Light Curves of Type Ia Supernovae as a Probe for an Explosion Model

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Abstract. We present theoretical UBVI- and bolometric light curves of SNe Ia for several explosion models, computed with our multi-group radiation hydro code. We employ our new corrected treatment for line opacity in the expanding medium. The results are compared with observed light curves. Our goal is to find the most viable thermonuclear SN model that gives good fits not only to a typical SN Ia light curve, but also to X-ray observations of young SNIa remnants. It appears that classical 1D SNIa models, such as deflagration W7 and delayed detonation DD4, fit the light curves not so good as a new 3D deflagration model by Reinecke et al (which is averaged over angles for our LC modelling). This model seems good also in reproducing X-ray observations of Tycho SNR. We believe that the main feature of this model which allows us to get correct radiation during the first month, as well as after a few hundred years, when an SNR forms, is strong mixing that pushes material enriched in iron and nickel to the outermost layers of SN ejecta.

1 Introduction

At the moment, there are many models of thermonuclear explosion of a star, that lead to the event we know as a Type Ia Supernova (SN Ia). Some of them were discussed in the talk by J.Niemeyer \cite{Niemen_02}. Only a few parameters, such as kinetic energy and total $^{56}$Ni production, can be derived directly from the explosion modelling and compared with the observational values. The subsequent evolution of the exploded star gives us much more possibilities to compare models and to decide which one fits observations better by reproducing more details in SN Ia light curves and spectra. We will focus here on the broad-band UBVI and bolometric light curve computations for SN Ia models.

There are several effects in SNe physics which lead to difficulties in the light curve modelling of any type of SNe. For instance, an account should be taken correctly for deposition of gamma photons produced in decays of radioactive isotopes, mostly $^{56}$Ni and $^{56}$Co. After being emitted, gamma photons travel through the ejecta and can finish up in either thermalization or in non-coherent scattering processes. To find this one has to solve the transfer equation for gamma photons together with hydrodynamical equations. Full system of equations should involve also radiative transfer equations in the range from soft X-rays to infrared for the expanding medium. There are millions of spectral lines that form SN spectra, and it is not a trivial problem to find a convenient way how to treat them even in the static case. The expansion makes the problem much more difficult to solve:
hundreds or even thousands of lines give their input into emission and absorption at each frequency.

On the first glance, modelling of SNe Ia seems easier than of other types of supernovae, since the hydro part is very simple: coasting stage starts very early, there are no shocks, and no additional heating from them.

On the other hand, much more difficulties arise in the radiation part. SNe Ia becomes almost transparent in continuum at the age of a few weeks. This means that NLTE effects are stronger than for other types of supernovae. Radiation is decoupled from matter within the entire SN Ia ejecta even before maximum light (which occurs around the 20th day after explosion), see e.g. [4] or Fig. 2 in [15]. In this case one cannot ascribe to radiation the gas temperature, or any other temperature, since SN Ia spectrum differs strongly from a blackbody one. One has to solve a system of time-dependent transfer equations in many energy groups instead, with an accurate prescription for treatment of a huge number of spectral lines, which are the main source of opacity in this type of SN [2,11].

2 Method

We compute broad-band UBVI and bolometric light curves of SNe Ia with a multi-energy radiation hydro code STELLA. Time-dependent equations for the angular moments of intensity in fixed frequency bins are coupled to Lagrangean hydro equations and solved implicitly. Thus, we have no need to ascribe any temperature to the radiation: the photon energy distribution may be quite arbitrary.

While radiation is nonequilibrium in our approximation, ionization and atomic level populations are assumed to be in LTE. The effect of line opacity is treated as an expansion opacity according to Eastman & Pinto 1993 [5] and to our new recipes [15]. We have compared the results and found that infrared bandpass (in which the ejecta are the most transparent) is more sensitive to the treatment of opacity than UBV (see Fig. 4 in [15] for the comparison of SN Ia light curves calculated with these two approaches), so one should be very careful on this point.

To simulate NLTE effects we used the approximation of the absorptive opacity in spectral lines. NLTE results [2] and ET LA approach [11] demonstrate that fully absorptive lines gives us an acceptable approximate description of NLTE effects.

We treat gamma-ray opacity as a pure absorptive one, and solve the γ-ray transfer equation in a one-group approximation following [17]. The heating by decays $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ is taken into account.

In the calculations of SN Ia light curves we use up to 200 frequency bins and up to $\sim 400$ zones as a Lagrangean coordinate.

3 Light curves of SNe Ia

In our previous work [16] we studied the behaviour of the broad-band optical and ultraviolet light curves for classical 1D models of SNe Ia: Chandrasekhar-
mass models W7 (deflagration) [10] and DD4 (delayed detonation) [19], and sub-Chandrasekhar-mass models LA4 (helium detonation; actually, an averaged 2D model) [8] and WD065 (detonation with low $^{56}$Ni production) [14]. Here we concentrate on a new 3D deflagration model by M.Reinecke et al. [12] (MR, hereafter). Working in more dimensions they have to involve less free parameters than was needed in 1D, so they get their model almost from the “first principles”.

The main features of the 3D model are compared with the ones of classical 1D models in the Table. From the first glance it seems that the light curves for the models which differ so much could not be similar.

![Table 1. Parameters of SN Ia models](image)

| Model | Mass ($M_\odot$) | $E_{\text{kin}}$, foe | $M_{56Ni}$ ($M_\odot$) |
|-------|------------------|------------------|-----------------|
| W7    | 1.38             | 1.2              | 0.6             |
| DD4   | 1.38             | 1.23             | 0.6             |
| MR    | 1.4              | 0.46             | 0.42            |

Nevertheless, Fig. 1 demonstrates that they are similar in many details. The possible reasons for this can be understood if one has a look at the element distribution over the ejecta. The compositions for W7 and MR models are shown in Fig. 2. At the moment of our light curve computation the full nuclide yields for MR were not yet obtained. Therefore, the model consisted of the elements,
which were chosen as representative examples for the energy release calculation, namely “Fe” for iron group elements that were divided onto 80% of $^{56}\text{Ni}$ and 20% of $^{56}\text{Fe}$, “Mg” for intermediate mass elements, and unburned C and O in equal proportion. The instabilities that have developed in the 3D model were not supposed to be so huge in approximate 1D models of explosion. This has led to the differences in the nickel distribution over the ejecta: it is mixed to the outermost layers in the 3D model. These layers became much more opaque than in the 1D models, and, despite having less than a half of kinetic energy, the 3D model has a photospheric velocity comparable to that in the 1D models. It is probably still a bit too low, so the light curve is wider, since the ejecta expand a bit slower, and photons are locked inside them for a bit longer time. The broad-band light curves for MR model fit the observations of one of the typical SN Ia, SN 1994D, in U and B bands surprisingly well, while classical 1D models, such as W7 and DD4, show faster decline in the optics than it is observed. Unfortunately, the bolometric light curve for MR model (Fig. 3) is somewhat too slow. The ejecta must expand with higher speed to let photons to diffuse out faster.

Since our light curve code is 1D, we cannot model 3D effects directly. We tried to estimate them by averaging the model over different solid angles. The main question we wished to answer was: how different can the SN Ia look like for an observer from different sides. To start with, we just compared the models averaged over cones with opening angles of 14° with the one averaged over the whole $4\pi$ [13]. We tried to choose two limiting cases: the angles with minimal and maximal nickel abundances, i.e. one with nickel bubble extended to the surface, and another one between such bubbles, with nickel only in the center. Since total $^{56}\text{Ni}$ mass differs in these models, the light curves are also very different (Fig. 4). They just simulate different models, but not a model observed from different sides.
In reality, the total energetics one observes is defined by total $^{56}$Ni mass. So we have to preserve it when averaging the model over different directions. In the next experiment we have taken the same solid angle with low $^{56}$Ni abundance and enhanced the mass of $^{56}$Ni in every mass zone by the same ratio, so that the total $^{56}$Ni mass became equal to the one of the original 3D model. The resulting light curve is compared with the fully averaged case in the fig. 5. Since $^{56}$Ni mass fixes the brightness of SNe Ia [1], the light curves become equally bright, but the maximum is shifted in time due to a bit different energetics and mixing. We believe that differences between 1D and 3D light curve calculations should not be much stronger than the difference between these two light curves, when other physical assumptions are fixed.

There is also another reason which allows us to believe that the MR model is better than the classical 1D models. Tycho SNR is believed to be the remnant of SN Ia. We calculated in details the X-ray emission of Tycho SNR, allowing for time-dependent ionization and recombination, and compared the computed X-ray spectra and images in narrow filter bands with XMM-Newton observations of the Tycho. Our preliminary results [7] show that all Chandrasekhar-mass models produce similar X-ray spectra at the age of Tycho, but they differ strongly in the predictions of how the remnant should look like in the lines of different ions due to very different distribution of elements in the ejecta for 1D and 3D models. We found that W7 and DD4 models produce rather wide ring in Fe lines, while it is narrow for MR model. The image for the latter model is very similar to what is observed.
Fig. 4. UBVI light curves of 3D MR model averaged over different opening angles. Solid line for the whole $4\pi$; dashed for a $14^\circ$ cone with maximum $^{56}\text{Ni}$ abundance; dotted for a $14^\circ$ cone with minimum $^{56}\text{Ni}$ abundance.

4 Conclusions

The new 3D SN Ia model MR [12] is very appealing. Yet it is not a final one: a detailed post-processing of nucleosynthesis changes the composition. It has been done very recently [18], and it is not yet checked in the light curve calculation. Our light curve computations are also preliminary, since more work is needed on the expansion opacity. Hopefully, none of the required improvements will spoil the light curve of this model and its X-ray spectra on the SNR stage, since the specific qualities of the model can be primarily explained by the enrichment of the outermost layers of SN ejecta by Fe and Ni.

The SN light curve modelling still has a lot of physics to be added, such as a 3D time-dependent radiative transfer, including as much as possible of NLTE effects, which are especially essential for SNe Ia [6]. All this will improve our understanding of thermonuclear supernovae.

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Fig. 5. Comparison of light curves of the MR model averaged over $4\pi$ (red solid); and for a $14^\circ$ cone with $^{56}\text{Ni}$ abundance rescaled to preserve the total $^{56}\text{Ni}$ mass (black dashed).

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