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Multicolor light curve and spectrum simulations of superluminous supernovae and hypernovae

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Photometry is the easily acquired information about the supernovae. The light curves provide information about initial mass of presupernovae, an evolutionary state, explosion energy, and metallicity.

The phenomenon of a supernovae (SN) in most cases should start with a bright flash caused by a shock wave emerging on the surface of the star. Thus some features of the physics of radiation-dominated shock are important for correct numerical modelling of supernovae light curves. With account of those peculiarities, we construct a number of models for superluminous supernovae (SLSNe) and hypernovae (PTF12dam, SN 1998bw, SN 2013dx) based on multigroup radiation transfer coupled to hydrodynamics.

The results of our numerical simulations of light curves and spectra can be used to analyze and interpret available and future data from space and ground-based observatories. The modeling of SLSNe and hypernovae is also one of the way to shed some light on a possible connection of these phenomena.

Methods and models

For calculation of the light curves we use the multi-group radiation hydrodynamics numerical code STELLA [1–3] and for hypernovae simulations we include special relativistic corrections in the hydro code. STELLA solves implicitly time-dependent equations for the angular moments of intensity averaged over fixed frequency bands and computes variable Eddington factors that fully take into account scattering and redshifts for each frequency group in each mass zone. The explosion is initialized as a thermal bomb just above the mass cut, producing a shock wave that propagates outward.

We also use RADA code [4, 5] to take into account relativistic effects of fast moving ejecta in the model. In comparison with STELLA, RADA calculates exact Eddington factors at each time step and takes into account time delay effects more accurately.

In addition to the light curves we also calculate spectra of the supernovae using numerical code TARDIS. TARDIS is a Monte Carlo radiative transfer spectral synthesis code for 1D models of supernova ejecta. It is designed for rapid spectral modeling of supernovae [6].

The presupernovae models for SLSNe in this work are constructed from the core-collapse SN 2007bi model [7]. At a large explosion energy, Moriya [7] obtains a very large amount of radioactive ^{56}Ni, about 6.1 $M_\odot$, which is quite comparable to pair-instability SN (PISN). The combination of mechanisms, a collapse with a large energy and some amount of ^{56}Ni and a shock in an envelope, actually operates in nature. To make an interacting model we surround the ejecta by a rather dense envelope with the mass M_{env} extended to the radius R_{env}. For all our models the outer radius of the envelope is about $2\cdot10^6$ $R_\odot$, or ~ 10^{16} cm. For most of the models the envelope has power-law density distribution $\rho \propto r^{-p}$, which simulates the envelope or the wind that surrounds the exploding star. Chemical elements in the envelope are distributed uniformly. Typically we use carbon-oxygen models with different C to O ratios.

The prehypernova models are constructed from the core-collapse SN 1998bw model [8]. Light curves and spectra are computed for various C+O star models with different values of the kinetic energy and the ejecta mass. We use hypernova model CO138E30, the progenitor C+O star of M_{CO} = 13.8. The model has the explosion energy $3\cdot10^{52}$ ergs. The ejecta mass is i.e., $M_{ej} \cong 10$–11.5 $M_\odot$, $M_{cut} \cong 2.5$–4 $M_\odot$. The hydrodynamics at early phases were calculated using a Lagrangian piecewise parabolic method (PPM) code [9]. Explosive nucleosynthesis takes place behind the shock wave. Radioactive ^{56}Ni is produced in the deep, low-velocity layers of the ejecta. At calculation time t =1 day we start to use the codes for the calculation of the light curves: STELLA and RADA.

Results

The results of the light curves and spectra calculations for several SNe (PTF12dam, SN 1998bw) are presented in Figure 1–3.

Our modeling of PTF12dam shows that an increase in the mass of the circumstellar envelope to M ~40–70 $M_\odot$ leads to good agreement in the light curves not only for the bolometric light curve but also in optical bands (see Figure 1). In this case, we considered a carbon–oxygen envelope with C:O = 1:4, which is required to obtain the correct relationship between the peak fluxes in various spectral bands. The power-law decline in the luminosity of PTF12dam continues at least for +400 days after the peak. To explain this behavior of the light curves, Nicholl et al. [10] had to revise the magnetar model from their previous paper [11], which gives over-estimated values for the late points on the bolometric light curve.

In our modeling of multicolor light curves of SN 1998bw (Figure 3) our best fit is obtained if we adopt the following ad hoc ^{56}Ni distribution: $X(^{56}\mathrm{Ni})$ = 0.062 at velocity from 11,000 km s^{-1} to 40,000 km s^{-1}, where $X(^{56}\mathrm{Ni})$ denotes the mass fraction of ^{56}Ni. The total mass of ^{56}Ni is equal to 0.65 $M_\odot$. We note that the total mass

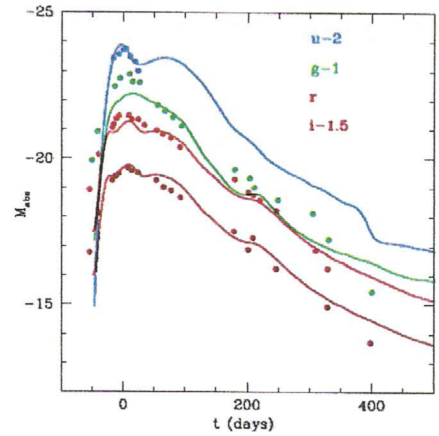

Fig. 1. Multicolor light curves simulation for PTF12dam in the model of the interaction and radioactive decay of ^{56}Ni in comparison with observational data [12]

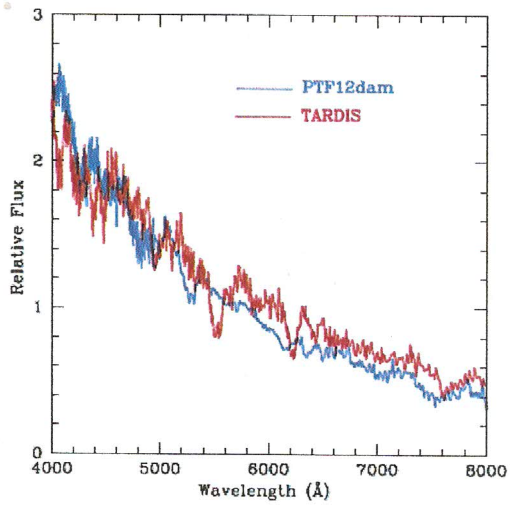

Fig. 2. Spectrum simulations for PTF12dam in the model of the interaction and radioactive decay of ^{56}Ni in comparison with observational data [11]

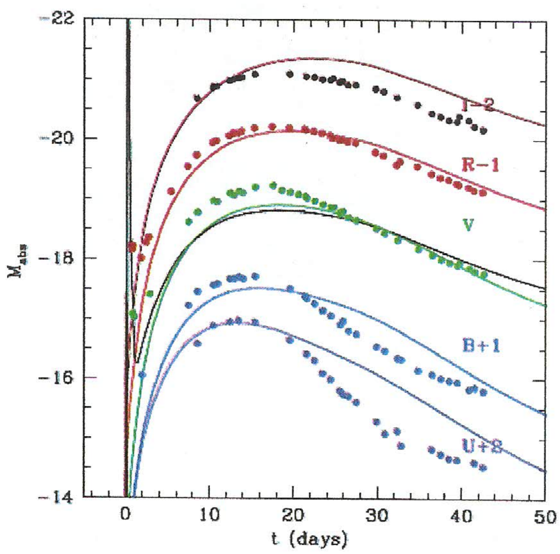

Fig. 3. Multicolor light curve simulations of SN 1998bw in comparison with observational data [13]

of the ^{56}Ni is larger than in the paper of Nakamura et al. [8] (0.4 $M_\odot$). The distribution of ^{56}Ni might be due to the mixing caused by Rayleigh-Taylor instability or reflect a complicated structure of possible jetlike ejecta. Based on the model of SN 1998bw we also constructed a model with lower mass $M = 9M_\odot$ to use it for the modeling of SN 2013dx, which has a lower mass and lower mass of radioactive ^{56}Ni. In Figure 2 we compare a spectrum of PTF12dam in the paper of Nicholl et al. [11] at the age estimated as +23 days after the maximum with our modeled spectrum.

Conclusions

Using detailed radiation-hydrodynamics calculations, we constructed models for the SLSN PTF12dam in combined model of shock wave interaction with CSM and ^{56}Ni radioactive decay. The modeling shows that all of the main characteristics (the multicolor light curves, the color temperature, and the photospheric velocities) could be reproduced satisfactorily with a minimum set of model parameters. The large explosion energy ~ 20–30 foe is required to produce a large mass of ^{56}Ni: 6$M_\odot$. The explosion energy has the same magnitude as it is required in PISN models, but in PISN models do not easily reproduce short rise time of the light curve.

Our modeling of hypernovae SN 1998bw shows that all of the main characteristics (the rise time, the peak luminosity, the decay time, and the color temperature behavior) could be reproduced satisfactorily with a minimum set of model parameters. The modeling of SN 1998bw is only the first step in calculation of the light curves for similar type of SNe.

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