The circumstellar gas around SN 1987A and SN 1993J

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Abstract

The observational evidence for circumstellar gas around SN 1987A and SN 1993J is discussed along with interpretations of these observations. For SN 1987A we focus on its ring and for SN 1993J we mainly concentrate on its radio and N V λ 1240 emission.

1. Introduction

The circumstellar gas (CSG) around supernovae (SNe) provides information on the mass loss history of the dying star. When the SN explodes, the CSG is ionized by the radiation from both the SN and the gas shocked by the expanding ejecta. By looking at spectral signatures from the ionized CSG at increasingly large radii, we may peer deeper and deeper back through time into the mass loss history of the pre-SN. The recent bright and well-studied Type II SNe 1987A and 1993J have given us an unprecedented chance of doing so. Here we briefly discuss the CSG of these two SNe.

2. SN 1987A

Light curves for the narrow UV emission lines from SN 1987A (Sonneborn *et al.* 1994) show that the emission starts ~ 70 days after the outburst with a roughly linear increase in strength until day ~ 400, followed by a gradual decline up to day ~ 1000 when the lines start to fall below detectability. In the optical there is very good information on the spatial flux distribution from observations with the NTT (Wampler *et al.* 1990; Wang & Wampler 1992) and the HST (Jakobsen *et al.* 1991; Plait *et al.* 1994); the emission mainly comes from a patchy, elliptically shaped ring with semimajor and semiminor axes of ~ 0.830 (corresponding to $\sim 6.2 \times 10^{17}$ cm at 50 kpc) and ~ 0.605 arcsec, respectively. Even before the imaging observations, it was realized that the lines must be circumstellar since they were very narrow ($\lesssim 30$ km s^{-1}) (Fransson *et al.* 1989; Wampler & Richichi 1989) and indicated high N/O and N/C ratios (Fransson *et al.* 1989).

Models (e.g., Lundqvist & Fransson 1991) show that the source of excitation of the lines was the EUV/soft X-ray burst accompanying the shock

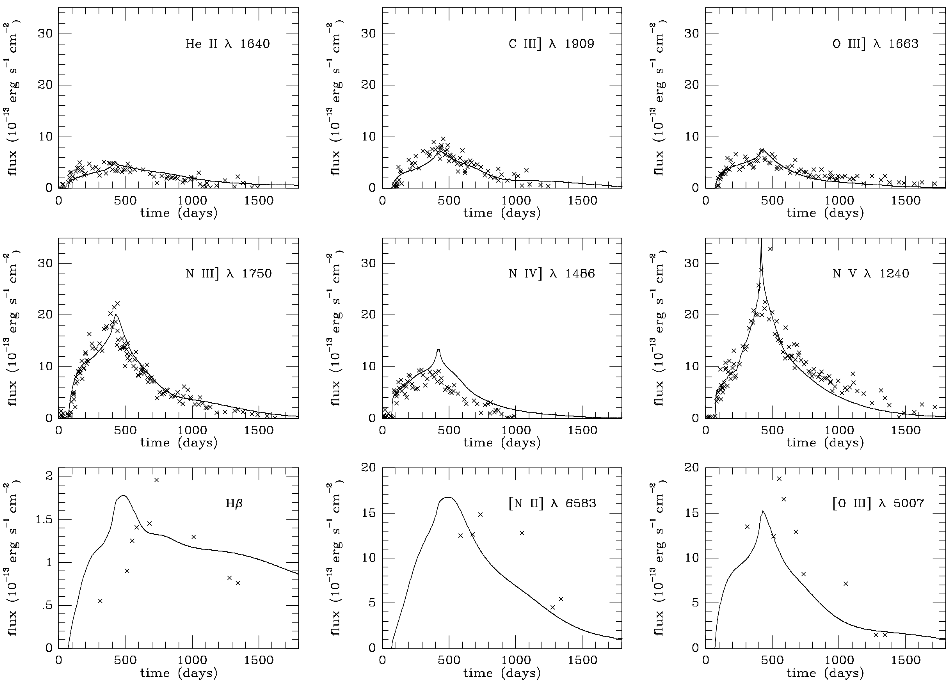

Fig. 1. Evolution of the narrow emission lines from the ring around SN 1987A. Model parameters are described in the text. The UV line fluxes are from Sonneborn *et al.* (1994), and the optical fluxes from Wampler & Richichi (1989); Wampler, Richichi & Baade (1989); Menzies (1991); Wang (1991) and R. Cumming (priv. comm.)

outbreak from the SN, and that the evolution of the lines provide information on the characteristics of the burst. Lundqvist, Fransson & Blondin (1994) focus on fitting the light curves in greater detail, using more elaborate calculations for the burst (Ensman & Burrows 1992). Lundqvist *et al.* find that most of the ring has to be optically thick to the outburst in order for all light curves to start rising simultaneously around ~ 70 days. Using the 500full2 model by Ensman & Burrows (which has a peak effective temperature of $\sim 7 \times 10^5$ K), the innermost part of the ring is heated to $\sim 2 \times 10^5$ K and ionized up to C^{5+}, N^{5+} and O^{6+}. There is a gradual decline in temperature and ionization away from the inner edge of the ring. The subsequent phase of cooling and recombination is governed by the density of the ring, and to model the bulk of the line emission the electron density, n_e, has to be $\sim 4 \times 10^4$ cm^{-3}. To account for the emission after day 1000, a low-density component with $n_e \sim 1.5 \times 10^4$ cm^{-3} needs to be added.

Preliminary results are shown in Figure 1, where the total ionized mass of the ring is 0.03 $M_{\odot}$, 90 % of the mass being confined to the high-density component. Best fits are obtained if the low-density component is truncated just after the N^{4+}-zone, in order not to overproduce N IV] λ 1486. The He/H-ratio = 0.3, by number, and the overall metallicity is 0.3 times solar with C/N/O = 1/3.5/2.3. All lines were calculated with light travel time effects taken into account. For N V λ 1240 (the only resonance line in Figure 1), it is also necessary to include scattering outside the ring to extend the modeled emission beyond $\sim$ 900 days. In Figure 1, the scattering medium has been approximated by a cylinder with inner radius 8×10^{17} cm, with thickness 3×10^{17} cm and with height 1×10^{18} cm. This roughly simulates the densest part of the wind exterior to the bipolar nebula in the hydrodynamic calculations by Blondin & Lundqvist (1993), and also gives good fits to the light curve. The line center optical depth through the cylinder in the equatorial plane is 2. The scattering gas is assumed to expand radially at 10 km s^{-1}, and it is too dilute to contribute to any line emission. It is interesting that the imaging observations, the light curve model and the results by Blondin & Lundqvist all agree if the high-density component is confined to the equatorial plane, and is coated by a partially optically thick low-density component. The lobes extending further away from the equatorial plane are optically thin so that the wind exterior to the lobes is ionized at least up to N^{4+}.

Most light curve models use the assumption that the ring is smooth, thin and circular. If the modeled ring has either a finite width and/or height as in Lundqvist (1991), or if one allows for the patchy structure seen in the HST images (Plait *et al.* 1994) this only marginally changes the shape of the model light curves at times less than $\sim$ 500 days, and even less at later times. The density estimates in these models are also rather insenstive to whether the ring is intrinsically elliptical or circular. The HST images are compatible with both these geometries.

However, an intrinsically elliptical ring may introduce errors into a distance estimate to the LMC of the type carried out by Panagia *et al.* (1991). They assume a circle-like structure. In order to quantify this uncertainty we extend the analysis by Dwek & Felten (1992) to construct the sweeping of the ring by the light echo paraboloid, assuming a tilted ellipse instead of a circle. We also assume that the turn on of the UV line emission occurs when the light echo paraboloid starts intersecting parts of the ring, and that the peak of the light curve occurs when the entire ring is enclosed by the paraboloid. One may then estimate the distance to the LMC, as long as one is also able to fit the shape and size of the observed ring. Allowing for the turn on occurring at epochs in the range 60 – 80 days and for the peak between 400 – 450 days (cf. Fig. 1), we get a distance to the LMC in the range 43 – 55 kpc. The ratio of minor to major axis in these calculations is $\gtrsim 0.9$, so even a rather mild intrinsic ellipticity causes almost a factor of ~ 2 larger uncertainty in the distance estimate than found by Panagia *et al.* . Only with high-resolution observations (both spatially and spectroscopically) when the ejecta shock reaches the ring may we somewhat reduce this uncertainty. It should be emphasized that the estimated ring velocity obtained from line profiles, ~ 10.3 km s^{-1} (Crotts & Heathcote 1991), would not be affected by such a small ellipticity as the one just discussed.

3. SN 1993J

SN 1993J was first observed on 28 March, and quickly showed evidence for CSG both in optical (Cumming *et al.* 1994) and UV (Sonneborn 1994) spectra. On 5 April X-rays and, shortly thereafter, gamma rays were detected. This radiation is thought to be a result of the SN ejecta interacting with CSG (Fransson, Lundqvist & Chevalier 1994, and references therein). Another signature of such interaction was the detection of radio emission (Pooley & Green 1993; Weiler *et al.* 1994). The first detection occurred at 1.3 cm only five days after the optical outburst, and then later at longer wavelengths.

It was quickly realized that the standard Chevalier (1982) model, in which the SN ejecta run into a stellar wind with an r^{-2} density dependence, and which has been very successful in accounting for radio emission from previous SNe (e.g., Chevalier 1984), could not explain the observed radio light curves for SN 1993J (Fransson *et al.* 1994). A slower density decrease with radius, more like an $r^{-1.5}$ law, fits the data better. This is shown in Figure 2, where we have compared models with the observations by Pooley & Green at $\lambda = 2$ cm. The model parameters and their values are discussed below.

The importance of the unshocked CSG in Chevalier's model is that it provides free-free absorption producing an optical depth, $\tau_{\rm ff}$, that falls below unity shortly before the time of the observed maximum. Assuming a constant temperature and composition throughout an r^{-2} wind we get

$$\tau_{\rm ff} \approx 8.2 \times 10^2 \lambda^2 \left(\frac{1 + 2\frac{n_{\rm He}}{n_{\rm H}}}{1 + 4\frac{n_{\rm He}}{n_{\rm H}}} \right) \left(\frac{\dot{M}_{-5}}{v_1} \right)^2 T_5^{-3/2} V_4^{-3} t_{\rm days}^{-3}$$

where $\dot{M}_{-5}$ is the mass loss rate in units of $10^{-5}\ M_\odot\ yr^{-1}$, v_1 the wind velocity in units of 10 km s^{-1}, T_5 the wind temperature in 10^5 K, V_4 the maximum ejecta velocity at time t, in 10^4 km s^{-1}, and where we have evaluated the Gaunt factor for $\lambda = 2$ cm and $T_5 = 1$, as well as used a typical shock thickness of 30 % of the shock radius. The observations roughly give

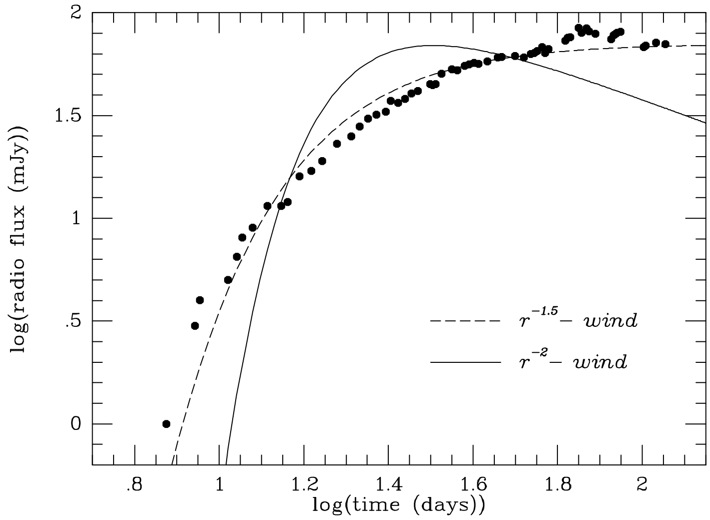

Fig. 2. Evolution of the radio flux from SN 1993J at 2 cm. Models are for the wind density falling off either as $r^{-1.5}$ (dashed line) or as r^{-2} (solid line). Other model parameters are described in the text. Observations are from Pooley & Green (1993)

$\tau_{\rm ff}$ = 0.5 at 2 cm on 22.5 April (Fransson *et al.* 1994), which translates into $\dot{M}_{-5}/v_1 \approx 4\ T_5^{3/4}$, assuming $n_{\rm He}/n_{\rm H}$ = 0.1, V_4 (25.5 days) = 2, and taking limb darkening into account. For an $r^{-1.5}$ wind, $\dot{M}/v$ would be lower than this estimate at radii smaller than $\sim 4 \times 10^{15}$ cm, but higher further out in the wind. The $r^{-1.5}$ wind appears to be present at least until day $\sim$ 60. This suggests a variation of $\dot{M}/v$ on a time scale of a few hundred up to one thousand years, depending on the wind velocity. Inside $\sim (1-2) \times 10^{15}$ cm we cannot say anything about the mass distribution from the radio observations.

The observed decline of the radio flux after maximum is roughly $\propto t^{-0.25}$ and the spectral index $\alpha \approx -0.8$ (Weiler *et al.* 1994). Chevalier's model would for this spectral index predict $\propto t^{-0.8}$ for a freely expanding shock, and an even faster decline if the shock is retarding. Changing the radial dependence of $\dot{M}/v$ to $\dot{M}/v \propto r^{0.5}$ gives the right decline. However, a time-varying $\dot{M}/v$ is not the only way to produce a slow decline of the radio flux. This can also be made for constant mass loss at constant wind speed if the mass was lost from the progenitor preferentially in a plane to form a disk-like structure. A disk model is motivated by the fact that many groups (see Podsiadlowski 1994, and references therein) argue that the SN was a member of a binary system, and that it lost a substantial fraction of its envelope prior to the explosion. The mass not captured by the companion may have been focussed to the orbital plane of the system.

Assuming a disk with a thickness that increases with radius as r^{ϕ}, though still retaining other assumptions inherent in Chevalier's model, we are able to model the observed flux decline for a freely exanding shock, if we choose $\phi = 0.4$ and $\alpha = -0.8$. Because the density in this model (assuming $\dot{M}/v$ to be constant with time) roughly falls off with radius as $\propto r^{-1-\phi}$, a value of ϕ close to 0.4 gives a radial density dependence similar to the $r^{-1.5}$ model in Figure 2. If the disk is viewed nearly edge-on the $\phi = 0.4$ model would thus provide a good fit also to the early part of the radio light curve If not, the radio maximum occurs too early (Fransson *et al.* 1994). More detailed models have to consider tilt angle effects for the optically thick part of the light curves, and also take into account the fact that the circumstellar shock in a disk model is expanding faster away from the disk plane than within the disk. This increases the shock area and also the amount of radiation produced. In order to test the disk geometry, one should also consider line profiles. Given the observed line widths (see below), we can state immediately that the disk is not being viewed face on, unless it is very thick.

Our estimate for $\dot{M}/v$ is sensitive to the wind temperature close to the circumstellar shock. For the spherically symmetric case, Fransson *et al.* (1994) find that this is $\sim (2-4)\times 10^5$ K, using the burst model by Shigeyama *et al.* (1993) together with hydrodynamic simulations for the ejecta/wind interaction. The main uncertainty in this calculation is the time of formation of the circumstellar shock. For a disk-like structure the detailed geometry is also important.

In order to map the CSG around SN 1993J and to gain understanding about the time of shock formation, it is important to consider the narrow emission lines, in particular the strong N V λ 1240 line. This was already present when IUE was pointed at the SN for the first time, on 30.2 March. The line then declined by nearly two orders of magnitude in a week. During the same epoch, the line first indicated a velocity of $\sim 10^3$ km s^{-1}, decreasing to ~ 100 km s^{-1} (see Sonneborn 1994, for details.) To explain both the width of the line and its high luminosity, Fransson *et al.* (1994) argued that the gas forming the line was preaccelerated by the radiation from the SN outburst; collisional excitation is not enough, photoexcitation boosted by a velocity gradient in the wind is also needed. It is interesting to note that N V λ 1240 drops roughly at the same rate as the continuum near the line.

One problem with N V λ 1240 is that it shows that N^{4+} has to be present at least until day 4, even when light echo effects are allowed for (Fransson *et al.* 1994). However, the calculations for spherical symmetry by Fransson *et al.* show that as soon as the circumstellar shock forms, i.e., no later than after ~ 0.5 days, the wind is completely ionized and the temperature is raised to $\sim (2-10)\times 10^5$ K. The X-ray observations on day 7 confirm this; the circumstellar X-ray optical depth is negligible.

Although hydrodynamic models invoking spherical symmetry show that the gas should be fully ionized, there are two explanations as to why N^{4+} could be present. Either the shock does not form until after day 4, or the geometry is such that the densest part of the CSG subtends a rather small part of the volume swept up by the ejecta. In the first model, no ionizing flux except that from the photosphere is produced prior to day 4, and in the second the flux of ionizing radiation is lower than in the spherically symmetric case. We believe that the latter model is the most appropriate, because with only the photospheric radiation included, the gas recombines in less than ~ 2 days to ionization stages lower than N^{4+}, resulting in no N V λ 1240 emission. In particular, a model with a disk-like structure is attractive since it should be possible to tune this so that it takes ~ 4 days for the ionization front to move radially through the disk, hence producing a N^{4+}-zone persisting this long. The shock in this model also produces the continuum radiation around 1240 Å needed to photoexcite the line. In the delayed shock formation scenario, there is no such continuum emission.

Once the circumstellar shock has formed, the ionizing radiation produced by the shocked gas is a mix of inverse Compton scattered and free-free emission. The calculations by Fransson *et al.* (1994) show that it is difficult to avoid producing so much inverse Compton scattered radiation that the models are incompatible with the observations. A disk structure will act to decrease the importance of inverse Compton scattered relative to free-free emission (Fransson *et al.* 1994), so this may also argue for a disk geometry.

Finally, it should be noted that a model with blobs instead of a disk shares many of the virtues of a disk model. However, having the high density gas distributed radially to form a disk makes it easier to have a long period of high N^{4+} abundance.

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