A NEW SUPERNOVA LIGHT CURVE MODELING PROGRAM

ZOLTÁN JÄGER[1], ANDREA P. NAGY[2], BARNA I. BIRO[1], JÓZSEF VINKÓ[2,3]

[1] *Baja Astronomical Observatory, University of Szeged*
Szegedi út KT766, 6500 Baja, Hungary
[2] *Department of Optics and Quantum Electronics, University of Szeged*
Dóm tér 9, 6720 Szeged, Hungary
[3] *Konkoly Observatory of the Hungarian Academy of Sciences*
Konkoly Thege Miklós út 15-17, Budapest H-1121, Hungary

Abstract.

Supernovae are extremely energetic explosions that highlight the violent deaths of various types of stars. Studying such cosmic explosions may be important because of several reasons. Supernovae play a key role in cosmic nucleosynthesis processes, and they are also the anchors of methods of measuring extragalactic distances. Several exotic physical processes take place in the expanding ejecta produced by the explosion. We have developed a fast and simple semi-analytical code to model the the light curve of core collapse supernovae. This allows the determination of their most important basic physical parameters, like the the radius of the progenitor star, the mass of the ejected envelope, the mass of the radioactive nickel synthesized during the explosion, among others.

Key words: Extragalactic astronomy – Supernovae – methods:data analysis – Light curve modeling.

1. INTRODUCTION

Supernovae (SNe) exhibiting substantial hydrogen in their spectra are classified as Type II. These events are thought to result from the sudden core collapse (CC) of massive stars that still retain substantial hydrogen envelopes. Core collapse SNe (CC SNe) originate from massive stars with $M_{\text{ZAMS}} > 8M_\odot$ (Burrows (2013)) which at the end of nuclear burning phase, having insufficient thermal energy, start to collapse under self gravity. The massive core overcomes the electron degeneracy state followed by neutronization that releases large amount of energetic neutrinos which helps driving the explosion. SNe II manifest in a variety of subtypes, with Type IIP SNe yielding distinctive plateaus of bright optical emission lasting roughly 100 days. The most common sub-type is IIP. The plateau phase is believed to arise from a particularly extended hydrogen outer layer that sustains optical emission through recombination as the photosphere expands and the outer envelope cools over time. Shortly after the explosion, the ejecta is not transparent, because most of the photons are Thompson-scattered on the free electrons. When the hydrogen recombines, the electron density reduces, and the ejecta becomes transparent. During this phase the recombination front can be considered as the photosphere. While the ejecta expands, the recombination front propagates inward the ejecta, resulting in an about constant-sized photosphere. Because both the radius and the temperature of the photosphere are roughly constant, the luminosity does not vary in time, hence the plateau (Fig. 1). After the plateau phase ends, the evolution is powered by radioactive decay, SNe IIP experience a rapid drop in luminosity settling onto a slow linearly declining tail phase. During this phase the ejecta are powered by gamma rays emitted from the radioactive decay of ^{56}Co to ^{56}Fe which in turn depends upon the amount of short-lived radioactive ^{56}Ni synthesized in explosion.

A general approach to determine the properties of supernova explosions is the modeling of observed data with hydrodynamical codes. However, a simple analytical method may also be used to get approximate results (Arnett & Fu (1989)). With the help of these analytic light curve models, the basic physical parameters, such as the explosion energy, the ejected mass and the initial radius, can be estimated (Arnett & Fu (1989); Popov (1993)). Although such simple estimates can be considered only preliminary, they can be obtained without running complicated, time-consuming hydrodynamical simulations. Analytic codes may be useful in providing constraints for the most important physical parameters which can be used as input in more detailed simulations. Also, analytic codes may also give first-order approximations when the observational information is limited, for example when only photometry and no spectroscopy is available for a particular SN.

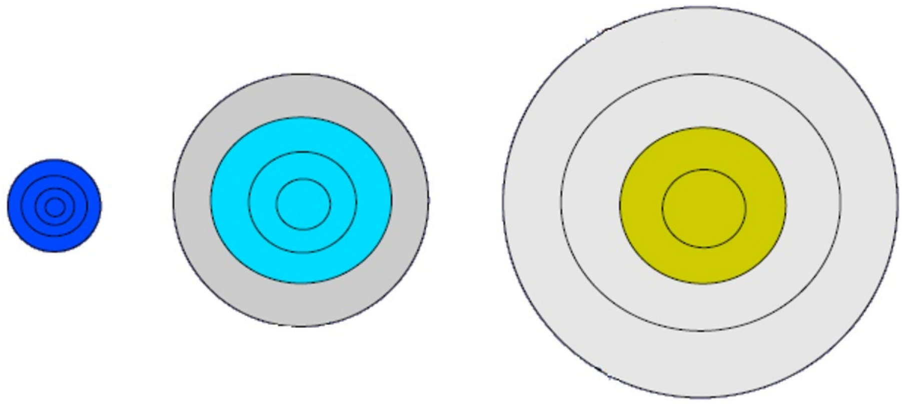

Fig. 1 – The evolution of the photosphere (colored area) inside a SN ejecta.

2. THE MODELING CODE

To fit the bolometric light curve we used an upgraded version of the LC2.2 semi-analytic light curve code (see Nagy and Vinko (2016)), which was originally described by Arnett & Fu (1989) and later extended by Popov (1993); Blinnikov & Popov (1993) and Nagy *et al.* (2014), to model the double-peaked light curves of CCSNe. This model is able to produce a wide variety of SN light curves depending on the choice of the initial parameters, such as the ejected mass ($M_{\rm ej}$), the initial radius of the progenitor (R_0), the total explosion energy (E_0), and the mass of the synthesized ^{56}Ni ($M_{\rm Ni}$) which directly determines the emitted flux at later phases. The model assumes a homologously expanding and spherically symmetric SN ejecta having a uniform density core and an exponential density profile in the other layers. Radiation transport is treated by the diffusion approximation. The effect of recombination causing the rapid change of the effective opacity in the envelope is taken into account in a simple form introduced by Arnett & Fu (1989).

The LC2.2 code is only a modeling tool, thus it does not contain any routine for fitting the output model to the observed light curves. Fitting the observed light curves with semi-analytic models is complicated due to the strong correlation between the physical parameters (Arnett & Fu (1989), Nagy *et al.* (2014)), which makes the parameter uncertainties high. Here we present an upgrade of the code by adding a powerful parameter optimization method. We chose to use a Markov Chain Monte Carlo (MCMC) method, implemented using the Metropolis-Hastings Algorithm with Gibbs sampler (Metropolis et al. (1953), Hastings *et al.* (1970), Gilks *et al.* (1996)), to search for the best fits to the bolometric light curve, and plotting the regions of best fit in the parameter space. The MCMC method is a well-established technique for constraining parameters from observed data, and especially suited for the case when the parameter space has a high dimensionality. This method is ergodic*, but the probability is higher where the χ^2 (goodness of the fit) is smaller. Because of the ergodicity, the uncertainties can be also be determinated.

Moreover, we also improved the numerical routines within the code that resulted in a significant improvement in the running time. While the running time of original LC2.2 was minutes, it takes less than a second for the upgraded version to finish. The MCMC method needs to run the code hundred thousand or million times, so the speed-up was essential for the applicability of MCMC for the fitting. The physical equations and method remained identical with those used in LC2.2. Also, the upgraded version has less numerical instabilities.

The MCMC program uses a 64 bit random number generator to sample the parameter space of the initial radius (R_0), ejected mass ($M_{\rm ej}$), and the energies (total explosion energy: $E_0 = E_{\rm kin} + E_{\rm th}$, kinetic; $E_{\rm kin}$, thermal: $E_{\rm th}$). The accepted

*Ergodic: the method wander around the whole parameter space maximum parameter region is based on Hamuy (2003), however the range has been extended. The MCMC method has more samples where χ^2 is lower, and uses random steps to jump to the next sample. The distribution of the random steps is Gaussian with zero mean, and its sigma parameter is an empirical number which depends on the value of χ^2. The jump may, or may not be accepted. The step is always accepted whenever it leads to a decrease of χ^2 from its previous value. However, it also accepts the step if the ratio of the old and new sample χ^2 exceeds a random number between 0 and 1.

Because this method is ergodic, any correlation between the parameters can also be seen. There are two known main parameter correlations (Arnett & Fu (1989), Nagy *et al.* (2014)): between M_{ej} and E_{kin}, and between R_0 and E_{th}, so $E_{\text{kin}}(M_{\text{ej}})$ and $E_{\text{th}}(R_0)$ should be plotted. There are other parameters: ionization temperature (T_{ion}), date of explosion (t_0), distance (d), opacity (κ), exponent of the power-law density profile (s). t_0 and d can be determined independently, and $T_{\text{ion}} = 5500K$ was adopted as the ionization temperature of the hydrogen. Nagy and Vinko (2016) showed that the constant density model $s = 0$ gives a good agreement with the hydrodynamical models, so $s = 0$ were used. The κ opacity is not independent from the E_{kin} and M_{ej}, thus it must be fixed. Two values used: $\kappa = 0.3$ cm^2/g and $\kappa = 0.2$ cm^2/g, These are the average opacity calculated from SNEC (Morozova et al. (2015), see Nagy and Vinko (2016) for details).

The nebular phase was fitted separately. This be can be done because there are only two parameters that describe the nebular phase: the nickel mass M_{Ni}, and the effective gamma-ray trapping T_0 (Clocchiatti and Wheeler (1997)).

3. MODELED LIGHT CURVES

We chose the very well-observed Type IIP SNe 2005cs (Pastorello et al. (2009)) and 2004et (Sahu *et al.* (2006)) for testing our MCMC-fitting code. SN 2005cs is a type II-P, ^{56}Ni-poor, low energy, underluminous SN (Pastorello et al. (2009)), and SN 2004et is a normal type II-P SN (Sahu *et al.* (2006)). The modeling program requires the bolometric light curve as input. Both SN 2005cs and SN 2004et has existing optical and near-infrared (NIR) observations, while in addition, SN 2005cs also has existing SWIFT UVOT data. (Pastorello et al. (2009), Brown et al. (2007); Sahu *et al.* (2006), Maguire *et al.* (2010)). The bolometric fluxes were generated by integrating the de-reddened observed fluxes over the spectral bands with the trapezoidal rule.

4. RESULTS

The output parameter space of SN 2004et is shown in Fig. 2, and SN 2005cs is shown in Fig. 3. The top 10 best fits are shown in Fig. 4. The mean values, their uncertainties, and the comparison with the literature are shown in Table 1 and 2 for SN 2004et and 2005cs, respectively.

Type IIP SNe arise from massive progenitors ranging from 8 to 25 $M_{\odot}$. Our results are consistent with this theoretical expectation, which validates our code. The values in Table 1 and 2 are in good agreement with the results by Nagy and Vinko (2016), and others. The median of the energies is somewhat larger, but the literature values are within our lower error limits. The other parameters have very good agreement.

So our modeling program seems quite accurate and simple. It automatically searches for the solutions and their uncertainties without the need for supervision from the user. It will be public as soon as finished.
Contact: `jagerz24@titan.physx.u-szeged.hu`.

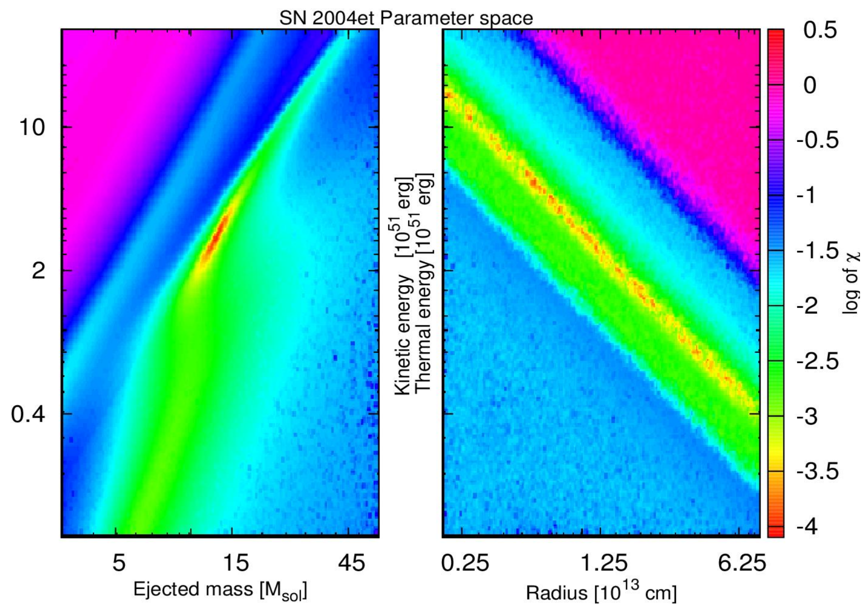

Fig. 2 – SN 2004et parameter space, $\kappa = 0.3$ cm^2/g. The colour shows the goodness of the fits.

Table 1

SN 2004et fit and literature values. Nagy, Vinko: Nagy and Vinko (2016), Sahu: Sahu *et al.* (2006), Bose: Bose *et al.* (2013), Utrobin: Utrobin and Chugai (2009), Misra: Misra et al. (2007). Formulae: Litvinova & Nadyozhin (1985), Nadyozhin (2003).

Parameter	**This paper**	**This paper**	**Nagy, Vinko**	**Sahu**	**Bose**	**Utrobin**	**Misra**
Method	semi-analytic	semi-analytic	semi-analytic	formulae	formulae	hydro	formulae
R_0 $[10^{11} cm]$	44-323	43-336	420	-	351-477	952-1148	-
$M_{\rm ej}$ $[M_\odot]$	10.9-14.5	15.2-19.9	11.0	10-20	7-11	23.5-25.5	8-16
$E_{\rm kin}$ $[10^{51} erg]$	1.65-4.10	2.00-5.27	1.35	-	-	-	-
$E_{\rm th}$ $[10^{51} erg]$	0.94-7.12	0.89-6.87	0.60	-	-	-	-
E_0 $[10^{51} erg]$	2.58-11.2	2.89-12.1	1.95	0.90-1.58	0.4-0.8	2.0-2.6	0.73-1.23
$M_{\rm Ni}$ $[M_\odot]$	0.06	0.06	0.06	0.06	-	0.068	0.06
κ $[cm^2/g]$	0.3	0.2	0.3	-	-	-	-

Table 2

SN 2005cs fit and literature values. Nagy, Vinko: Nagy and Vinko (2016), Utrobin: Utrobin and Chugai (2008), Pastorello: Pastorello et al. (2009), Takats: Takats and Vinko (2006) Formulae: Litvinova & Nadyozhin (1985), Nadyozhin (2003).

Parameter	**This paper**	**This paper**	**Nagy, Vinko**	**Utrobin**	**Pastorello**	**Takats**
Method	semi-analytic	semi-analytic	semi-analytic	hydro	semi-analytic	formulae
R_0 $[10^{11} cm]$	35-152	30-109	120	322-518	70	54-305
$M_{\rm ej}$ $[M_\odot]$	8.1-10.0	9.3-11.2	8.00	16-18	8-14	4.3-15.1
$E_{\rm kin}$ $[10^{51} erg]$	0.48-0.72	0.46-0.65	0.32	-	-	-
$E_{\rm th}$ $[10^{51} erg]$	0.16-0.70	0.18-0.64	0.16	-	-	-
E_0 $[10^{51} erg]$	0.64-1.42	0.64-1.29	0.48	0.41	0.3	0.09-0.36
$M_{\rm Ni}$ $[M_\odot]$	0.0028	0.0026	0.002	0.0082	0.003	0.003
κ $[cm^2/g]$	0.3	0.2	0.3	-	-	-

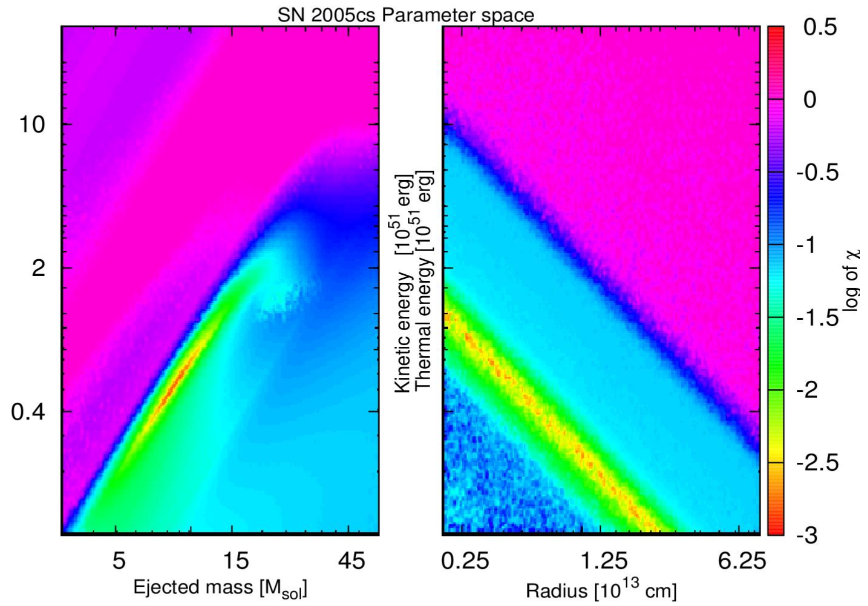

Fig. 3 – SN 2005cs parameter space, $\kappa = 0.3\,\mathrm{cm}^2/\mathrm{g}$. The colour shows the goodness of the fits.

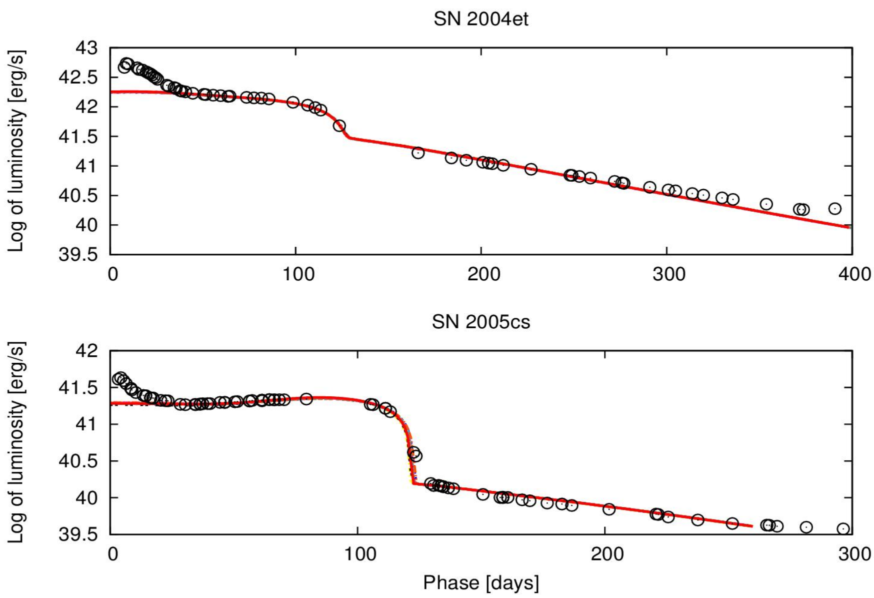

Fig. 4 – The best fits, $\kappa = 0.3\,\mathrm{cm}^2/\mathrm{g}$.

Acknowledgements. This work was presented in the framework of the International Conference "Connections in Astronomy, Astrophysics, Space and Planetary Sciences. Cluj-Napoca, 29-30 May 2017", which was supported by a grant of the Romanian Ministry of National Education and Scientific Research, RDI Programe for Space Technology and Advanced Research - STAR, project number 513.

REFERENCES

Arnett, W. D., Fu, A.: 1989, *Astrophys. J.* **340**, 396.
Blinnikov, S. & Popov, D. V.: 1993, *Astron. Astrophys.* **274**, 775
Bose, Subhash, Kumar, Brijesh, Sutaria, Firoza, Kumar, Brajesh, Roy, Rupak, Bhatt, V. K., Pandey, S. B., Chandola, H. C., Sagar, Ram, Misra, Kuntal, Chakraborti, Sayan: 2013, *Mon. Not. Roy. Astron. Soc.* **433**, 1871B.
Brown, Peter J.; Dessart, Luc; Holland, Stephen T.; Immler, Stefan; Landsman, Wayne; Blondin, Stéphane, *et al.*: 2007, *Astrophys. J.* **659**, 1488B.
Burrows, Adam: 2013, *RvMP* **85**, 245B.
Clocchiatti, A.; Wheeler, J. C.: 1997, *Astrophys. J.* **491**, 375C.
Gilks W. R., Richardson S., and Spiegelhalter D. J.: 1996, *Markov Chain Monte Carlo in Practice*, Chapman & Hall, London.
Hamuy, M.: 2003, *Astrophys. J.* **582**, 905H.
Hastings W. K.: 1970, *Biometrika* **57**, 97.
Litvinova Y., Nadyozhin D. K.: 1985, *SvA Lett.* **11**, 45.
Misra, Kuntal; Pooley, Dave; Chandra, Poonam; Bhattacharya, D.; Ray, Alak K.; Sagar, Ram; Lewin, Walter H. G.: 2007, *Mon. Not. Roy. Astron. Soc.* **381**, 280M.
Morozova, V. S., Piro, A. L., Renzo, M., Ott, C. D., *et al.*: 2015, arXiv:1505.06746.
Metropolis N., Rosenbluth A. W., Rosenbluth M. N., Teller A. H., and Teller E.: 1953, *J.Chem.Phys.* **21**, 1087.
Maguire, K.; Di Carlo, E.; Smartt, S. J.; Pastorello, A.; Tsvetkov, D. Yu.; Benetti, S.; Spiro, S., *et al.*: 2010, *Mon. Not. Roy. Astron. Soc.* **404**, 981M.
Nagy, A. P., Vinkó, J.: 2016, *Astron. Astrophys.* **589**, A53.
Nagy, A. P., Ordasi, A., Vinkó, J., Wheeler, J. C.: 2014, *Astron. Astrophys.* **571**, A77.
Nadyozhin D. K.: 2003, *Mon. Not. Roy. Astron. Soc.* **346**, 97.
Pastorello, A., Valenti, S., Zampieri, L., Navasardyan, H., Taubenberger, S., Smartt, S. J., *et al.*: 2009, *Mon. Not. Roy. Astron. Soc.* **394**, 2266P.
Popov D. V.: 1993, *Astrophys. J.* **414**, 712.
Sahu, D. K., Anupama, G. C., Srividya, S., Muneer, S.: 2006, *Mon. Not. Roy. Astron. Soc.* **372**, 1315S.
Takáts, K., Vinkó, J.: 2006, *Mon. Not. Roy. Astron. Soc.* **372**, 1735T.
Utrobin V. P., Chugai N. N.: 2008, *Astron. Astrophys.* **491**, 507.
Utrobin, V. P.; Chugai, N. N.: 2009, *Astron. Astrophys.* **506**, 829U.

Received on 14 December 2017