Observable Effects of Shocks in Compact and Extended Presupernovae

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Abstract. We simulate shock propagation in a wide range of core-collapsing presupernovae: from compact WR stars exploding as SNe Ib/c through very extended envelopes of the narrow-line SNe IIn. We find that the same physical phenomenon of radiating shocks can produce outbursts of X-ray radiation (with photon energy $3kT \sim 1$ keV) lasting only a second in SNe Ib/c, as well as a very high flux of visual light, lasting for months, in SNe IIn.

1 Introduction

Shock waves created at supernova explosions are observed mostly at the stage of supernova remnants due to their x-ray emission. For supernovae themselves shocks are not observed directly: normally the stage of shock break-out through the presupernova surface layers produces a short-lived transient of hard radiation. Yet those transients may have important observational consequences. Moreover, in some supernovae the shock propagation in surrounding CSM may be decisive in producing their light on time-scales from days to years.

A shock propagating down the profile of decreasing density should accelerate \cite{1}. The acceleration ends when the leakage of hard photons from the shock front into outer space becomes efficient enough. We simulate shock propagation in a variety of core-collapsing presupernova models using a code with hydrodynamics coupled to multi-energy-group time-dependent radiation transfer. In our previous work on extended type II SNe \cite{2}, with radii of a few hundred $R_\odot$, we have found the peak effective temperature at the shock break-out, $T_{\text{eff}} \sim 1.5 \times 10^5$K. For SN 1987A, with its presupernova radius of only $\sim 50R_\odot$, we have got $T_{\text{eff}} \sim 6 \times 10^5$K \cite{3}. Due to effects of scattering the maximum color temperature is a factor of 2-3 higher.

In compact presupernovae, like SNe Ib/c, the shock can become relativistic \cite{4} and is able to produce a burst of X-ray and even $\gamma$-ray radiation \cite{5–7}.

Supernovae of type Ib/c are also interesting for theory due to problems with their light curve and spectral modeling. Their understanding may serve as diagnostics of mass loss from massive stars at the latest phases of evolution.
2 Compact presupernovae: SNe Ib/c

Numerical modeling of shock breakout in SNe Ib/c was done previously using some simplifying approximations [8]. Our method, realized in the code STELLA, allows us to get more reliable predictions for the outburst. Improvements in the theory done in the current work are: multi-energy-group time-dependent radiation transfer, and taking into account of (some) relativistic effects.

A representative presupernova in our runs was a WR star built by the code KEPLER [9] (model 7A). Late light curves and spectra for this model were studied in [10].

The Model 7A has mass $3.199\, M_\odot$ (including the mass of the collapsed core). Its radius prior to explosion is not strictly fixed because the outer mesh zones in KEPLER output actually model the strong stellar wind and are not in hydrostatic equilibrium. So, we fixed the radius by hand and we got four models with radii from $0.76$ up to $2\, R_\odot$ which are in hydrostatic equilibrium. Our results are summarized in the Table.

Explosions with KEPLER [10] gave a maximum temperature of photons $T \sim 5 \times 10^5$ K at shock breakout. We have much finer mesh zoning at the edge of the star (down to $1 \times 10^{-12} M_\odot$) and better physics and we find much higher values of $T$. The left plot in Fig. 1 shows the difference between effective and color temperatures (labels ‘e’ and ‘c’, respectively, in the Table). One should note that the peak values of luminosity and temperature given in the table and on the left plot of Fig. 1 do not contain the light travel time correction. Its effect on the luminosity, i.e. smearing the peak on the time-scale of $\sim R/c$ is shown on the right plot of Fig. 1. Models, labeled as 3.5N were computed by one of us.

![Figure 1](image-url)

Fig. 1. Effective and color temperatures of emerging radiation (left). Shock breakout luminosity found by the hydrocode SNV (right) Dashed lines demonstrate the effect of averaging the light curve due the light travel time correction.

(D.K.N.) in 1992 with the equilibrium radiation diffusion hydrocode SNV.
### Table 1. Parameters of shock breakouts

| $M^a$ | $R_0^a$ | $E_{\text{kin}}^b$ | $L_p^c$ | $T_p^c$ | $\Delta t^d$ |
|-------|---------|-------------------|--------|--------|-------------|
| $M_\odot$ | $R_\odot$ | foe | erg/s | $10^6K$ | s |
| 3.2 | 0.76 | 1.24 | $4.2 \times 10^{44}$ | 4.2c | 0.021 |
| 3.2 | 1.00 | 1.32 | $5.8 \times 10^{44}$ | 4.3c | 0.026 |
| 3.2 | 1.23 | 1.30 | $6.8 \times 10^{44}$ | 4.3c | 0.043 |
| 3.2 | 2. | 1.39 | $9.4 \times 10^{44}$ | 4.3c | 0.12 |
| 3.2 | 2. | 4.36 | $3.6 \times 10^{45}$ | 5.3c | 0.028 |
| 3.2 | 2. | 8.86 | $4.8 \times 10^{45}$ | 7.2c | 0.020 |
| 3.5N | 0.76 | 1.30 | $1.4 \times 10^{45}$ | 5.1e | 0.028 |
| 3.5N | 1.23 | 1.30 | $8.1 \times 10^{44}$ | 3.5e | 0.067 |

- $^a$ presupernova mass and radius, respectively, in solar units.
- $^b$ kinetic energy at infinity in $10^{51}$ ergs.
- $^c$ peak luminosity and temperature.
- $^d$ the width of the light curves at 1 stellar magnitude below $L_p$.

## 3 Shocks in CSM in Type IIn supernovae

The narrow-line Type II supernovae (SNe IIn) are embedded in massive circumstellar shells (wind) extending from tens of thousands solar radii (SN 1998S) to $\sim 10^{17}$ cm (SN 1988Z). One of the brightest SNIIn, SNII 1994W in NGC 4041, displays a spectrum dominated for $\sim 200$ days by low-ionization P-Cygni lines with widths of order $10^3$ km/s, and at late times by narrower H$_\alpha$ in pure emission. The lightcurve shows a plateau for $\sim 120$ days, after which the luminosity drops by $\sim 3.5$ magnitudes in $V$ in only 12 days. The existence of such a drop, caused by circumstellar shells, was emphasized in paper [12]. The interpretation of spectra and light curve of SN 1994W leads to a coherent model in which the supernova interacts with a massive circumstellar shell ejected roughly 2 years prior to the explosion [11].

Main features of SN 1994W are well reproduced by the radiative shock propagating at relatively low speed for several months in the circumstellar shell. This shock forms its unique lightcurve with a plateau quite different from a classical SNeII-P. (In the latter $UBV$ light curves diverge at the end of $V$ plateau, while here all colors converge.) The sudden drop of V-flux by $\sim 3.5$ magnitudes in 12 days is also explained quite naturally. The results presented in Fig. 2 are computed for the supernova model with ejected mass $7M_\odot$ and huge radius of presupernova $R_0 = 2 \times 10^4R_\odot$ surrounded by a shell with the density $\rho_{\text{wind}} = 12/r$ in CGS units. The CS envelope has an outer cut-off radius $R = 6.6 \times 10^4R_\odot$. The ejection of this dense extended CS envelope might be related to weak explosions occurring several years prior to the collapse of the core [13] (see also [14]).
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