Light Curve Models of Supernovae and X-ray spectra of Supernova Remnants

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Abstract. We compare parameters of well-observed type II SN1999em derived by M. Hamuy and D. Nadyozhin based on Litvinova & Nadyozhin (1985) analytic fits with those found from our simulations using our radiative hydro code Stella. The same code applied to models of SN1993J allows us to estimate systematic errors of extracting foreground extinction toward SN1993J suggested by Clocchiatti et al. (1995) which is based on the assumption of black body radiation of the supernova envelope near the first maximum light after shock break out. A new implicit two-temperature hydro code code Suprema is introduced which self-consistently takes into account the kinetics of ionization, electron thermal conduction, and radiative losses. Finally, a combination of Stella and Suprema allows us to use the same SNIa models both for building their light curves and predicting X-ray spectra of young Supernova remnants such as Tycho and Kepler. For the comparison of theoretical results with the observations we used data on Tycho SNR obtained with XMM–Newton space telescope.

1. Introduction

Three topics will be discussed briefly here. First, we show a way for extracting SN II parameters from $UBV$ light curves (using SN1999em as an example). Then we turn to estimating foreground extinction (example of SN1993J). And finally, we demonstrate using SN Ia models for predictions both of $UBVRI$ light curves of SNe and X-ray spectra of young SNRs.

2. SN II light curve theory vs. observations

Nadyozhin (2003) and Hamuy (2003) have obtained masses $M$, radii $R$, and explosion energies $E$ for a set of SNe II. Both have taken the observed values of $M_V$, $\Delta t$, $u_{ph}$ on the light curve plateau and extracted $M$, $R$, $E$, based on the relations found by Litvinova & Nadyozhin (1983, 1985), — LN85 hereafter.

Let us look into parameters found by Nadyozhin (2003) and Hamuy (2003) for an example of well-studied SN 1999em. Note that Nadyozhin’s (2003) Eq. (1) changed units of $E$ from LN85 and 2 typos are introduced by MN into this paper; see the original version astro-ph/0303411.

From the Table we see that the discrepancy of derived parameters for the same supernova is large. While input parameters differ within 10% only, the derived ones may be in disagreement by a factor of 2. There is an appreciable difference in the assumed distance $D$ in the two papers, and hence in $M_V$. The
values of $E$, $M$, and $R$ scale with the distance as:

$$E \sim D^{-0.675}, \quad M \sim D^{-1.17}, \quad R \sim D^{2.86}. \quad (1)$$

Thus, it is very important to know $D$ with as high accuracy as possible. But the difference may be explained by different $D$ only for $R$, but not for $E$ and $M$: other small differences are also important. Hence, the LN85 process is rather unstable.

If one looks into the $UBV$ light curves in Litvinova & Nadyozhin (1983) one can see that they are all similar with a pronounced plateau, because they were built in a simple equilibrium diffusion approximation, while well observed SNe II have a good plateau only in $V$ and redder filters, but not in $B$ and $U$ – see, e.g. Leonard et al. (2002) and Fig.1 below.

This means that more detailed models are needed in order to reproduce the observed $UBV$ behavior. We have considered an example of the well-studied SN 1999em with a goal to extract its parameters using more sophisticated modern multi-group SN II LC modeling. We have used our code stella (Blinnikov et al. 1998; Sorokina & Blinnikov 2003, 2004). See Baklanov (2002) where a theoretical catalog of $UBV$, $M_{bol}$ light curves is built for very different SN II presupernovae for a set of $M, R, E$. In addition to those parameters used by LN85 the mass $M_{Ni}$ of radioactive $^{56}$Ni is also accounted for.

To model SN 1999em we construct non-evolutionary preSN models with extended hydrogen-rich envelopes, similar to LN85, but a bit more realistic because they have a compact massive core and $^{56}$Ni mixed to the envelope as in the models for SN 1987A (Blinnikov et al. 2000). The envelope has mass fraction of H, X=0.7, and the fraction of metals was assumed Z=0.03 for the first models (in proportion to cosmic distribution with this Z).

The Fig.1 shows our model light curves when the presupernova parameters (and reddening) are those of Hamuy (2003) & Nadyozhin (2003). We see that fluxes on the plateau disagree up to two stellar magnitudes with observations.

In search of best-fitting model were have varied the input parameters in wide range and found a reasonably good fit for $M = 15M_\odot$, $R = 450R_\odot$, $E = 7 \times 10^{50}$ ergs, $M_{Ni} = 0.04M_\odot$ (Fig.2 left). This set is good only for $D = 7.5$ Mpc (EPM, Hamuy et al. 2001), which is much shorter scale than the Cepheid distance found by Leonard et al. (2003). A very nice fit is found for the same parameters, but for low metal abundance, Z=0.004 (Fig.2 right). Not only $UBV$, but also

| Input | Nadyozhin (2003) | Hamuy (2003) |
|-------|-----------------|--------------|
| $D$   | 12.38           | 10.7         |
| $M_V$ | -16.78          | -16.44       |
| $\Delta t$ | 110          | 124          |
| $u_{ph}$ | 2900       | 3290         |
| Derived |
| $E$   | 0.63            | $1.2^{+0.6}_{-0.3}$ |
| $M$   | 13.2            | $27^{+243}_{-150}M_\odot$ |
| $R$   | 569             | $249^{+243}_{-150}R_\odot$ |
the dependence of photospheric speed $u_{ph}(t)$ is good for the last model. Low metal abundance agrees well with the results of spectral modeling by Baron et al. (2000). For the long distance scale one can get a satisfactory $UBV$ only for huge $R \sim 10^3 R_\odot$. Work on this is in progress.

3. Extinction toward SN 1993J

The determination of foreground extinction toward supernovae (SNe) is very important. A technique for estimating the extinction has been suggested by Clocchiatti et al. (1995) which is based on the assumption of black body SN radiation near the first maximum light after shock breakout. Here we note that the true spectrum of an SN after the shock breakout, theoretically, is not a pure black body (due to importance of scattering and non-gray absorption...
in the ejecta). Using spectra which were calculated by the STELLA code for the 13C model of SN 1993J (Woosley et al. 1994; Blinnikov et al. 1998) and which fit energy distribution in the observer frame sufficiently well, we found that the values of $A_V$ may differ substantially from found under the black body assumption (Fig.3).

![Figure 3](image.png)

Figure 3. Left. 1.12 days after SN explosion. Solid: model. Dashed: black body fitted to the model in the visible range (labeled ‘FIT’) with Cardelli et al. (1989) absorption law. The best fit gives $T = 39300 \text{ K}$ and $A_V = 0.241$ (while true absorption in this numerical experiment is zero!). Right. Dependence of faked extinction parameter $A_V$ on time for different extinction laws: solid for a simple exponential law and dashed for Cardelli et al. (1989)

4. **SN Ia models: light curves and Tycho Supernova Remnant**

Here we concentrate on 3D SN Ia models computed at MPA (Reinecke, Hillebrandt, & Niemeyer 2002). Our assumptions on their light curve models using STELLA are described in Sorokina & Blinnikov (2003), Blinnikov & Sorokina (2004). The composition of early MPA models was rather crude. Recently Travaglio et al. (2004) computed a detailed explosive nucleosynthesis for some of them. We show $V$ light curves for those models and a bolometric flux for centrally ignited c3_3d_256 in Fig.4. The curves are in reasonably good agreement with observations.

It is interesting to compare the properties of young SNRs, such as Tycho, with predictions of the same models that have been used for LC modeling. For the first hundreds years the pattern of flow has a forward shock sweeping up ISM material and a reverse shock propagating into the slower-moving ejecta which we call Nadyozhin-Chevalier stage: a self-similar solution by Nadyozhin (1981, 1985) and Chevalier (1982) is much more realistic than widely used Sedov solution. For this stage Sorokina et al. (2004) have developed a new 1D Newtonian implicit hydro code SUPREMNA which allows us to study dynamics and radiation of young SNRs without using approximate solutions.
The main features of the code: ionization energy is taken into account in the equation of state; electron thermal conduction with saturation at the sound speed and radiative losses are not neglected; $T_e \neq T_i$ (equilibration by Coulomb collisions). The X-ray spectrum is computed by a time-dependent ionization code which calculates evolution of the ionization stages for every mesh zone at each hydro time step for all ions of 15 elements; it takes into account collisional ionization, autoionization, photorecombination, dielectronic recombination, and charge transfer. Comparison with other codes used for young SNRs is given in the table.

| Work                     | Hydr- | Ioni- | Rad. | Th. | $T_e$ vs. $T_i$ |
|--------------------------|-------|-------|------|-----|----------------|
| Hamilton & Sarazin(1984) | 0     | Neq   | +    | -   | $2-3T_i$       |
| Itoh et al.(1988)        | 1     | Neq   | -    | - (+)| $2T_i$         |
| Brinkmann et al.(1989)   | $\rightarrow$ | Neq | -    | -   | $1T_i$         |
| Badenes et al.(2003)     | $\gamma$ | Neq | -    | -   | $2T_i$         |
| Sorokina et al.(2004)    | $\rightarrow$ | Neq | +    | +   | $2T_i$         |

As an example, we show in Fig. 5 the X-ray spectra for the age of Tycho 430 years for W7 model and for the same MPA model MR0 and for the same parameters of ISM as used by Blinnikov & Sorokina (2004) and Kosenko et al. (2004). The 1D W7 model has a problem reproducing iron K$_\alpha$ emission without an additional mixing, as noted already by Itoh et al. (1988), while MPA models are well mixed from the beginning and they show a prominent iron line. There may be a problem with lines of intermediate mass metals, such as Ca and Si, but the development of thermonuclear 3D deflagration models may resolve this problem.

An important result of our work is the development of thermal instability in metal-rich ejecta in the models with low electron conduction. This confirms the old result found by Hamilton & Sarazin (1984) which was ignored in numerical models of young SNRs.
5. Conclusions

- To get SN parameters, one has to craft a full light curve model and $v_{\text{ph}}(t)$.
- In case of SN 1999em we easily find reasonable parameters and low $Z$ for EPM distance of 7.5 Mpc. The Cepheid distance requires a larger $R$ of the presupernova.
- Using black body assumption for early SN spectra may introduce a systematic error into estimates of $A_V$.
- New MPA 3D models of SN Ia produce faster bolometric LCs, closer to observed ones.
- Current 3D deflagration MPA models can easily explain iron in spectra of young SNRs.
- Energy losses may be very important in the evolution of metal-rich ejecta of SN Ia. They must be taken into account in realistic simulations of their dynamics.

Acknowledgments. The work is supported by grants RFBR 02-02-16500a, 04-02-16793a, NSF AST-02–06111, NASA NAG5-12D36, and by MPA (Garching) visitor program. SB and ES are grateful to W. Hillebrandt and to S. Woosley for their hospitality. SB thanks F. Röpke for help on density structure of MPA models and organizers of this meeting in Padua and the INT at the University of Washington (program INT-04-2) for their support.
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