UNIVERSITY OF SZEGED
FACULTY OF SCIENCE AND INFORMATICS
DOCTORAL SCHOOL OF PHYSICS

Light curve modeling of core-collapse supernovae

PhD thesis statements

Andrea Nagy

SUPERVISOR:
Dr. József Vinkó
associate professor

Szeged
2016

Scientific background

Formation and evolution of massive stars, which end up their lifes in supernova (SN) explosions, is one of the most dynamically developing fields in astrophysics. The death of massive stars play an important role in the cosmic nucleosynthesis, being the main source of the heavy chemical elements, such as silicon and iron. Thus, these objects have significant effects on the enhanced metallicity of the newly formed stars. Another strong motivation of studying the life and death of massive stars is that these objects are visible even from large distances due to their high luminosities. This is especially true for supernovae, which are one of the most energetic explosions in the entire Universe, so, they are very important in cosmic distance measurements.

The different mechanisms of supernova explosions mainly depend on the initial mass of the progenitor star. If the initial mass of the progenitor is between 8 and 100 solar masses ($M_\odot$), the nuclear fusion finally forms an iron core, and the massive star finishes its life with the so-called core-collapse mechanism. However, if the mass of the progenitor is above 100 $M_\odot$, the final fate of the star can be different. In this case a more feasible scenario is the pair-instability mechanism, which occurs after the carbon fusion stage of stellar evolution when the core becomes dynamically unstable and creates electron-positron pairs.

In spite of this fact, the initial mass is not the only physical property which affects the evolution and the explosion mechanism of massive stars. For example, mass-loss can be an important process, which indirectly depends on numerous different physical parameters such as rotation, metallicity or magnetic flux. Thus, stars having larger initial masses ($M > 25M_\odot$) tend to lose their H-rich envelope, leading to Type IIb, or Type Ib/Ic transients, unlike the lower mass progenitors which usually produce Type IIP SNe.

All-sky (e.g.: LOSS,PTF) and dedicated transient (e.g.: ASASSN, Texas Supernova Search) surveys discover more and more supernovae every year. However, some of them do not fit into the well-known taxonomical categories. On the other hand, many open questions exist about the classic types, too, such as the nature of their progenitors, or the physical mechanisms taking place during and after the supernova explosion. So, it is crucial to determine the most important astrophysical parameters, which influence the different explosion mechanisms. This is not a trivial problem, because it is difficult to directly examine the progenitor of the supernova. Thus, theoretical models are important to describe the physical configurations of the exploding stars, as well as the properties of the temporal evolution of the radiation emitted after explosion (i.e. the light curve). Nowadays two different methods can be used for modeling supernova light curves. The first possibility is the construction of a simplified 1-dimensional (spherical) model with many simplifying assumptions, which can be used only for getting order-of-magnitude estimates of the SN properties. In the literature such a configuration is called as a "semi-analytic model". On the other hand, more complex, multi-dimensional hydrodynamic simulations can be built to infer the physical parameters in a more plausible, although much more complicated way.

Research methods

The main topic of my research project was to model the variation of the emitted radiation of core-collapse supernova explosions. First, I generalized a diffusion-recombination light curve model, which was originally published by David Arnett and Albert Fu (1989). Later, I used this configuration to develop a semi-analytic code (LC2), which I applied in estimating the initial parameters of the progenitors by fitting the shape of the quasi-bolometric light curves of 12 supernovae, including Type IIP, IIb and IIn explosion events. In each case I compared the fitting results with available hydrodynamic calculations and matched the derived expansion velocities with the observed ones.

To test the reliability of my calculations, I examined the variation of the theoretical light curves by changing the input parameters. In this case the individual physical properties were varied one by one, while holding the others constant. Moreover, the correlation between parameters may also be important, which is a major limitation of the light curve fitting method. The correlation between the parameters was examined by computing the Pearson correlation coefficients, which measures the linear correlation between two variables. For this comparison two different methods were applied. First, I synthesized a test light curve for both the radioactive decay and magnetar-controlled energy input model with my code. Then, I tried each parameter combinations to create the same light curve and determine the correlation among the model parameters. On the other hand, I examined the effect of the parameter correlation via a Type IIP light curve model, which was synthesized by the SNEC (SuperNova Explosion Code) program. After that, this test light curve was compared with the light curves calculated by my semi-analytic code, where all parameter combinations were used one by one.

SNEC is an open-source, spherically-symmetric (1D) Lagrangian code (Morozova et al., 2015), which is able to follow the hydrodynamic evolution of the expanding envelope of core-collapse supernovae. SNEC is able to generate the bolometric light curve, as well as the light curves in different wavelength bands. The essential input data are the explosion energy, the amount of the radioactive nickel and a model of the whole structure of the presupernova star. This progenitor model describes the spatial distribution of many physical parameters, such as density, temperature, velocity and abundance of different chemical elements. To create the progenitor model I used the open-source, 1D stellar evolution software package, MESA (Modules for Experiments in Stellar Astrophysics). Using MESA we are able to create the evolutionary track of a model star from its initial formation up to the final core-collapse phase (Paxton et al., 2011; 2013). Thus, MESA can be an appropriate tool to generate the progenitor configuration of a supernova, which can be exploded by SNEC code.

Results

1. To estimate the physical properties of different types of core-collapse supernovae showing double-peaked light curve structure, I generalized the semi-analytic model presented by Arnett & Fu (1989), which assumes a homologously expanding, spherically symmetric ejecta structure. Later, I used this model to create a program to fit the light curves of the studied transients. The source code of the program is available in the following link: `http://titan.physx.u-szeged.hu/∼nagyandi/LC2`. I have shown that for Type IIP supernovae, a two-component ejecta configuration can be appropriate to model a double-peaked light curve with a semi-analytic diffusion-recombination code. This ejecta configuration is similar to the one used for Type IIb SNe, assuming an inner, denser core and a hydrogen-dominated outer envelope. While fitting the entire LCs of both Type IIb and Type IIP transients, I found a good agreement between the results of my semi-analytic calculations and the parameters from hydrodynamic simulations taken from recent literature. My conclusion was that the two-component semi-analytic model can be a useful tool for deriving order-of-magnitude estimates for the basic parameters of Type IIP and IIb SNe, which may be used to constrain the parameter regime in more detailed hydrodynamic computations.
   (Nagy et al., 2014; Nagy & Vinkó, 2016)

2. To test the two-component model I examined the effects of the numerous simplifications and caveats in my simple diffusion-recombination model. I showed that only four parameters are independent (the recombination temperature, the initial nickel mass, and the exponent for both exponential and power-law density profile), while the other parameters are more or less correlated with each other. Furthermore, the parameter correlations, especially the one between the constant opacity and the ejected mass, may have a major role to explain the observable discrepancies between the ejected masses derived from hydrodynamic calculation and semi-analytic models. Another limitation of the two-component model is the uncertainty of the explosion date, which can be very uncertain, when pre-explosion observations at the supernova site are not available. Determining the moment of first light of a supernova explosion is very important, because the shape of the rising part of the light curve depends critically on the exact date of the explosion. The physical parameters inferred from such a light curve may suffer from large systematic errors. For example, 7 day uncertainty in the explosion time may cause 5 - 50 % relative errors in the derived physical parameters. Thus, if the exact time of the explosion is not known, the fitting parameters of the two-component model can be estimated only with an order-of-magnitude accuracy.
   (Nagy et al., 2014; Nagy & Vinkó, 2016)

3. One of the strongest simplification in the two-component model is the assumption of the constant Thompson-scattering opacity, which can be considered as the average opacity of the ejecta. Although this approximation simplifies the diffusion equations, in this case the chosen opacity naturally limits the accuracy of the derived physical properties of the explosion. To estimate the proper average opacity for Type IIP and Type IIb transients, I synthesized the light curve of these events with the SNEC code. After that I integrated the calculated Rosseland mean opacity from SNEC, and finally determined the average opacity values for both the cooling and the photosperic phase. From this calculation I realized that the average opacities from the SNEC models show adequate agreement with the opacities frequently used in the literature. Thus, the Thompson-scattering opacity can be used for fitting observed light curves. Therefore, if we choose an appropriate opacity value, we are able to predict the approximate chemical composition of the supernova ejecta.
   (Nagy & Vinkó, 2016)

4. My fitting results for the Type IIb supernova SN 2013df seems to resolve the ejecta mass discrepancy inferred from the early- and late-time light curves of stripped envelope (Type IIb, Ib and Ic) supernovae (Wheeler et al. 2016), if we suppose that the opacity of the ejecta is determined by the appropriate chemical composition of the envelope. I found that the solution of the ejecta mass problem is possible by taking into account two physical processes. First, the explicit handling of positron deposition during the tail fitting is essential, because if we use the general approximation, that the radioactive decay of cobalt only produces gamma-rays, we overestimate the characteristic time scale of the late-time light curve as well as the ejected mass. Second, the careful handling of the rise time of the light curve peak is also important. For Type IIb supernovae the commonly used approach that the rise time is equal to the effective diffusion time scale (Arnett, 1980) is not entirely valid. In this case, due to the extended progenitor ($R_0 \gg 10^{11}$ cm) of these transients, the recombination in the envelope makes the effective diffusion time scale longer. In the case of SN 2013df the ejected mass and the kinetic energy of the explosion was determined by the complete fit of the early-time light curve, instead of simply adopting the observed rise time. The values of the ejecta mass resulting from my fitting of the late-time light curve assuming separate time scales for the gamma-ray and positron deposition agree well with those determined from the modeling of the early-time bolometric light curve.
   (Szalai et al., 2016)

Publications

I. Publications associated with the thesis

Refereed papers:

- **Nagy, A. P.**, Vinkó, J: *A two-component model for fitting light curves of core-collapse supernovae*, 2016, A&A, 589, 53
- Szalai, T., Vinkó, J.,**Nagy, A. P.** et al.: *The continuing story of SN IIb 2013df: new optical and IR observations and analysis*, 2016, MNRAS, 460, 1500
- **Nagy, A. P.**, Ordasi, A., Vinkó, J., Wheeler, J. C.: *A semianalytical light curve model and its application to type IIP supernovae*, 2014, A&A, 571, 77

II. Other publications associated with the topic of the thesis

Refereed papers and conference proceedings:

- Kumar, B., Pandey, S. B., Sahu, D. K., ... , **Nagy, A.** et al.: *Evolution of the Type IIb SN 2011fu*, 2014, IAUS, 296, 336
- Kumar, B., Pandey, S. B., Sahu, D. K., ... , **Nagy, A.** et al.: *Light curve and spectral evolution of the Type IIb supernova 2011fu*, 2013, MNRAS, 431, 308

Conference posters:

- **Nagy, A. P.**, Vinkó, J: *Two-component light curve model of core-collapse supernovae*, "The 9th Harvard-Smithsonian Conference on Theoretical Astrophysics" (Cambridge, USA, May 16. - 19. 2016)
- Szalai, T., Vinkó, J.,**Nagy, A.** et al.: *The chemical composition of the ejecta of the rare type IIb supernova 2013df*, "Supernova in the Local Universe: celebrating 10,000 days of Supernova 1987A" - CAASTRO Meeting (Coffs Harbour, Australia, Aug. 11. - 15. 2014)

Conference talks:

- **Nagy, A.**: *Light Core Modelling of Core-collapse Supernovae*, "Workshop of Young Reasearchers in Astronomy and Astrophysics (FIKUT VII.)" (MTA Wigner Research Centre of Physics, Budapest, Sept. 17. - 19. 2014)
- **Nagy, A.**: *A Semi-Analytical Light Curve Model of Core Collapse Supernovae*, "XII. Nuclei in the Cosmos Summer School" (MTA Institute for Nuclear Research, Debrecen, July 7. - 11. 2014)

III. Other publications

Refereed papers:

- Dhungana, G., Kehoe, R., Vinkó, J., ... , **Nagy, A.** et al.: *Extensive Spectroscopy and Photometry of the Type IIP Supernova 2013ej*, 2016, ApJ, 822, 6
- Chatzopoulos, E., Wheeler, J. C., Vinkó, J., Horváth, Z., **Nagy, A.**: *Analytical Light Curve Models of Superluminous Supernovae: χ^2-minimization of Parameter Fits*, 2013, ApJ 773, 76

Conference posters:

- Vinkó, J., Szalai, T., Ordasi, A., ..., **Nagy, A.** et al.: *Photometric distances to the Type Ia Sne 2012cg, 2012ht, 2013dy and 2014J*, "Type Ia Supernovae: progenitors, explosions, and cosmology" (Chicago, USA, Sept. 15. - 19. 2014)