Coupling of matter and radiation at supernova shock breakout

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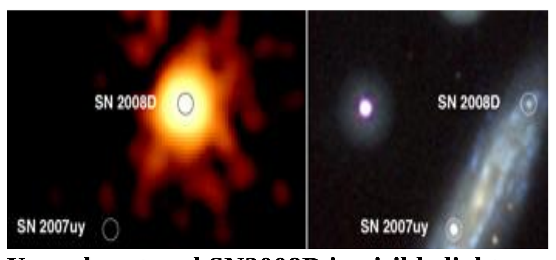
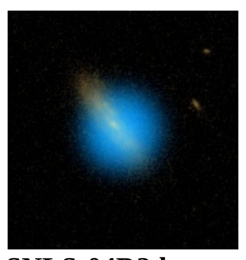
INTRODUCTION

The phenomenon of a supernova in most cases should start with a bright flash, caused by a shock wave emerging on the surface of the star after the phase of collapse or thermonuclear explosion in interiors. The detection of such outbursts associated with the supernova shock breakout can be used to obtain information about the explosion properties and presupernova parameters, which is necessary to understand the physical processes that underlie this phenomenon.

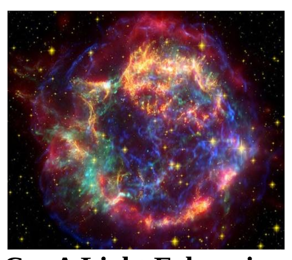
For an accurate treatment of the shock wave propagation near the surface of a presupernova it is necessary to perform numerical calculations which, in addition to hydrodynamics, should account correctly for radiative transfer in moving media. In some cases, e.g. in compact type Ib/c presupernovae, shock waves can reach relativistic velocities (Blinnikov et al. 2002, 2003). Then one has to include into consideration a number of relativistic effects. Here we present the results of numerical simulation of shock waves in several models for type Ib and type II supernovae, taking into account these features.



X-ray burst and SN2008D in visible light



SNLS-04D2dc



Cas A Light Echoes in Infrared (red color)

Studying the supernova shock breakout becomes particularly topical in connection with the recent detection of this phenomenon by the SWIFT spacecraft (Soderberg et al. 2008). In addition, a flash from the shock wave on the surface of red supergiant in type II supernova SNLS-04D2dc (Schawinski et al. 2008; Gezari et al. 2008) and the light echo from the shock wave of a supernova Cas A (Dwek & Arendt 2008) are detected. The luminosity of the most powerful supernova SN2006gy is most successfully explained by models where the radiative shock wave provides almost all radiation for many months (Woosley, Blinnikov & Heger 2007). There is the possibility of obtaining new data if the experiments similar to LOBSTER space observatory (Calzavara & Matzner 2004), EXIST (Energetic X-ray Imaging Survey Telescope, see Grindlay et al. 2003; Band et al. 2008) or any X-ray station of a similar type would be started in future. E.g., the experiment MAXI (Monitor of All-sky X-ray Image) on board the module Kibo at ISS (Matsuoka et al. 1997) is already started.

OBJECTIVES

The methods of constructing shock breakout models must have a number of refinements. Among them we consider how the relativistic and geometric effects in radiative transfer in a comoving frame of reference influence the predictions of supernova light curves and spectra at the epoch of shock breakout.

We also check the sensitivity of the predictions of the shock emission to the parameters of the numerical scheme, such as the boundaries of the frequency interval (including the X-ray range), and to the approximations in the opacity description.

METHODS

We use the code STELLA (STatic Eddington-factor Low-velocity Limit Approximation) (Blinnikov et al. 1998, Blinnikov et al. 2006), which is designed to solve the problem of the radiative transfer of nonequilibrium radiation with allowance made for hydrodynamics and, subsequently, to model the light curves of supernovae. Thus, we use the method of complete multigroup radiation hydrodynamics in which the defects of older approaches were corrected.

STELLA includes in full opacity photoionization, free-free absorption, lines and electron scattering. The number of lines included into consideration in standard versions is about 100 thousand in the range from 10^2 Å to $5{\cdot}10^4$ Å. The default number of frequency groups used in calculation is 100. The equation of state treats the ionization by equilibrium Saha's approximation.

STELLA is well applicable for the models of type II supernovae, such as SN 1987A and SN 1993J (Blinnikov et al. 1998, Blinnikov et al. 2000). The method provides the most reliable predictions for an outburst to be made as long as the matter velocity u is less than ~ 20% of the speed of light c, the error of the method is ~ (u/c).

If the velocity of matter behind the shock wave reaches a significant proportion of the speed of light, $\beta \equiv u/c > 0.2$, then STELLA uses an algorithm RADA (fully Relativistic rADiative transfer Approximation) (Tolstov 2010) based on short characteristics approach, which solves the radiative transfer equation in comoving frame up to the values of the Lorentz factor, $\gamma \equiv (1-\beta^2)^{-1/2}$ equaled to ~ 1000. Exact values of Eddington factors, calculated by RADA, are used in STELLA code. Apart from the radiative transfer equation in a comoving frame of reference, RADA takes into account the delay of the radiation from the supernova explosion. This stems from the fact that the radiation from the edge of the star visible to an observer comes later than that from the central regions.

RESULTS

SN 1987A

For our calculations of the SN 1987A outburst, we used the presupernova model constructed by the Tokyo group (Shigeyama 1987; Shigeyama, Nomoto 1990). For details on this model and the versions of our calculations (see Blinnikov (1999), Blinnikov (2000)).

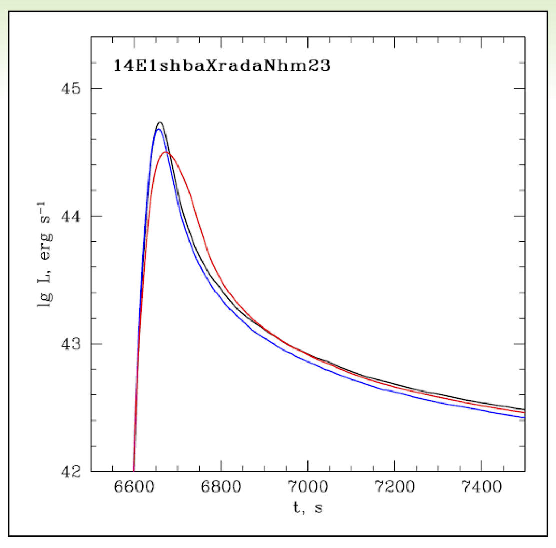


Fig. 1. Comparison of the bolometric light curves at the epoch of shock breakout for an SN1987A-type presupernova model. The black and blue lines represent, respectively, the STELLA and RADA calculations in the comoving frame of reference. Red line - RADA calculations in observer's frame of reference taking into account radiation time delay.

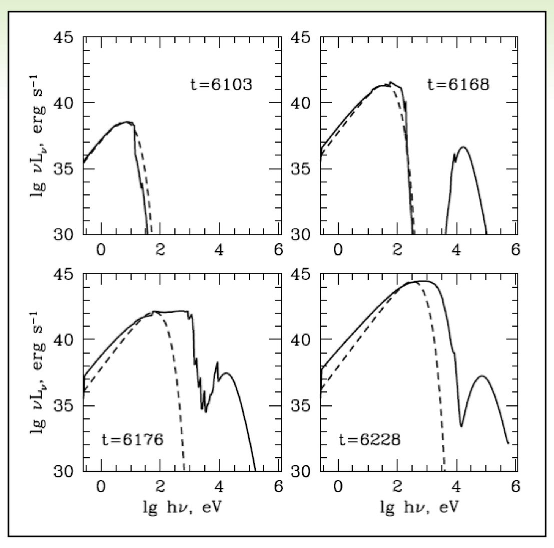


Fig. 2. Spectral flux distributions νL_ν for four instants of time (shown in seconds) for the version 14E1X2 (left) at shock breakout (solid line) and the best fit by a blackbody spectrum (dashed line). The time lag is disregarded.

The velocity of the outer layers in the model is not relativistic and the contribution from the RADA algorithm to the computation manifests itself mainly in a careful allowance for the radiation delay, which leads to a decrease in radiation flux at maximum and to a broadening of the light curve peak (Fig. 1). We also have performed a calculation for the **14E1X2** version, where the thermalization of photons at the first scattering was switched off. We note that our equations include all terms of final equation of Blandford & Payne (1981b), but our approach is more accurate due to all variables are considered in Lagrangian frame (Blandford & Payne (1981b) did not distinguish clearly between the fluid and the inertial frame (Fukue et al. 1985)), we do not add any inconsistent terms and do not confine ourselves to the diffusion limit. Another difference of the 14E1X2-type versions is a wider frequency grid: the number of frequency bins was doubled and the minimum wavelength was set equal to was set equal to 10^{-2} Å (instead of 1Å in the standard series 14E). Increasing the grid shows that the shock breakout in X-rays becomes visible much earlier than in visible light, because the absorption is weaker there (Fig. 2).

The hardest semirelativistic version, the SN Ib/c model

The maximum ejecta velocity depends strongly on presupernova radius: it is higher in more compact stars. Therefore, it is interesting to consider the shock breakout for type Ib/c supernovae (their progenitors are Wolf-Rayet stars with radii of the order of the solar one or even smaller). The type-Ib/c presupernova model that we use was constructed with the KEPLER code by an evolutionary computation from a main-sequence star in Woosley, Langer & Weaver (1995), the model 7A. At the end of its evolution, the presupernova star has a core composed of helium and heavy elements with amass of $3.199M_\odot$ and a radius of $1.41{\cdot}10^{11}$ cm. The radius in this case was fixed "manually", because in the outer stellar layers KEPLER models the stellar wind and the model is not in hydrostatic equilibrium. This model was chosen because the velocity of matter at shock breakout reaches the values about a half of speed of light. We see from the computational data that allowance for the delay effect and a strict allowance for the relativistic radiative transfer affect the light curve shape. It leads to decrease in radiation flux at maximum and to a broadening of the light curve peak (Fig.3).

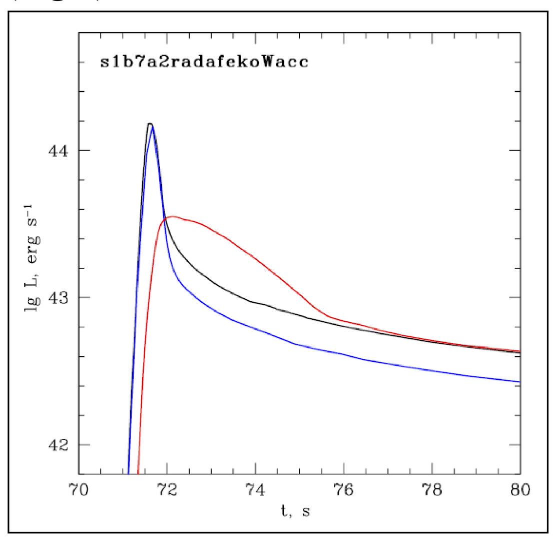


Fig.3. Comparison of the bolometric light curves at the epoch of shock for a type Ib/c presupernova model. The black and blue lines represent, respectively, the STELLA and RADA calculations in comoving frame of reference. Red line represents RADA calculations in observer's frame of reference taking into account radiation time delay in the observer's frame of reference.

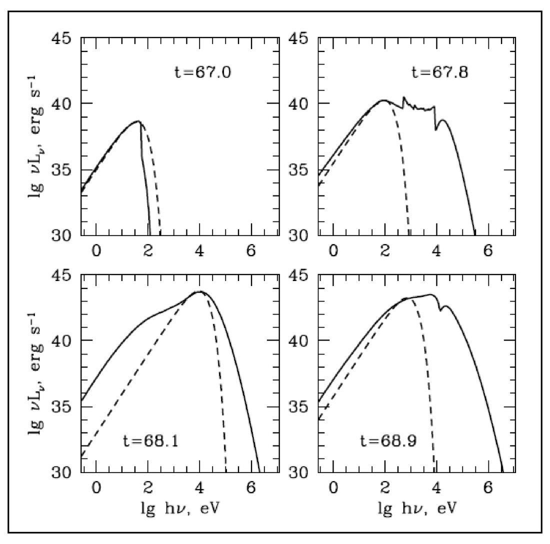


Fig.4. Spectral flux distributions νL_ν for four instants of time (shown in seconds) for the version s1b7a2Xm6 at shock breakout (solid line) and the best fit by a blackbody spectrum (dashed line). The time lag is disregarded.

Like for the 14E1X2 version above we switched off the thermalization of photons at the first scattering and increase the number of frequency bins for the version **s1b7a2X** (Fig.4). The maximum temperature becomes enormous (~ 10^{10} K), but small admixture of true "gray" (i.e. frequency-independent) absorption, 10^{-6} of the Thomson scattering in an SN Ib progenitor, makes the temperature lower for several orders of magnitude (the version **s1b7a2Xm6**) (Fig.5).

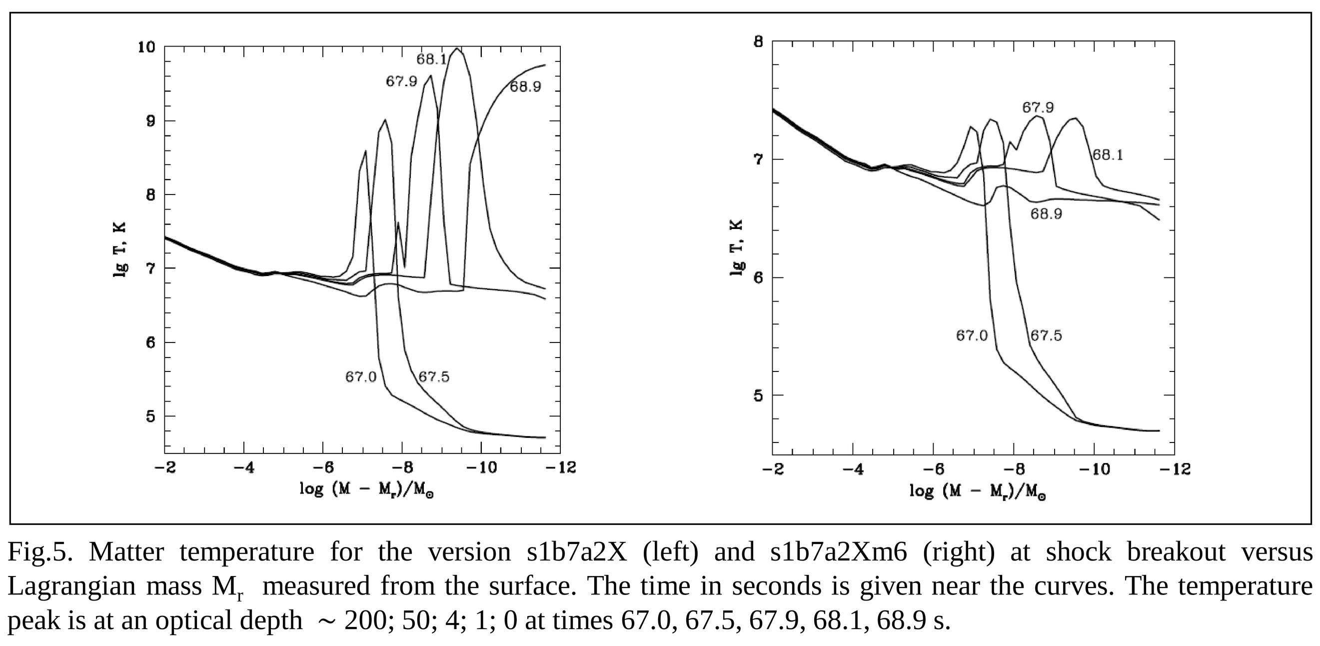


Fig.5. Matter temperature for the version s1b7a2X (left) and s1b7a2Xm6 (right) at shock breakout versus Lagrangian mass M_r measured from the surface. The time in seconds is given near the curves. The temperature peak is at an optical depth ~ 200; 50; 4; 1; 0 at times 67.0, 67.5, 67.9, 68.1, 68.9 s.

CONCLUSIONS

- We found that the high-temperature peak behind the shock front and the possibility of the formation of a hard power-law "tail" in the radiation spectrum are suppressed through a very weak process of photon absorption and production with a cross section at a level of one millionth of the Thomson scattering cross section in a presupernova SN Ib. At this level, the absorption can be provided by the double Compton effect (see e.g. Weaver 1976), so it must be taken into account in realistic models of radiation-dominated shockwaves in a supernova.
- In theoretical models of type Ib/c supernavae shock breakout the motion of matter at velocities near the speed of light should be taken into account. Development of the numerical algorithm RADA for solving radiative transfer with the hydrodynamic part of the algorithm STELLA provides a reasonable allowance for the relativistic effects.
- Our calculations of supernova shock breakouts can be used for evaluating and interpreting the detection of supernova explosions in existing and planned space experiments.
- Multidimensional algorithms and more complete description of radiation mechanisms, including Compton scattering and pair production, are under development.
- The possibility of observing shocks on the surface of the supernova and the development of our theoretical modeling can also help to answer several pressing astrophysical questions. These issues include an unknown number of supernova outbursts for type 1987A and Ib/c, which are difficult to observe due to their short duration. The detection of type Ib/c explosions is very important for the theory of hypernovae, since it will allow us to better describe the connection of supernovae with gamma-ray bursts and, in the case of nearby supernovae, there can be a correlation between the events and the detection of gravitational waves and neutrinos.
- The use of SNIa for distance measurements requires the determination of their absolute luminosity - in the strict sense, they are not standard and they are the **secondary** distance indicators. SNe of type II and Ib/c may serve as the **primary** distance indicators, independent of local calibrations.

REFERENCES

1. Band D. L., Grindlay J. E., Hong J. et al., 2008, ApJ, 673, 1225
2. Blandford R. D., Payne D. G., 1981b, MNRAS, 194, 1033
3. Blinnikov S., Chugai N., Lundqvist P. et al., 2003, in W. Hillebrandt & B. Leibundgut ed., From Twilight to Highlight, p. 23
4. Blinnikov S., Lundqvist P., Bartunov O. et al. 2000, ApJ, 532, 1132
5. Blinnikov S. I., 1999, Astronomy Letters, 25, 359
6. Blinnikov S. I., Eastman R., Bartunov O. S. et al., 1998, ApJ, 496, 454
7. Blinnikov S. I., Nadyozhin D. K., Woosley S. E., Sorokina E. I., 2002, in W. Hillebrandt & E. Müller ed., Nuclear Astrophysics Shock breakouts in SNe Ib/c. pp 144–147
8. Blinnikov S. I., Röpke F. K., Sorokina E. I. et al., 2006, A&A, 453,229
9. Calzavara A. J., Matzner C. D., 2004, MNRAS, 351, 694
10. Dwek E., Arendt R. G., 2008, ApJ, 685, 976
11. Fukue J., Kato S., Matsumoto R., 1985, PASJ, 37, 383
12. Gezari S., Dessart L., Basa S. et al., 2008, ApJL, 683, L131
13. Grindlay J. E., Craig W. W., Gehrels N. A. et al., 2003, in J. E. Truemper & H. D. Tananbaum ed., Vol. 4851 of SPIE Conference Series, pp 331–344
14. Matsuoka M., Kawai N., Mihara T. et al., 1997, in O. H. Siegmund & M. A. Gummin ed., Vol. 3114 of SPIE Conference Series, pp 414–421
15. Schawinski K., Justham S., Wolf C. et al, 2008, Science, 321, 223
16. Shigeyama T., Nomoto K., 1990, ApJ, 360, 242
17. Shigeyama T., Nomoto K., Hashimoto M., et al.1987, Nat, 328, 320
18. Soderberg A. M., Berger E., Page K. L. et al., 2008, Nat, 453, 469
19. Tolstov A. G., 2010, Astronomy Letters, 36, 109
20. Weaver T. A., 1976, ApJS, 32, 233
21. Woosley S. E., Blinnikov S., Heger A., 2007, Nat, 450, 390
22. Woosley S. E., Langer N., Weaver T. A., 1995, ApJ, 448, 315

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