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Radiation hydrodynamics of supernova shock breakouts

S. Blinnikov [a,b,c,*], A. Tolstov [a,c], E. Sorokina [b], A. Dolgov [a,c,d]

[a] ITEP 117218 Moscow, Russia
[b] SAI, Moscow State University, 119992 Moscow, Russia
[c] Novosibirsk State University, 630090 Novosibirsk, Russia
[d] University of Ferrara and INFN, Ferrara 44100, Italy

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ABSTRACT

The first powerful burst of photon radiation in a supernova appears when the shock front is a few photon mean-free paths below the star photosphere. This is called "shock breakout" and it is the first observable event after the neutrino and gravitational wave bursts in core-collapsing supernovae. Any early information about collapse is vitally important for understanding the physics of explosion, constraining speed of neutrino propagation etc. Direct observations of shock breakouts have been carried out in a few supernovae. We discuss some puzzles related to those objects. Finally, we describe our current understanding of the most luminous (hyper-)supernovae. Their long living radiative shocks pause many interesting problems in numerical and laboratory astrophysics and may have important applications in cosmology.

1. Shocks in standard supernovae

The power of supernova radiation at the epoch of shock-breakout may be much higher than at the epoch of its "maximum light". E.g. SN1987A was rather weak in absolute luminosity when it was observed, but its peak power at shock-breakout, $L \gtrsim 3 \times 10^{44}$ erg/s, had to outshine the whole giant galaxy like Milky Way (see Fig. 1). The problem of detecting these events is the rather short duration of the flash (from seconds to hours, depending on the radius of the presupernova). Nevertheless, direct observations of shock breakouts are available in a few supernovae now. Moreover, we know several examples of extremely luminous supernovae which emit 10^{44} erg/s for months, and we believe that this photon luminosity is produced by long living radiative shocks.

A shock with velocity D inside the star remains in *adiabatic* phase while the optical depth is large, $\tau \equiv \delta R/\ell > c/D$, where ℓ is the photon mean free path, δR is the distance from the shock to the photosphere, and c is the speed of light [1]. When $\tau \lesssim c/D$ the burst of photon luminosity begins: this is the *shock break-out*. The shock is highly non-adiabatic then and a density peak is built up similar to the old Supernova Remnants.

The shock waves inside supernovae are supercritical, that is the principal transport of energy is carried out by radiation through the leading Marshak wave [2]. Moreover, they are radiation dominated: the radiation pressure and energy density exceed the kinetic pressure and energy of ions and electrons. At this point we basically have a shock in a photon gas, trapped in plasma, which has $\gamma = 4/3$. The maximum shock compression is then $(\gamma + 1)/(\gamma - 1) = 7$.

But this is true only for an adiabatic shock. For radiative (almost isothermal) shocks the compression may be orders of magnitude higher, cf. Fig. 3 below, and the definition of radiative shocks given by Carolyn Kuranz [3] and other presentations at this meeting.

In radiation dominated shocks the preheating effect becomes so large that one of the most typical features of classical shock waves, namely, the *viscous jump* in pressure and density at the hydrodynamic shock front – diminishes and completely disappears in a sufficiently strong shock. Laboratory experiments can reach this regime [4].

In the equilibrium diffusion approximation the jump disappears when the ratio between radiation pressure and gas pressure is $P_r/P_g \simeq 4.4$ [5,6], and also [7], cited in Ref. [2].

In radiation dominated shocks not only the preheating effect is important. The *momentum transfer* from photons to electrons (and hence to ions, via the electric field) is very large. This also destroys the viscous jump in pressure and density at the hydrodynamic shock front. Imshennik and Morozov [8] have found with account of photon momentum transfer (but ignoring scattering) that this happens when $P_r/P_g \simeq 8.5$. Anyway, the disappearance of the viscous jump is a feature of strong shocks which makes their simulations easier when one has at hand a reliable numerical scheme for radiative transfer.

* Corresponding author. ITEP, 117218 Moscow, Russia.
E-mail address: sergei.blinnikov@itep.ru (S. Blinnikov).

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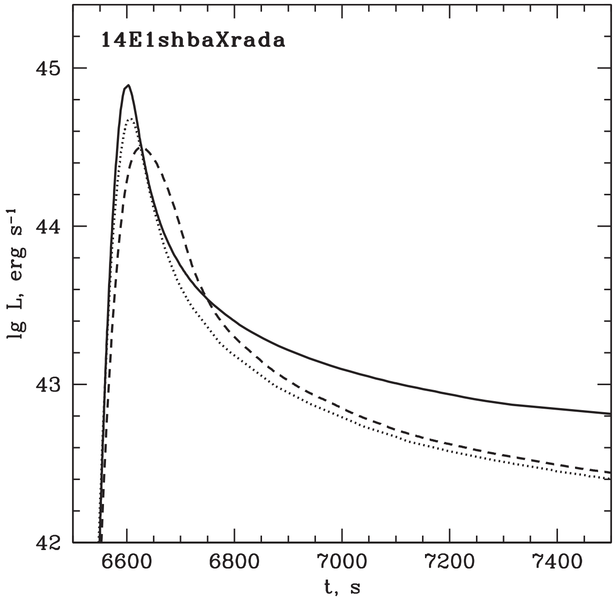

Fig. 1. Models for SN 1987A taken from Ref. [14]. New radiation hydrodynamics runs stella (solid) vs rada (dotted). Dashed line represents rada results in observer's frame with light-travel-time correction.

2. Simulations of shock-breakouts in supernovae

We are using two multi-group Lagrangian implicit radiation hydro codes for spherically symmetric problems: STELLA (STatic Eddington-factor Low-velocity Limit Approximation) [9–11], and rada (Relativistic rADiation transfer Approximation) [12,13]. Fig. 1 illustrates the differences of the predictions of the two codes for the flash at shock-breakout of SN1987A.

What is the temperature T of matter and radiation at this epoch? It is a very important question. Old simulations [15,16] predicted a hard X-ray spectrum for large stars like Red Supergiants and SN1987A at shock-breakout. There were even hopes to explain gamma-ray bursts by shock-breakouts [17,18]. We predict (with STELLA and RADA) rather soft spectra. Numerically this was already studied by Weaver [19] but for higher density. He never gets very high T in shocks. What is the reason for the discrepancy with the old result?

In Fig. 2, the matter temperature T at the shock-breakout for an SNIb model is plotted against the Lagrangian mass M_r measured from the surface. We see on the left panel that the peak values of T are enormous – up to 10^{10} K (i.e., of the order of MeV), and the spectrum is hard. Since the stella algorithm includes the evolution of photons in a converging flow in the shock in the same approximation, as considered by Blandford and Payne [20], one could think that our computation confirms their analytical result.

In fact, however, the high density and hardness of the radiation obtained in the simulation require a more careful treatment of the photon production, absorption, and scattering. It turns out that allowance even for a very weak double Compton effect [19,21,22] leads to a drastic change of the results. We have simulated this effect by a very small admixture of true grey absorption, 10^{-6} of the Thomson scattering, in the same presupernova. The right panel of Fig. 2 shows that the matter temperature decreases sharply compared to the almost pure scattering case on the left plot. The radiation is much softer and it appears impossible to get a hard power-law spectrum predicted in Ref. [20].

3. Direct observations of shock-breakouts

Shock-breakouts in SNe II have been observed at high redshift z [23,24] and simulations [25,26] with STELLA show good agreement with observations.

More puzzling is SN2008D where the shock-breakout with duration Δt of a few minutes was caught by Soderberg [27] as an X-ray flash, XRF080109. The puzzle is that this duration should be typical for a presupernova with the radius $R \sim c\Delta t$ like SN1987A, and not with the more compact SNIb as SN2008D [28], where one would expect Δt around 10 s or less. There are many theoretical papers claiming that the spectral features of this event are in agreement with expectations with the scattering-dominated envelope, e.g., Ref. [29]. Our runs with rada confirm this [13]. It is believed that the discrepancy in Δt persists without the scattering shells which are denser than the winds typical for the progentors of SNIb [29]. However, our self-consistent radiation hydrodynamics simulations show that the needed duration can be obtained even for the steady wind with parameters found in Ref. [27]. The simulations show that the radiative shock forms the scattering

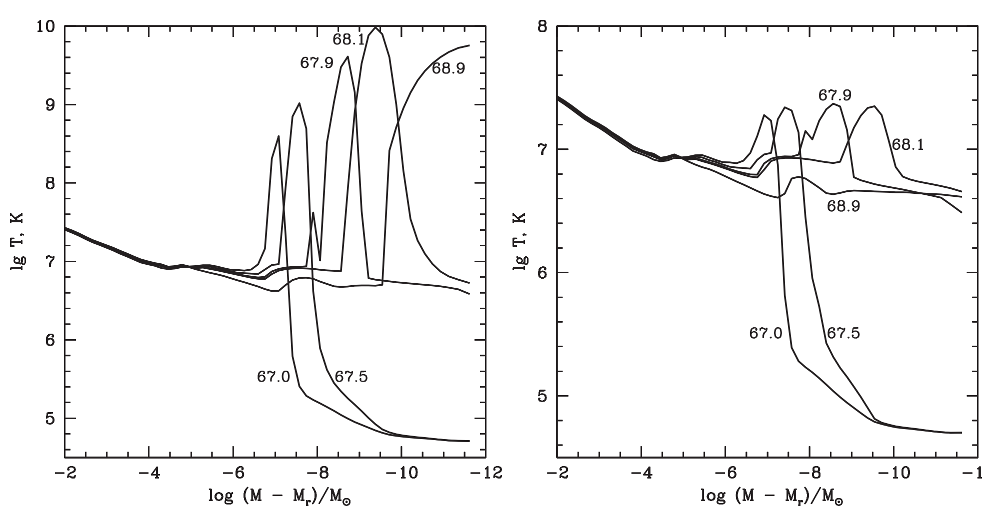

Fig. 2. Matter temperature for a type Ib SN model in Ref. [13] at shock breakout versus Lagrangian mass M_r measured from the surface. The time in seconds is given near the curves. Left: Standard opacity dominated by Thomson scattering σ. The temperature peak is at optical depth $\tau \sim 200, 50, 4, 1, 0$. Right: weak absorption $\alpha = 10^{-6}\sigma$ added. The temperature peak is reached at similar values of τ but virtually disappears near the surface.

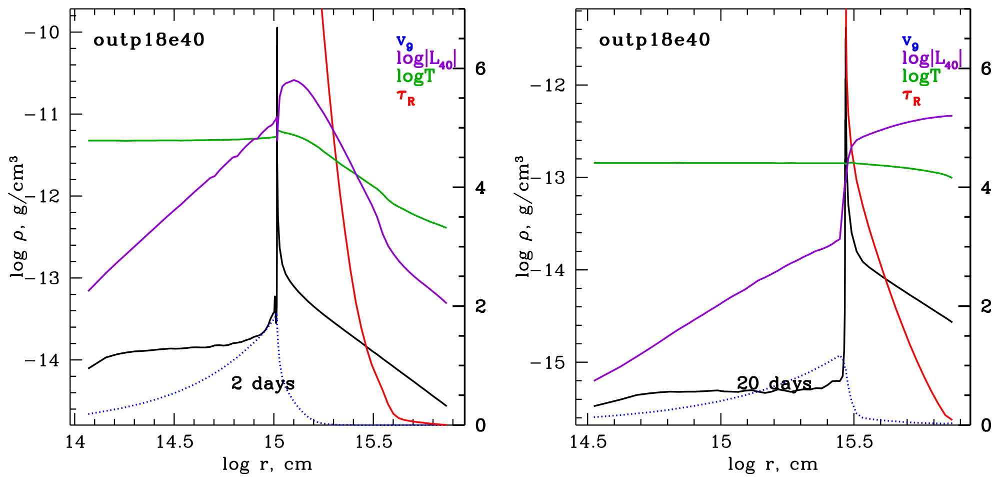

Fig. 3. Long living dense shells for two epochs in a model with C/O "wind", $\rho_w \propto r^{-1.8}$, $E = 4$ Bethe. The scale for the density (black solid line) is on the left *Y*-axis, and on the right *Y*-axis there is a scale for the velocity $v_9 \equiv v$[cm/s]/10^9 (blue, dotted line), for the absolute value of luminosity $L_{40} \equiv L$[erg/s]/10^{40}, for the logarithm of temperature in K, and for the Rosseland optical depth τ_R. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

atmosphere in the wind which is large enough to explain the observed duration.

The shock-breakout nature of XRF080109 was questioned by Li-Xin Li [30]. He finds a two-temperature black-body spectrum fits to observations and claims that the hard emission radius is too small for the shock. Actually, there is no problem! "Two-temperature" spectra are obtained naturally in detailed multi-group simulations, see Figs. 8, 10, and 12 in Ref. [13]. Hard emission comes from deep layers of a star and it is visible simply because photo-ionization cross-section is smaller at higher photon energy.

4. Circumstellar matter

The main puzzle for XRF080109-SN2008D is its long duration (for a compact preSN Ib). This is explained by a rather dense wind, a circumstellar cloud, surrounding the presupernova star. It may be a general feature for some of the *Super-Luminous Supernovae*, SLSN, or hyper-supernovae, on much larger and longer scale.

There are extremely luminous Type IIn SNe [31–34]. Super-luminous supernovae of other types are being discovered currently, e.g., in the Palomar Transient Factory survey [35]. Their luminosity is higher than for famous "Hypernovae" like SN1998bw, associated with GRBs. Total light energy is 2 orders of magnitude higher than for normal core collapsing SN and 1 order more than for the brightest thermonuclear SN used for cosmology. SLSNe shine for a longer time. To explain this light we inevitably involve long-living radiative shocks. An example is our model for SN1994w of type IIn [36] and SN2006gy [33].

Normal stellar winds are too weak to produce those dense CSM clouds. One has to invoke multiple explosions of supernovae in this case. This is the old idea by Grasberg and Nadyozhin [37].

We have extended this idea to explosions in dense hydrogen-free envelopes [38]. In this way we are able to explain some superpowerful type Ic SNe. Our synthetic models are built of ejecta which have a quasi-polytropic mass distribution and of a dense envelope, or "wind", with a power-law density distribution $\rho \sim r^{-p}$. The composition is uniform for most of the models (it is always uniform for the wind): 0.5C + 0.5O + 2% of metals with Solar abundances, or He + 2% of metals. As a rule, we put no ^{56}Ni in order to check the influence of the pure shock on the light curves. Normally, we assume zero velocity in the "wind": $v_w = 0$, but some runs are done for high v_w, because some SLSNe do not show narrow lines in their spectra. A couple of typical light curves are presented in Fig. 4. The left panel presents a model with $v_w = 0$, and the right one has $v_w > 0$ with $E = 2$ Bethe in ejecta and $E = 2$ Bethe in the more massive "wind".

The results are encouraging. We need the explosion energy of only 2–4 Bethe for shells with $M = 3 - 6M_\odot$ and $R \lesssim 10^{16}$cm to explain SLSNe.

Those very powerful supernovae are interesting also because of the potential use of their long living radiative shocks as a tool for measuring distances and cosmological parameters. This will

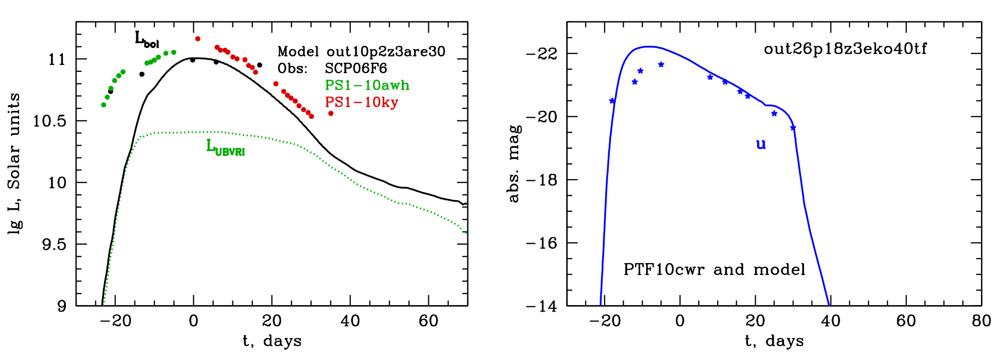

Fig. 4. Left: comparison of observed bolometric luminosity for 3 hyper-supernovae [35] (dots) with C/O "wind" model, $\rho_w \propto r^{-2}$, $v_w = 0$, and $E = 3$ Bethe of central explosion (solid line). Right: observations in *u* filter for PTF10cwr = SN2010gx (dots) and the model with double explosion, fast moving "wind", $\rho_w \propto r^{-1.8}$, $E = 2$ of central explosion and $E = 2$ in the "wind" (solid line).

be complimentary to standard applications of supernovae in cosmology [39,40], because it can be done without invoking the distance ladder as discussed in our paper [41]. Most luminous SN events may be observed at high z [for years due to $(1+z)$] and may be useful as direct, *primary*, distance indicators in cosmology.

5. Conclusions

Radiating shocks are the first observable signals of supernovae which can be observed at cosmological distances. They are the most probable sources of light in most luminous supernovae of different types.

The shock wave which runs through rather dense matter surrounding an exploding star can produce enough light to explain very luminous SN events. No ^{56}Ni is needed in this case to explain the light curve near maximum light (some amount may be needed to explain light curve tails). We need a modest explosion energy of 2–4 Bethe. Narrow lines are not necessarily produced.

There are many questions on the latest phases of stellar evolution leading to those events. One encounters many technical problems in light curve calculations, like line opacities, multi-dimensionality (3D is needed, since the envelope can most probably be clumpy), NLTE effects in spectra. Some of these problems are attacked in experiments in laboratory astrophysics [42–46].

The main complication to the whole picture is possible fragmentation of the dense shell. The attempts on multi-D treatment of SN ejecta evolution are rather old [47–49], more recent results and references may be found in Refs. [50,51]. See also Ref. [52] for the case of SN2006gy, but without real treatment of radiative transfer. There are several 3-D MC transport codes for supernovae [53–59] but they are not actually coupled to hydrodynamics and there are many difficulties in doing this [60–63], because even spherically-symmetric hydrodynamics coupled to radiative transfer is a 3D problem numerically, and 3D hydrodynamics means a 6D problem with transport.

The salient feature of the radiative shock breakout is the formation of a dense shell. Its evolution, dominated by the radiative transfer, is very hard to compute in multi-dimensional simulations. The laboratory experiments clearly show the compression in radiative shocks (e.g., Ref. [3]). It would be very interesting to advance the laboratory experiments to the stage where one can observe the evolution of the dense shells and to benchmark the numerical simulations.

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