THE CIRCUMSTELLAR STRUCTURE AROUND SUPERNOVAE

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Abstract: The time dependent ionization and temperature structure of the circumstellar medium around supernovae has been calculated, in order to interpret recent supernova radio observations. For a stellar wind origin of the circumstellar medium, we relate the time of radio turn-on to the progenitor mass loss rate. We also show that large column densities for the UV resonance lines are expected. The results are applied to SN 1979c, SN 1980k and SN 1987A.

1. Introduction

Observations of recent Type Ib and Type II supernovae (cf. reviews by Chevalier, 1984, Fransson, 1986 and Panagia, 1987) can be explained by a model where the supernova ejecta expands into a dense circumstellar medium (Chevalier, 1982). The wavelength dependent delay between the optical and radio outbursts (Weiler et al., 1986) is well explained in terms of free-free radio absorption in the circumstellar medium outside the expanding blast wave. If we parametrize the pre-supernova mass loss with a steady rate $\dot{M}$ and expansion velocity u, the free-free optical depth between the radio emitting region and the observer scales as $\tau_{ff} \propto (\dot{M}/u)^2 \ T_e^{-3/2} \ x_e^2 \ \lambda^2 \ R_s^{-3}$, where T_e the wind temperature, x_e the fraction of free electrons in the wind, λ the wavelength and R_s the shock radius. The delay between optical and radio outbursts, and hence also the estimated mass loss rate, is thus, in addition to the mass loss rate, sensitive to both the temperature and the degree of ionization. To calculate these parameters, we have made time dependent photoionization calculations, including the ionizing effects of the supernova. A detailed discussion may be found in Lundqvist and Fransson (1987), here we only summarize the main results. In addition, we report similar calculations for SN 1987A.

2. Results and Discussion

The progenitors of 'normal' Type II SNe are thought to be red supergiants with masses $\gtrsim 10 \ M_\odot$ and extended atmospheres. Stars of this type are observed to have strong winds with mass loss rates 10^{-6}–$10^{-4} \ M_\odot$/yr and wind velocities of ~10 km/s. For this type of supernovae, the wind structure is mainly influenced by the ionizing photons produced by Compton scattering. Here, photospheric photons are scattered by hot (~10^9 K) electrons in the shocked stellar wind close to the blast wave, thereby roughly doubling their energy in each scattering (e.g. Fransson, 1986). For SN 1979c we find that the total number of ionizing photons is ~10^{60}. The photons will ionize both the wind and create an H II-region of radius ~20 $n_H^{-1/3}$ pc in the interstellar gas. This is roughly consistent with the observations of Cas A (~5.7 pc for n_H~15 cm^{-3}, Peimbert and van den Bergh, 1971). For low

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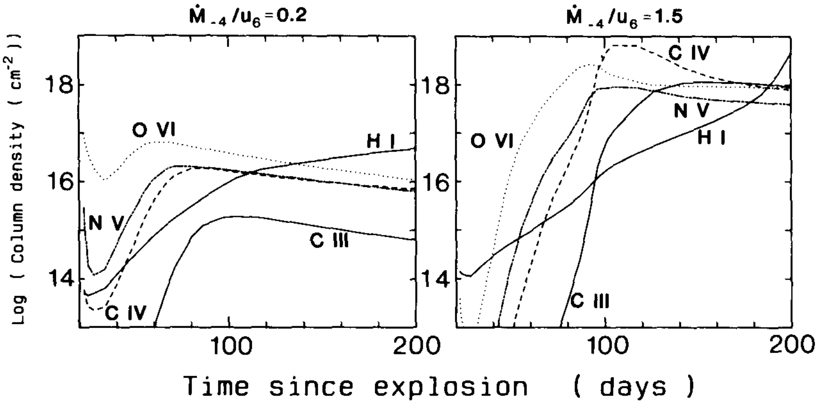

Fig. 1. The temporal dependence on the column densities of the most interesting ions for models representing SN 1980k (left) and SN 1979c. $\dot{M}_{-4}$ is the pre-supernova mass loss rate in 10^{-4} $M_\odot$/yr and u_6 the wind speed in 10^6 cm/s.

density stellar winds, $\dot{M}_{-4}/u_6 \lesssim 0.01$, where $\dot{M}_{-4}$ is the pre-supernova mass loss rate in 10^{-4} $M_\odot$/yr, and u_6 the wind speed in 10^6 cm/s, the initial EUV/soft X-ray outburst dominates the ionization of the circumstellar medium, creating roughly 10^{58}-10^{59} ionizing photons (Chevalier and Klein, 1979). Another important ionizing source for low density winds is the reverse shock propagating into the supernova ejecta. For dense winds, this contribution is severely absorbed in the thin interaction region between shocked supernova ejecta and shocked stellar wind, but increases in importance with time and dominates the total ionization after 50-300 days.

For parameters representing SN 1979c, we find that the wind temperature close to the blast wave rises to ~2×10^5 K during the first month, and decreases to ~1.3×10^4 K after ~400 days (Fig. 2). At the same time, the initially fully ionized wind recombines to ions like C II, N II and O I close to the blast wave. Outside ~0.1 pc, the density is too low for the gas to recombine and it remains almost fully ionized. This temporal behaviour is reflected in the column densities of the UV absorbing ions, shown in Fig. 1. For normal Type II supernovae, the optical depth in both C IV(λ1548-51) and N V(λ1239-43) should increase during the first months, due to recombination in the innermost part of the wind. They then remain roughly constant due to the increasing recombination time scale close to the blast wave. Considering the large column densities, these lines should be easily observable with the resolution of the Space Telescope.

The temperature and ionization structure close to the blast wave determines the radio absorption, and in Fig. 2 we show these parameters together with the resulting radio light curves for a model with $\dot{M}_{-4}/u_6=1.0$, roughly representing SN 1979c. An interesting point is that the dip at ~350 days in the 6 cm light curve is due to rapid cooling of

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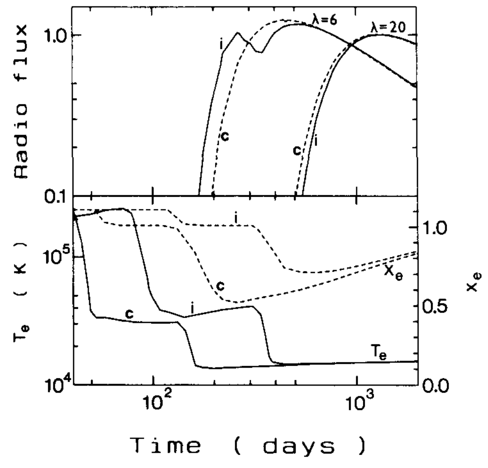

Fig. 2. Radio light curves for $\dot{M}_{-4}/u_6$=1.0. Lines marked 'i' are for equal ion and electron temperatures in the shocked wind, whereas those marked 'c' are for Coulomb heating of the electrons only. Note that the dip in the 6 cm light curve coincides with the temperature drop in the gas close to the blast wave, shown in the lower panel. This should be compared with a similar drop seen for SN 1979c.

the gas, temporarily increasing τ_{ff}. A similar dip is present in the observations of SN 1979c (Weiler et al., 1986) and thus reflects the cooling of the gas.

In Fig. 3 we relate the time of radio onset to the precursor mass loss rate. The full lines are for equal ion and electron temperatures in the shocked wind, dashed lines for Coulomb heating of the electrons only. For comparison the dotted lines show the $\dot{M}/u$ versus t relation for a fully ionized wind with temperature 10^4 K. For high mass loss rates with a turn-on of more than ~200 days at 20 cm, the optical depth is determined mainly by the recombination and the cooling of the wind. It is thus insensitive to the properties of the early UV and EUV flux. For low mass loss rates, the turn-on is set by the temperature of the wind, which depends on the flux and spectral shape of the flux from the shock and early EUV burst. Comparing with the observations by Weiler et al. (1986), we find mass loss rates of 1.2×10^{-4} $M_\odot$/yr and 3×10^{-5} $M_\odot$/yr for the pre-supernovae of SN 1979c and SN 1980k, respectively, for a wind speed of 10 km/s.

The early radio turn-on of SN 1987A, at 20 cm only ~2.1 days after the core collapse (Turtle et al., 1987), indicates a much less dense wind than around SN 1979c and SN 1980k. Using the circumstellar absorption model, Chevalier and Fransson (1987) find a mass loss rate of 8.8×10^{-6} $M_\odot$/yr for a wind velocity of 550 km/s, assuming a wind temperature of ~10^5 K. With the results for the photosphere calculated by Shigeyama et al. (1987), and the ionizing radiation from the reverse shock estimated by Chevalier and Fransson (1987), we have made a calculation for this wind density, using the same method as described above. In this case all the elements in the wind attain their helium-

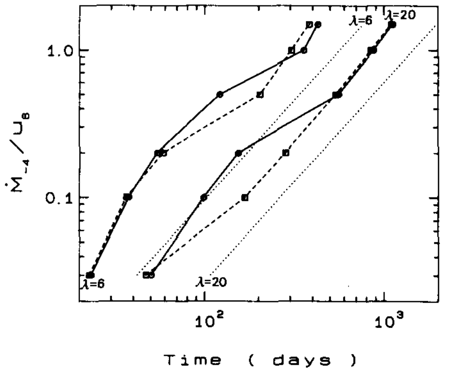

Fig. 3. The relation between radio turn-on at 6 cm and 20 cm, and pre-supernova mass loss rate. Solid and dashed lines have the same meaning as in Fig. 2. For a comparison, dotted lines are for a fully ionized wind at temperature 10^4 K. The radio turn-on is defined to occur when the radio flux is a factor e^{-1} times that extrapolated from the power law part of the light curve, corresponding to a free-free optical depth, $\tau_{ff}=1$.

like stages, except close to the blast wave where the wind becomes almost completely ionized. The temperature of the circumstellar medium is after ~1 day ~7.0×10^4 K throughout the wind, not very different from that used by Chevalier and Fransson. A more detailed discussion on the results for the structure around SN 1987A is presented elsewhere.

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