SN 1993J are good examples of how observations from several wavebands can be combined to give a coherent picture of the object. It also shows how important it is to have coordinated observations done on a short notice, and for these reasons we will mainly concentrate on these objects. For general reviews of SN 1987A we refer to Chevalier (1992) and McCray (1993), and for IUE observations of other supernovae to Blair & Panagia (1987).

2 The Ring of SN 1987A

The first detection of the now well known ring of SN 1987A was made with IUE (Fransson *et al.* 1989). The first spectra of SN 1987A taken on February 24, 1987 showed a strong UV continuum with a temperature of $\sim 14,000$ K (Cassatella *et al.* 1987; Kirshner *et al.* 1987). However, this quickly decreased in intensity, at the same time as a number of wide absorption features appeared. After a few days most emission had disappeared, and in the beginning of March 1987 there was very little emission shortward of ~ 1800 Å. The reason for this UV deficiency is now well understood (Fransson *et al.* 1987; Lucy 1987; Xu & McCray 1991; Fransson 1993). The large number of resonance lines present in the UV from neutral and singly ionized elements, in combination with the large velocity width of the lines (up to $\sim 25,000$ km s^{-1}), cause photons emitted in the UV from the ejecta to be scattered by the gas in the core and envelope. Solar abundances are sufficient to make most lines optically thick, so most of the scattering takes place in the extended hydrogen envelope. In each scattering the photon is redshifted by a factor $\sim V/c$. If there is one or more optically thick resonance lines within a wavelength $\Delta\lambda \approx V\lambda/c$ then the photon will again be scattered and redshifted. This continues until the photon finally escapes the ejecta by spatial diffusion, or finds a gap in the resonance line "forest", where it can escape (e.g., Xu & McCray 1991; Fransson 1993).

The disappearance of the UV had the advantage that there was little background emission from the supernova. Therefore, this wavelength range was the first from where one concluded that Sanduleak $-69°202$ had disappeared, and therefore was the progenitor (Gilmozzi *et al.* 1987; Sonneborn, Altner, & Kirshner 1987). Although the flux was virtually absent in the SWP part of the spectrum, IUE continued to observe the supernova. This payed off, and after $\sim$ 100 days it was found that several weak lines were present in the spectrum. These lines increased in strength over the next year and became very prominent features in the spectrum (see Fransson *et al.* 1989 for a display of the spectra from May 1987 to April 1988). The lines seen were N V λ 1240, N IV] λ 1486, He II λ 1640, O III] λ 1664, N III] λ 1750, and C III] λ 1909. From high dispersion spectra it was found that the velocities were less than $\sim$ 30 km s^{-1}. They therefore had to originate in a circumstellar medium around the supernova. Subsequently, optical emission lines were also discovered from the circumstellar medium (Wampler & Richichi 1989). High resolution observations indicated a very low expansion velocity, $\sim$ 10.3 km s^{-1} (Crotts & Heathcote 1991; Cumming & Meikle 1993). Because of the superior resolution of the ground based experiments, one was able to resolve the emitting region, and the now famous ring was found (Crotts, Kunkel, & McCarthy 1989; Wampler *et al.* 1990). From HST observations of the ring with higher resolution a radius of 6.3×10^{17} cm and an inclination of $\sim 43°$ could be determined (Jacobsen *et al.* 1991).

Figure 1 shows the complete IUE light curves of the UV lines from May 1987 until day 2000 (August 1992). These observations have been carefully reduced, correcting for the background continuum from the two neighboring stars in the IUE aperture. First, we note that the general shape of the light curves, with a steady increase in the fluxes up to day $\sim$ 410. After this epoch the lines all decreased on different time scales. A closer inspection shows that the light curves do not extrapolate to day zero, but have a turn-on at $\sim$ 60 days. This is a result of the inclination of the ring, since the light echo paraboloid must reach the ring before it can be excited by the emission. Therefore, it gives independent confirmation of the ring geometry.

The emission lines have yielded many different kinds of information about both the progenitor, its circumstellar medium and the supernova. From the C III], N III] and O III] lines ratios relative abundances of C, N and O could be derived , and it was found that N/O $\approx$ 7.8 and N/O $\approx$ 1.6, by number (Fransson *et al.* 1989).

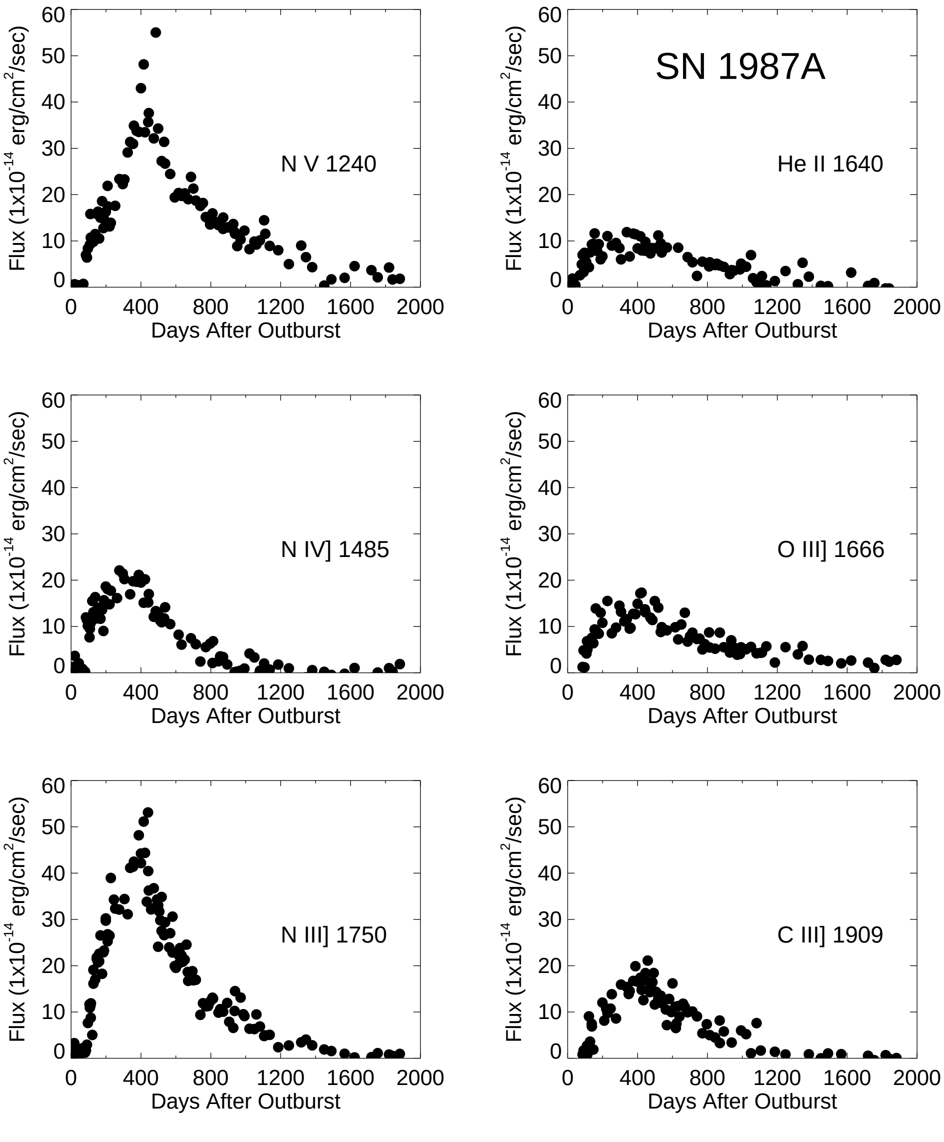


Fig. 1. Light curves of the UV lines from the circumstellar medium of SN 1987A as determined from IUE spectra.

These results clearly indicate that the circumstellar gas must have undergone CNO-processing before the explosion. This in turn, implies that substantial mixing must have occurred in the progenitor. The large nitrogen enhancement has turned out to provide one of the main constraints on the evolution of the progenitor. For reviews of various models see e.g. Podsiadlowski (1992) or the ESO/Elba proceedings (Danziger & Kjär 1991).

The shape of the light curves is a result of a combination of light echo, recombination and cooling effects (Lundqvist & Fransson 1991). At the time of the shock breakout in connection with the supernova explosion a strong burst of UV and soft X-ray emission was emitted. Shigeyama, Nomoto, & Hashimoto (1988) and Woosley (1988) find an effective temperature of $(2-5)\times 10^5$ K at outbreak. A careful study by Ensman & Burrows (1992) results in a peak effective temperature of $\sim 6\times 10^5$ K. The more relevant color temperature was $\sim 1\times 10^6$ K. Most of the emission above 100 eV, responsible for e.g. the N V emission, was emitted during the first $\sim$ 500 s. Twelve hours later the color temperature was only $\sim 3\times 10^4$ K. This burst of energetic radiation ionized and heated the circumstellar medium, explaining the presence of the highly ionized species.

The finite light travelling time implies that we see the gas closest to the line of sight first, and subsequently more and more of the ring is seen. After a time $\Delta t = (1+\sin\, i)R/c$, where i is the inclination of the ring, the full ring is seen. This therefore corresponds to maximum light, and from the time this occurs, $\sim$ 410 days, the radius of the ring can be determined, $\sim 6.1\times 10^{17}$ cm. Because the angular size of the ring can be directly determined from the HST observations, one has two independent measurements of the radius, one of which is dependent on the distance to the supernova. Panagia *et al.* (1991) have used this fact to derive a distance of 51.2 ± 3.1 kpc to the LMC. The assumptions behind this method have been critically discussed by Dwek & Felten (1992), and references therein.

From modelling of the state of ionization Fransson & Lundqvist (1989) find that a peak radiation temperature of $(3-6)\times 10^5$ K is necessary for the burst in connection with shock breakout, in approximate agreement with the models. The observation of the light echo therefore provides the earliest information we have about the supernova after shock breakout. The models for the light curves by Lundqvist & Fransson (1991) and Luo (1991) reproduce the shape of the light curves qualitatively, but the detailed agreement was not satisfactory. One important simplification, discussed by these authors, was the assumption of just one density component. Observationally, the density in the ring spans a range between $(1-4)\times 10^4$ cm^{-3}. The lowest densities recombine and cool slowest, and are therefore responsible for the emission at the latest stages, while the high densities dominate early. In addition, the ring geometry is important especially for the shape of the rising part of the light curve. This results in an "arcsine" shape of the peak (Lundqvist 1992; Dwek & Felten 1992). Optical depth effects also become important for a ring, in contrast to the optically thin spherical shell (Lundqvist 1992). New models including these factors give considerably better agreement with the observations (Lundqvist, Fransson & Blondin 1994). The models also provide an independent determination of the densities and temperature of the circumstellar medium. Shortly after the outburst the circumstellar medium was heated to $\sim 10^5$ K, but then cooled and recombined slowly. After a year the temperature was $\sim 5 \times 10^4$ K, in agreement with temperatures determined from the [O III] $\lambda\,\lambda\, 4363/4959 + 5007$ ratio (Wampler & Richichi 1989). On day 1334 the temperature in the ring, determined from the width of Hα, was 13,750 K (Cumming & Meikle 1993), in agreement with the models. Cumming & Meikle also find evidence for very cold gas with temperature $\lesssim 1000$ K outside the ring.

The origin of the ring is still unclear. Several different scenarios have been proposed. One scenario is based on the interaction of the fast blue progenitor wind with a slow, asymmetrical red wind (Luo & McCray 1991; Wang & Mazzali 1992; Blondin & Lundqvist 1993). A major problem for this kind of model is the large asymmetry needed. Blondin & Lundqvist find that the ratio of polar to equatorial mass loss has to be $\gtrsim 20$, more resembling a disk geometry. Binary models for the progenitor may be consistent with this (cf. Podsiadlowski 1992). Also the low expansion speed of the ring, ~ 10.3 km s^{-1} (Crotts & Heathcote 1991), is difficult to explain. Chevalier & Luo (1994) have suggested that the ring could be the result of magnetic compression of the circumstellar medium by a mainly toroidal field. The toroidal field arises as a natural result at large distances, if the progenitor star is rotating. McCray & Lin (1993) propose that the ring is the inner rim of a circumstellar disk, evaporated by the ionizing radiation from the progenitor. The nitrogen enrichment is explained as 'pollution' of the inner edge by the red supergiant wind.

For more exhaustive reviews of the circumstellar medium of SN 1987A we refer to Lundqvist (1992), Chevalier (1992) and McCray (1993).

3 SN 1993J

SN 1993J was discovered on March 28.86 1993 (Ripero & Garcia 1993). Already on March 30.2 the IUE satellite took the first spectra of this object. This clearly demonstrated the usefulness of a small and flexible space instrument. Other space borne instruments had considerably longer reaction times. Subsequently, it was regularly observed by IUE as a collaboration between the European and American ToO supernova teams (e.g., Wamsteker *et al.* 1993; Sonneborn *et al.* 1993).

The first photographic detection of the supernova was on March 28.30 at magnitude 13.6 (Merlin & Neely 1993). On March 27.95 the magnitude was less than 16, and a photograph taken on March 25.6 showed no supernova brighter than 17 magnitude (van Driel 1993). From modelling of the supernova light curve, the explosion is estimated to have occurred on March 27.8. Hydrodynamical models show that the shock took ~ 5 hours to propagate from the core to the surface (Shigeyama *et al.* 1993), so shock breakout should have occurred at approximately March 28.0.

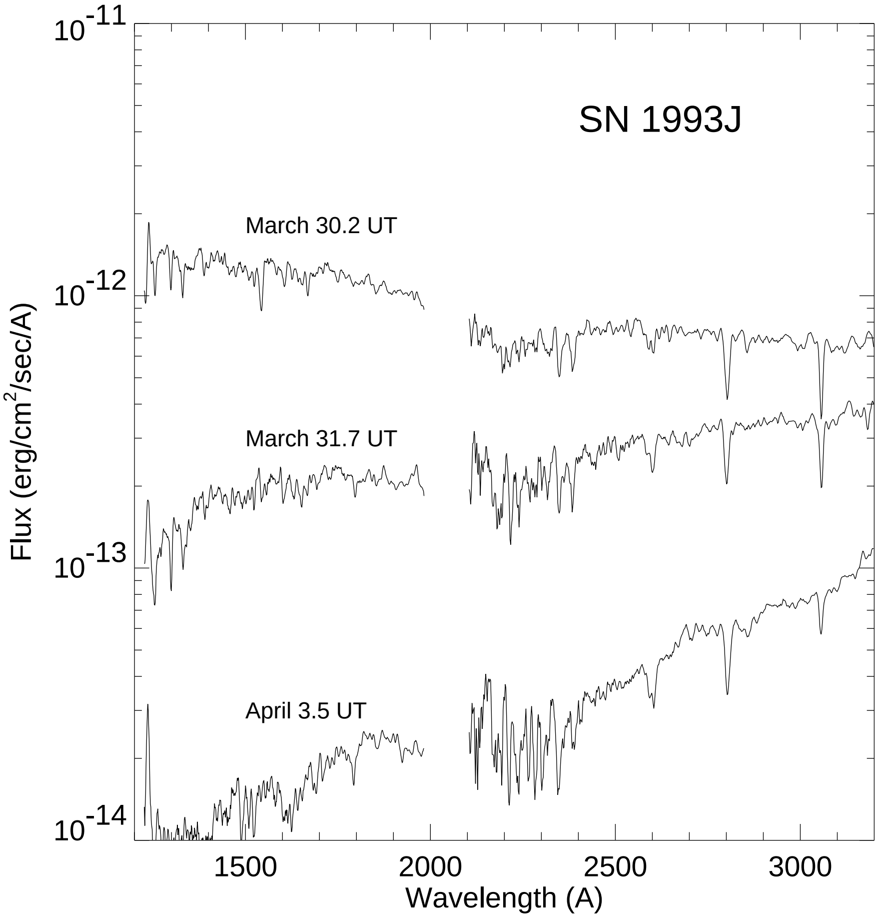


Fig. 2. Spectral evolution in the UV of SN 1993J during the first days after the explosion. The N V 1240 emission line is clearly visible; the short wavelength spectra in the figure were truncated at 1226Å to supress geocoronal Lyman alpha.

In Fig. 2 we show the first UV spectra of SN 1993J from March 30.21 to April 3.5. The most apparent result is the very rapid cooling of the photosphere during the first few days. On March 30.21 the temperature was 22,500 K. One day later on March 31.2 the temperature had decreased to 14,500 K. Here we have assumed a Galactic extinction law and $E_{B-V} = 0.18$, as determined from a fit of the 2200 Å dust feature, which is clearly seen in the spectra. Such a rapid cooling is expected just after shock breakout, and agrees quite well with the light curve calculations by Shigeyama *et al.* (1993). Shigeyama *et al.* 's model shows that immediately after outbreak the effective temperature was $\sim 3 \times 10^5$ K, decreasing after 24 hours to $\sim 4 \times 10^4$ K. The total energy during the first day was $\sim 1 \times 10^{49}$ ergs, most coming out as UV and soft X-rays. At the time of the first IUE observation, $\sim$ 2.2 days after outbreak, Shigeyama *et al.* find $T_{eff} \approx 22,500$ K, in nearly perfect agreement with the observations. A day later, 3.2 days after breakout, Shigeyama *et al.* find $T_{eff} \approx 16,000$ K, slightly higher than the observed. The initially strong ultraviolet continuum then faded rapidly, by a factor of $\sim$ 200 by April 4 shortward of 1600 Å; smaller decreases occurred at longer wavelengths.

The very rapid evolution was also apparent in the optical spectrum (cf. Meikle *et al.* 1993; Filippenko, Matheson, & Ho 1993). From having a featureless blue continuum, very broad lines became apparent after $\sim$ 15 days. On April 11 expansion velocities of at least 19,000 km s^{-1} can be seen for Hα. In early May the spectrum changed character from a H dominated Type II spectrum to a spectrum dominated by lines of He, resembling Type Ib. From this it was apparent that only a small fraction of the H envelope remained on the progenitor at the time of the explosion.

Except for a number of interstellar absorption lines, discussed by de Boer *et al.* (1993), the only clear spectral feature are two narrow N V $\lambda\,\lambda$ 1238.82 – 1242.80 emission lines. These are very strong in the first spectra, but weaken considerably with time. In Fig. 3 the N V flux is shown as a function of time. It is seen that the N V flux followed a light curve similar to the UV continuum, decreasing by a factor $\sim$ 43 between March 30.2 and April 4.5. By April 22 the N V emission was virtually absent. The N V luminosity on March 30.2 was $\sim 4 \times 10^{39}$ erg s^{-1}, assuming a distance of 3.5 Mpc to NGC 3031 and no extinction. With a Galactic extinction curve and $E_{B-V} = 0.18$ the luminosity is $\sim 2 \times 10^{40}$ erg s^{-1}.

During the first two days high resolution (FWHM $\sim$ 30 km s^{-1}) observations were also possible with IUE. In Fig. 4 the N V region is shown for March 30.4, clearly showing the two doublet components at 1238.82 Å and 1242.80 Å centered at a heliocentric velocity of -115 km s^{-1}. From the narrow widths of the lines it is clear that they can not arise in the supernova ejecta, but must originate in the circumstellar medium of the progenitor system. The relative fluxes and line profiles are, however, different from those expected. Under optically thin conditions the 1238.8 component is expected to be a factor two brighter than the 1242.8 component. Even if optically thick, the ratio is never less than one. In addition, the 1242.8 component clearly shows an extension to the red by at least $\sim$ 200 km s^{-1}, while the 1238.8 component has a FWHM of only $\sim$ 35 km s^{-1}.

One possible explanation is based on interstellar absorption of the emission by gas in M 81 and our Galaxy. The main argument being that the 1238.8 component has a gf-value twice as high as the 1242.8 component. Interstellar absorption

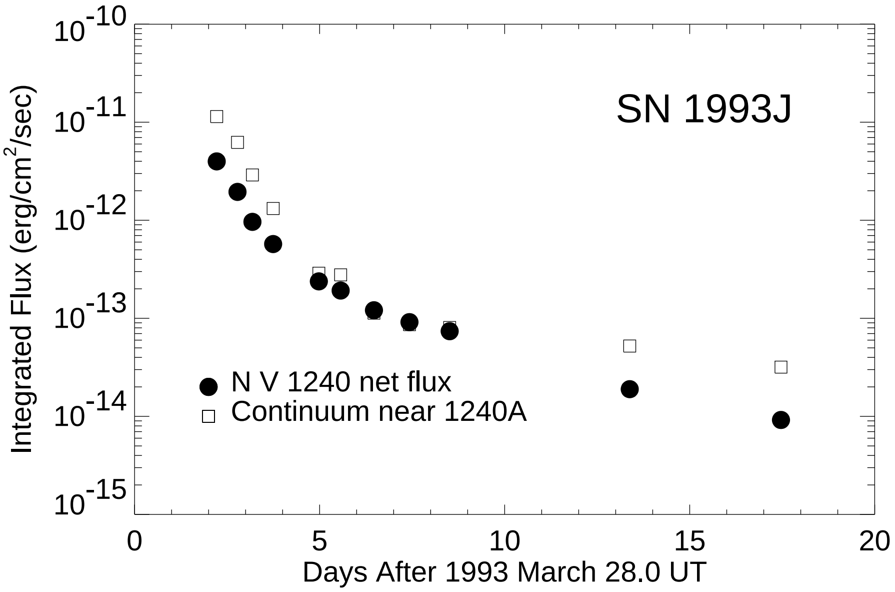


Fig. 3. Light curve of the N V λ 1240 line. The solid circles represent the N V flux above the continuum and the open squares the mean continuum level near the line.

therefore affects the 1238.8 line more than the 1242.8 line. This explanation suffers from several difficulties. One is that the interstellar N V lines seldom have optical depths larger than ~ 0.4 in different directions of the halo (e.g., Sembach & Savage 1992). Therefore, absorption effects are rather marginal for these lines. It is also difficult to explain the very asymmetrical shape of the 1242.8 line.

A more likely explanation is that the velocity of the circumstellar medium, V_{CSM}, where the N V line arises is $\gtrsim 1000$ km s^{-1}. In that case one expects a P-Cygni profile with an absorption component extending to $-V_{CSM}$ and an emission component with a lower extension to the red due to the occultation by the supernova ejecta. If $V_{CSM} \gtrsim 963$ km s^{-1}, the velocity difference of the doublet, the 1242.8 absorption will interfere with the 1238.8 emission component. The scattered 1238.8 photons will emerge in the 1242.8 component, explaining the higher luminosity of this line. The second high resolution spectrum on March 31.5 is noisier, and it is difficult to say anything definitive about differences in the line shape compared to the first spectrum. There is, however, some evidence for a

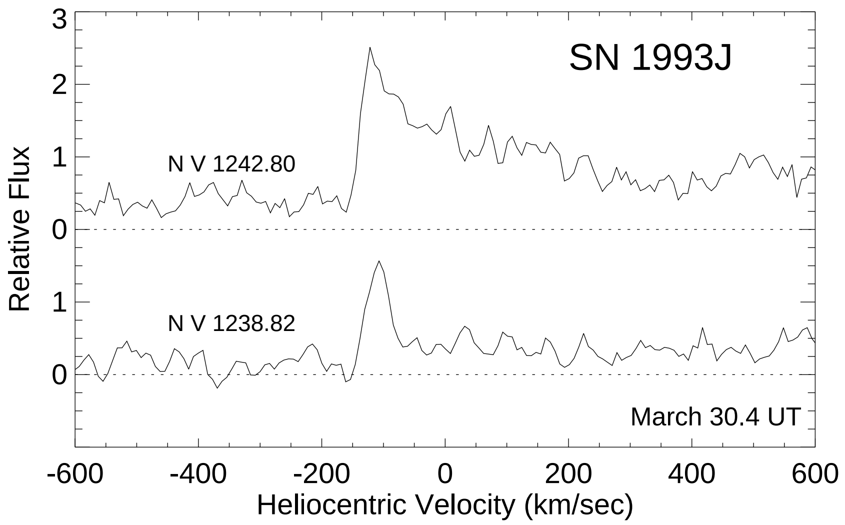


Fig. 4. The N V $\lambda\ \lambda$ 1238.82 − 1242.80 region from high resolution spectra on March 30.4. Note the difference of the line profiles and strength of the two lines.

decrease in the width of the 1242.8 line, as well as a more abnormal 1238.8/1242.8 ratio. The conclusion is therefore that the N V observations give evidence for velocities in the circumstellar medium of SN 1993J $\sim$ 1000 km s^{-1} on day 2. Additional evidence for high circumstellar velocities come from observations of Hα emission on March 29, 1993 (Cumming *et al.* 1993). The width of this line is also $\sim$ 1000 km s^{-1}.

Velocities $\sim$ 1000 km s^{-1} in the circumstellar medium of a late type star are much higher than expected. Typical wind velocities are of order 10 − 30 km s^{-1} (e.g., Jura & Kleinmann 1990). An explanation, proposed by Fransson, Lundqvist & Chevalier (1993) (in the following referred to as FLC93), is that radiative acceleration of the circumstellar gas by the very strong burst of UV and soft X-ray photons during the first days is responsible for the high velocity. If electron scattering is the main source of opacity, a burst of 10^{49} erg s^{-1}(E$_{49}$) will pre-accelerate the circumstellar gas to

$$V_{CSM} = 1.42 \times 10^4\ E_{49}\ V_4^{-2} \left(\frac{R_s}{r}\right)^2 t_{days}^{-2}\ \ \text{km s}^{-1}$$

where R_s is the shock radius and r the distance from the supernova. V_4 is the maximum velocity in the ejecta at a given time close to the interaction region in

Fig. 5. Radio light curves at 2 cm from Pooley & Green (1993). The full line gives a 'best fit' for a model with $\rho \propto r^{-2}$, while the dashed line corresponds to a model with $\rho \propto r^{-1.5}$ (from FLC93).

10^4 km s^{-1}. Optical and radio observations indicate that $V_4 \approx 3$ (cf. Meikle *et al.* 1993; FLC93). Hydrodynamical calculations by Shigeyama *et al.* (1993) show that up to day 2 a total energy $E = 0.6 \times 10^{49}$ ergs is emitted. The preshock velocity will therefore on day 2 be ~ 400 km s^{-1}. This is lower than needed, but either E could be larger or V lower. Resonance line scattering in the circumstellar medium may also increase the velocity. Because V_{CSM} is expected to decrease with time as t^{-2}, the velocities after a few days will be of the same order as the undisturbed wind velocity.

The UV was the first wavelength range to show evidence for a circumstellar medium. A few days later also radio emission was detected from SN 1993J (Weiler *et al.* 1993; Pooley & Green 1993), as well as X-rays (Zimmermann *et al.* 1993a; Tanaka 1993). The radio emission showed the same characteristic pattern as has earlier been observed for other Type II and Type Ib supernovae. First, emission was seen at short wavelengths, and later at longer. The radio flux at a given wavelength increased nearly linearly with time up to a maximum. In Fig. 5 the radio light curve at 2 cm is shown from Pooley & Green (1993), and it is seen that the maximum occurred $\sim$ 75 days after the explosion. This behavior has been explained for other supernovae as a result of decreasing free-free absorption by the ionized gas in a circumstellar medium around the supernova (Chevalier 1982b). As the supernova expands, the emission measure from the radio emitting region close to the shock through the circumstellar medium decreases, explaining the radio turn-on.

The most natural origin for the circumstellar medium is the wind from the progenitor (or possibly companion star). Assuming a wind with constant mass loss rate and wind velocity, the free-free absorption optical depth at wavelength λ is given by

$$\tau_{ff} \approx 7.1 \times 10^2 \lambda^2 \left(\frac{\dot{M}_{-5}}{v_{w1}} \right)^2 T_5^{-3/2} V_4^{-3} t_{days}^{-3}$$

where $\dot{M}_{-5}$ is the mass loss rate in units of 10^{-5} $M_\odot$ yr^{-1}, v_{w1} the wind velocity in units of 10 km s^{-1}, and T_5 the temperature of the circumstellar gas in 10^5 K. From the radio spectrum of Van Dyk *et al.* (1993b) and Phillips & Kulkarni (1993) on 22.5 April FLC93 estimate that $\tau_{ff} = 0.3$ at 2 cm on day 25.5. Because of the heating of the circumstellar medium by the outburst of the radiation, as well as by the shocks formed by the interaction of the ejecta and the circumstellar medium, FLC93 find from photoionization models of the circumstellar medium that the temperature is $\sim 3 \times 10^5$ K. With these numbers one finds that $\dot{M}/v_w \approx 3 \times 10^{-6} M_\odot$ yr^{-1}(km s^{-1})$^{-1}$, i.e. $\dot{M} = 3 \times 10^{-5} M_\odot$ yr^{-1} if $v_w = 10$ km s^{-1}, within approximately a factor two. This is of the same order as derived for other 'normal' Type II supernovae (cf. Chevalier 1990).

Although qualitatively correct, the form of the observed light curves do not agree with the expectations. In particular, the rising part is nearly linear, while models predict a more abrupt turn-on. The rising part of the light curves depends mainly on the density distribution of the circumstellar medium. FLC93 find that while a standard $\rho \propto r^{-2}$ wind does not fit the observations, a better fit is obtained for $\rho \propto r^{-1.5}$, as is shown by the dashed line in the figure. The departure from $\rho \propto r^{-2}$ may be a result of variations in the mass loss rate during the last ~ 1000 years before the explosion.

SN 1993J has been observed by ROSAT (Zimmermann *et al.* 1993a,b) in the 0.1 - 2.4 keV band and by ASCA (Tanaka *et al.* 1993) between 1 - 10 keV. The luminosity at the first observations, ~ 7 days after explosion, was 1.6×10^{39} erg s^{-1} between 0.1 -2.4 keV, and 5×10^{39} erg s^{-1} between 1 - 10 keV. There is eveidence for a decrease by $\sim 45\%$ from April 3.4 to May 4 in the ROSAT flux (Zimmermann *et al.* 1993c). The implications of these observations are discussed in detail in FLC93, and by Suzuki *et al.* 1(993).

The interaction of the ejecta and the circumstellar medium will give rise to a shocked region, bounded by one ingoing (in a Lagrangian sense) reverse shock wave and one outgoing circumstellar shock. Assuming that the ejecta density is described by a power law in velocity (or radius), $\rho_{ejecta} \propto t^{-3} v_{ejecta}^{-n}$, a very useful similarity solution, with the shock radius $R_s \propto t^{(n-3)/(n-2)}$, can be found (Chevalier 1982a,b). Typical values of n are $n = 7 - 12$. The maximum ejecta velocity then depends on time as $V \propto t^{-1/(n-2)}$. The velocity of the circumstellar shock, $\dot{R}_s$, in terms of $V = R_s/t$ is $v_{cs} \approx V(n-3)/(n-2)$ and the reverse shock velocity, $v_{rev} = V - \dot{R}_s = V/(n-2)$. The ion temperature of the shocked circumstellar gas is

$$kT_{cs} \approx 611 \frac{(n-3)^2}{(n-2)^2} \left(\frac{V}{25,000 \text{ km s}^{-1}} \right)^2 \text{ keV}.$$

and the reverse $T_{rev} = T_{cs}/(n-3)^2$. For $n = 7$ and 9 we get $kT_{rev} \approx 24.4$ keV and 12.5 keV, respectively. Electron-ion equipartition is slow above $\sim 10^9$ K, so $T_e << T_{ion}$ for the circumstellar shick, unless collisionless heating is important. The electron temperature of the two shocks will therefore be highly different, at 10 days $\sim (1-3) \times 10^9$ K for the circumstellar shock and $\lesssim 5 \times 10^8$ K for the reverse shock. The radiation from the reverse is therefore mainly in X-rays, while that from the circumstellar is above ~ 100 keV.

We can now estimate the free-free luminosity from the two shocks from $L_{rev} = 4\pi \int j_{ff}(T_e) n_e^2 r^2 dr \approx j_{ff}(T_{rev}) M_{rev} \rho_{rev}/(\mu_e m_p)^2$. The density behind the circumstellar shock is $\rho_{cs} = 4\,\rho_0 = \dot{M}/(\pi v_w R_s^2) = 2{\times}10^{-16} \dot{M}_{-5} v_{w1}^{-1} (R_s/10^{15} \text{ cm})^{-2}$ g cm^{-3}. The density ratio of the reverse and circumstellar shocks is $\rho_{rev}/\rho_{cs} = (n-4)(n-3)/2$. The swept up mass behind the circumstellar shock is $M_{cs} = \dot{M} R_s / v_w$ and that behind the reverse $M_{rev} = (n-4) M_{cs}/2$. With $j_{ff} = 2.4 \times 10^{-27} g_{ff}\, T_e^{0.5}$, we finally get

$$L_{rev} \approx 3.0 \times 10^{39}\, g_{ff}\, C_n \left(\frac{\dot{M}_{-5}}{v_{w1}} \right)^2 \left(\frac{t}{10 \text{ days}} \right)^{-1} \text{ erg s}^{-1}$$

where g_{ff} is the free-free Gaunt factor, which also takes relativistic effects into account. $C_n = (n-3)(n-4)^2/4(n-2)$; $C_7 = 9/5$ and $C_9 = 75/14$. The luminosity of the circumstellar shock is given by the same expression with $C_n = 1$. This assumes electron-ion equipartition, which is highly questionable. Also, g_{ff} may for this be substantially larger than one. Because of occultation by the ejecta only half of the above luminosity escapes outward. The fraction of this emerging between E_{min} and E_{max} is $\sim (1 - e^{-E_{max}/kT_{rev}})$. The outgoing luminosity at 10 days is therefore in the ROSAT band $\sim 2.7 \times 10^{38} \dot{M}_{-5}^2$ erg s^{-1} for $n = 7$ and $\sim 1.5 \times 10^{39} \dot{M}_{-5}^2$ for $n = 9$. In the ASCA band the corresponding luminosities are $\sim 1.0 \times 10^{39} \dot{M}_{-5}^2$ and $\sim 4.4 \times 10^{39} \dot{M}_{-5}^2$, respectively. Therefore, we find that $\dot{M} \approx (1-3) \times 10^{-5} M_\odot$ yr^{-1} is indicated by the X-ray observations. In FLC93 a more accurate estimate of the luminosity is given, taking into account departures from electron-ion equipartition and the hydrodynamic structure.

These simple estimates reproduce the observed luminosities quite well with mass loss rates compatible with those derived from the radio observations. The decrease in flux with time is somewhat slow compared to the expected, $dL/dE \propto$

$t^{-(n-4)/(n-2)}$. Again, an $\rho \propto r^{-1.5}$ distribution provides a better fit to the observations. However, the error bars are fairly large and it is premature to draw any conclusions from this.

γ-rays from SN 1993J have also been detected by OSSE on the Compton Observatory (Leising 1993). At $\sim$ 12 days the flux between 40 – 200 keV corresponded to $\sim 7\times10^{40}$ erg s^{-1}. FLC93 find that to explain the large OSSE/ASCA flux ratio, $\sim$ 10, an electron temperature of at least 3×10^9 K is necessary. Therefore, the OSSE emission must mainly be a result of emission from the circumstellar shock. In addition, collisionless heating of the electrons is necessary. Pure Coulomb collisions give too low an electron temperature to explain the high energy emission.

The high N V λ 1240 luminosity shows that there was during the first few days a high flux of photons above 77 eV. The models by FLC93 show that the burst in connection with the shock outbreak indeed ionizes the circumstellar gas nearly completely. Because of the high density, the gas inside $\sim 10^{15}$ cm has, however, time to recombine before the shock hits the gas, explaining the presence of the line. Once the reverse and circumstellar shocks are formed the radiation from these reionize the gas completely, effectively cutting off the emission. Light echo effects may prolong the emission for a few more days. As for SN 1987A, the UV lines are therefore good diagnostics of the very early spectral evolution of the supernova. The high ionization is also consistent with the ROSAT and ASCA observations, which gave a very low column density, $N_H \lesssim 10^{21}$ cm^{-2}, compatible with just the Galactic H I contribution.

The fact that SN 1993J has an appreciable circumstellar density is not surprising in view of the scenarios proposed for its origin. Several groups have concluded that in order to explain the bolometric light curve $\lesssim 1M_\odot$ of the hydrogen envelope can have remained on the progenitor (Nomoto *et al.* 1993; Podsiadlowski *et al.* 1993; Woosley *et al.* 1993; Utrobin 1993; Woosley *et al.* 1993). Most of these models invoke a binary scenario, but Höflich, Langer, & Duschinger (1993) propose that the mass loss is from a single star by a stellar wind. With a ZAMS mass of $\sim 15M_\odot$, about $10M_\odot$ must have been lost from the progenitor, either in the form of a wind, to a companion star, or by Roche lobe overflow as an excretion disk. Therefore, the total mass lost may be up to $\sim 10M_\odot$. The total mass swept up during this first half year by the supernova is only $\dot{M}\ t\ V/v_w \approx 0.02\ JM_\odot$. Emission from the circumstellar interaction may therefore be observable for a long time, as the case is for a number of other Type II supernovae (Chevalier & Fransson 1994, and references therein).

4 CONCLUSIONS

Mass loss from the progenitor is cruical for the properties of the explosion. The Type Ib supernovae are the most extreme examples of this kind, but also the "Type IIb" SN 1993J illustrates this. The combination of radio, optical, UV and X-ray observations has proven to be very powerful for understanding the mass loss history of the progenitor. In addition, as illustrated by the light echo from SN 1987A, the UV emission may give unique information about the first moments after the shock breakout. Much of this would not have been possible without IUE, with its flexibility and high efficiency.

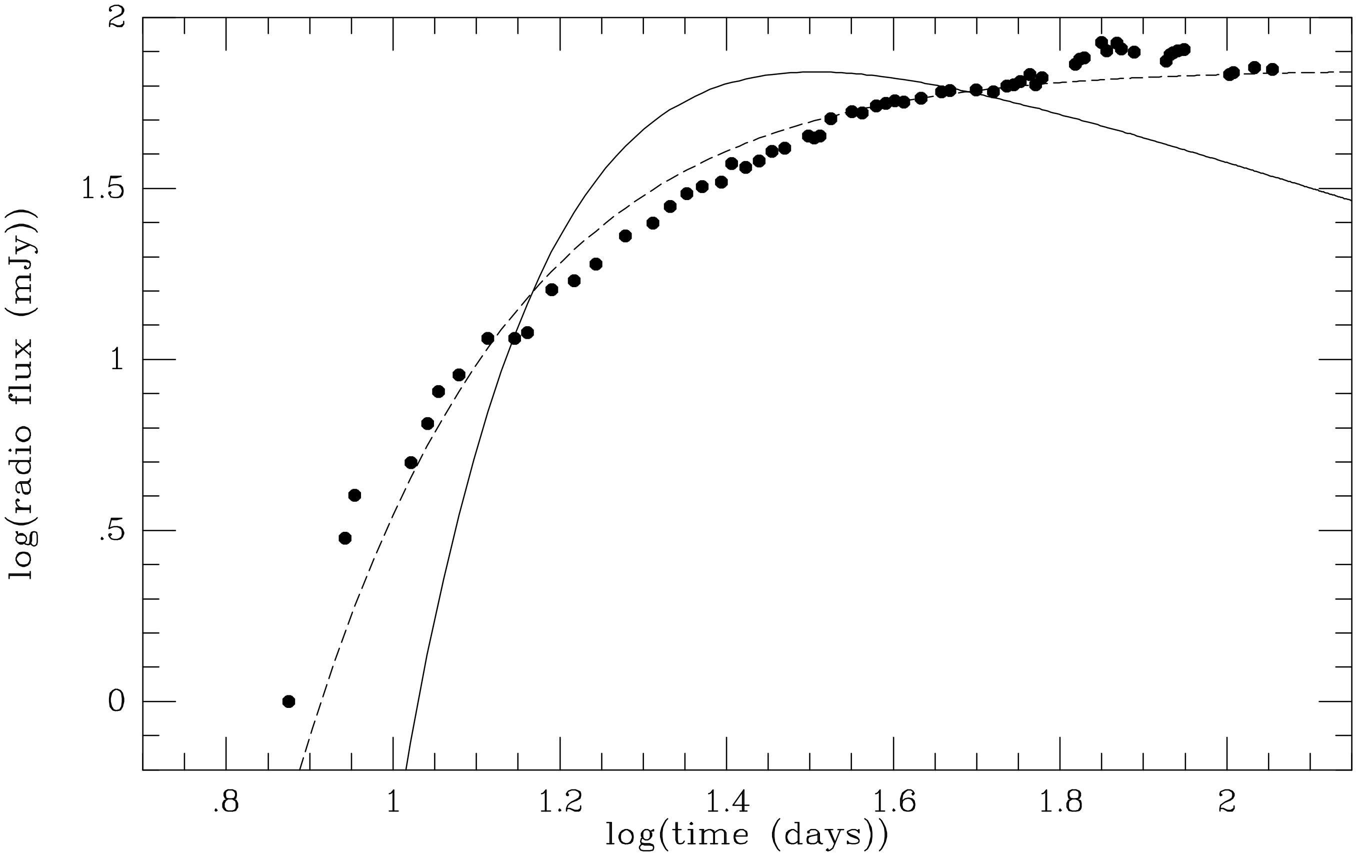
Acknowledgements

The UV observations of SN 1993J have been obtained in collaboration with R. Gonzalez, R. P. Kirshner, P. M. Rodriguez, and W. Wamsteker. The modeling of the observations has been done in collaboration with Roger Chevalier and Peter Lundqvist. We are also grateful to David Green for access to their observations prior to publication and to Peter Lundqvist for comments.

References

Blair, W. P., & Panagia, N. 1987 in *Scientific Accomplishments of the IUE*, Reidel, Dordrecht, p. 549
Blondin, J.M. & Lundqvist, P., 1993, ApJ **405**, 337
Cassatella, A., Fransson, C., van Santvoort, J., Gry, C., Talavera, A.,Wamsteker,W., & Panagia, N., 1987, A&A **177**, L29
Chevalier, R. A., 1982a, ApJ **258**, 790
Chevalier, R. A., 1982b, ApJ **259**, 302
Chevalier, R. A., 1990, in *Supernovae*, ed. A. G. Petschek, Berlin, Springer, p. 91
Chevalier, R. A., 1992, Nature **355**, 691
Chevalier, R. A., & Fransson, C., 1994, ApJ, in press
Chevalier, R. A., & Luo, D., 1994, ApJ, in press
Crotts, A.P.S. & Heathcote, S.R., 1991, Nature, **350**, 683
Crotts, A. P. S., Kunkel, W. E., & McCarthy, P. J., 1989, ApJ **347**, L61
Cumming, R., & Meikle, W. P. S., 1993, MN **262**, 689
Cumming, R., *et al.* , 1993, in preparation
Danziger, I. J. & Kjär, K. 1991, *SN 1987A and Other Supernovae*, ESO, Munich
de Boer, K., Rodriguez, P., Wamsteker, W., Sonneborn, G., Fransson, C., and Kirshner, R. P. 1993, A&A, in press
Dwek, E. & Felten, J.E. 1992, ApJ **387**, 551
Ensman, L. & Burrows, A., 1992, ApJ **393**, 742
Filippenko, A. V., Matheson, T., & Ho, L. C., 1993, ApJ **415**, L103
Fransson, C., (1993) in Les Houches, Session LIV, 1990, *Supernovae*, eds. J. Audouze, S. Bludman, R. Mochkovitch & J. Zinn-Justin, Elsevier Science Publishers B.V., Chap. 10
Fransson. C., & Lundqvist, P., 1989, ApJ **341**, L59
Fransson, C., Grewing, M., Cassatella, A., Panagia, N., & Wamsteker, W., 1987, A&A **177**, L33
Fransson, C., Cassatella, A., Gilmozzi, R., Kirshner, R.P., Panagia, N., Sonneborn, G., & Wamsteker, W., 1989, ApJ **336**, 429
Gilmozzi, R., Cassatella, A., Clavel, J., Fransson, C., Gonzalez, R., Gry, C., Panagia, N., Talavera, A., & Wamsteker, W. 1987, Nature 328, 318
Fransson. C., Lundqvist, P., & Chevalier, R. A. 1993, in preparation (FLC93)
Höflich, P., Langer, N., & Duschinger, M., 1993, A&A **275**, L29
Jakobsen, P. *et al.* J 1991, ApJ **369**, L63
Kirshner, R.P., Sonneborn, G., Crenshaw, D.M., & Nassiopoulos, G.E. 1987, ApJ **320**, 602
Jura, M. & Kleinmann, S. G. 1990, ApJ Suppl. **73**, 769
Leising, M.,1993, priv. comm.
Lundqvist, P., 1992, PASP, **104**, 787

Lundqvist, P., & Fransson, C., 1991, ApJ **380**, 575
Lundqvist, P., Fransson, C. & Blondin, J. M., 1994, in prep.
Luo, D. 1991, Ph.D. thesis, University of Colorado, Boulder
Luo, D. & McCray, R. 1991, ApJ **379**, 659
Lucy, L. B. 1987, A&A **182**, L31
McCray, R. 1993, Ann. Rev. Ast. Astr., **31**, 175
McCray, R. & Lin, D. N. C. 1993, preprint
Meikle, P., *et al.* , 1993, Gemini, **40**, 8
Merlin, J.-C. & Neely, A., 1993, IAU Circ., No. 5740
Nomoto, K., Susuki, T., Shigeyama, T., Kumagai, S., Yamaoka, H., & Saio, H., 1993, Nature, **364**, 507
Panagia, N., Gilmozzi, R., Macchetto, F., Adorf, H.-M., & Kirshner, R. P. 1991 ApJ **380**, L23
Phillips, J. A., & Kulkarni, S. JR. 1993, IAU Circ., No. 5763
Podsiadlowski, P., Hsu, J. J. L., Joss, P. C., & Ross, R. R. 1993, Nature **364**, 509
Podsiadlowski, P., 1992, PASP, **104**, 717
Pooley, G. G., & Green, D. A., 1993, MN, **264**, L17
Ripero, J., & Garcia, F., 1993, IAU Circ., No. 5731
Sembach, K. P. & Savage, B. D. 1992, ApJSupp **83**, 147
Shigeyama, T., Nomoto, K., & Hashimoto, M., 1988, A&A **196**, 141
Shigeyama, T., Suzuki, T., Kumagai, S., Nomoto K., Saio, H., & Yamaoka, H., 1993, ApJ, in press
Sonneborn, G., Altner, B., & Kirshner, R. P. 1987, ApJ **323**, L35
Sonneborn, G., Rodriguez, P. M., Wamsteker, W., Fransson, C., & Kirshner, R., 1993, IAU Circ., No. 5754
Suzuki, T., Kumagai, S., Shigeyama, T., Nomoto, K., Yamaoka, H., & Saio, H., 1993, ApJ, in press
Tanaka, Y. & the ASCA team, 1993, IAU Circ., No. 5753
Utrobin, V. 1993, A&A in press
van Driel, W., 1993, IAU Circ., No. 5737
Van Dyk, S. D., Weiler, K. W., Sramek, R. A., Rupen, M. P., & Panagia, N., 1993b, IAU Circ., No. 5776
Wampler, E. J., & Richichi, A., 1989, A&A **217**, 31
Wampler, E. J., Wang, L., Baade, D., Banse, K., D'Odorico, S., Gouiffes, C., & Tarenghi, M., 1990, ApJ **362**, L13
Wamsteker, W., Rodriguez, P. M., Gonzalez, R., Sonneborn, G., & Kirshner, R., 1993, IAU Circ., No. 5738
Wang, L. & Mazzali, P. A. 1992, Nature **355**, 58
Weiler, K. W., Sramek, R. A., Van Dyk, S. D., & Panagia, N., 1993, IAU Circ., No. 5752
Woosley, S.E., 1988, ApJ **330**, 218
Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. A., 1993, ApJ, in press
Xu, Y. & McCray, R. 1991, in *Proc. Tenth Santa Cruz Summer Workshop: Supernovae*, ed. S.E. Woosley, Springer, New York, p. 444
Zimmermann, H. U., Lewin, W., Magnier, E., Predehl, P., Hasinger, G., Pietsch, W., Aschenbach, B., Trumper, J., Fabbiano, G., van Paradijs, J., Lubin, L., & Petre, R., 1993a, IAU Circ., No. 5748
Zimmermann, H. U., Lewin, W., Magnier, E., Predehl, P., Hasinger, G., Pietsch, W., Aschenbach, B., Trumper, J., Fabbiano, G., van Paradijs, J., Lubin, L., & Petre, R., 1993b, IAU Circ., No. 5750
Zimmermann, H.-U., Lewin, W., Predehl, P., Aschenbach, B., Fabbiano, G., Hasinger, G., Lubin, L., Magnier, van Paradijs, J. E., Petre, R., Pietsch, W., & Trumper, J. 1993c, Astr. Ges. Abstract Series No. 9, 103



log(radio flux (mJy))
2
1.5
1
.5
0
.8
1
1.2
1.4
1.6
1.8
2
log(time (days))