Numerical Simulation of Weird Stellar Explosions

OTKA Postdoctoral Scholarship Final Report

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1. Scientific Background and Declared Project Aims

As was revealed in the past few decades the basic physical properties of core-collapse supernova explosions mainly depend on their mass-loss history which basically relies on their progenitors (e.g., Limongi 2017). However, we do not know exactly how and when do massive stars (especially Type Ib/c progenitors) get rid of their massive hydrogen and/or helium envelopes. We do also not really understand how can be a supernova explosion affected by a circumstellar matter (CSM) generated from an extreme eruption just days or weeks prior the core-collapse.

Moreover, theoretical studies (e.g., Clocchiatti & Wheeler, 1997; Wheeler, Johnson & Clocchiatti 2015) also revealed that there is a discrepancy in the derived ejecta masses (M_{ej}) from early- and late-time light curve (LC) fits of stripped-envelope supernovae (SESNe). Namely, estimations from the post-maximum light variation show systematically higher values than that can be received from the light curve peaks by the "Arnett's rule" (e.g., Khatami & Kasen 2019). For a typical Type Ib SN the ejecta mass from early- and late-time LC is approximately 2 - 3 and 4 - 6 solar masses, respectively. To solve this problem we should take into account two different scenarios. First, it is plausible that the mass discrepancy occurs due to the limitations and initial boundary conditions of the applied semi-analytic models. On the other hand, this mass discrepancy may have a real physical cause, such as low-mass, low-density ejecta or CSM around the supernova remnant.

My main scientific aim was to systematically study the modeling issues and physical causes of mass discrepancy problems related to stripped-envelope supernovae via further development of analytic models and computing hydrodynamic simulations.

To test the limitations of the generally applied semi-analytic models, I planned to examine the most commonly used boundary conditions and assumptions separately. Especially the ones related to the ejecta mass calculations from early- and late-time light curve (LC) fits:

- The R-band LC is a good approximation of the total bolometric light curve
- The density-profile and the opacity of the ejecta is constant
- Only the radioactive energy input affects the late-time light curve
- We do not need to fit the peak to get the ejecta mass, because it can be calculated from the rise time to maximum brightness
- At late times the trapping of the gamma-rays, generated from radioactive decay, is crucial, but the partial trapping of the positrons can be neglected.

Besides, I also planned to examine a possible physical origin of the mass discrepancy problem based on an interaction between the supernova ejecta and a surrounding circumstellar medium (CSM). To do so, I aimed to create single-star and binary progenitor models with MESA (Modules for Experiments in Stellar Astrophysics) code and alter them with a CSM structure. Then, generate the light curves of all these interacting progenitor scenarios.

I also aimed to investigate the effect of the mass and geometric structure of the circumstellar matter on the gained LCs via numerical calculations. Finally, I planned to compare these hydrodynamic results with observational data.

2. Results

2.1. Systematic study of semi-analytic model approximations

I began the OTKA project with the data selection by assembling a "master list" of all transients classified as Type Ib/Ic or Type IIb supernovae in the Open Supernova Catalog (Guillochon 2017), regardless of whether they have been included in a refereed publication or not. This first list of the available stripped-envelope supernovae (SESNe) contained 903 events, but most were poorly sampled or missing early- or late-time photometric data. From this, I selected the ones with light curves that are well sampled around and after the peak to determine the ejected masses from both early- and late-time light curves. Thus, for the final analysis, I focused on these selected 59 supernovae with sufficient data, and fit separately the early- and late-time light curves of these objects as well as their entire brightness variation with a generalized semi-analytic LC model (see details in Nagy & Vinkó 2016), which is based on the calculations presented by Arnett & Fu (1989). This model assumes a homologously expanding, spherically symmetric ejecta structure with constant Thompson-scattering opacity, and is also able to take into account both gamma-ray and positron-trapping. To test the limitations of this generally used model, I examine separately the commonly applied assumptions for both the early- and late-time light curve fits, as declared in my project statement:

- *The R-band LC of the SESNe is approximately equal to the total bolometric light variation.* Calculating the (quasi-)bolometric LC is always problematic because of the lack of observational data from UV to IR. When UV/IR observations are missing, one should approximate the entire bolometric LC from the R-band specific luminosities (Clocchiatti & Wheeler 1997; Wheeler, Johnson & Clocchiatti 2015). However, nowadays, near-IR (J, H, K) bands are getting available for more and more SNe, which allows us to examine the LCs of SNe with IR contribution. Thus, I was able to revise this approximation, and found that this estimation is not fully adequate to estimate the physical properties of the individual supernovae as the rise times, the width of the peaks, and the slope of the late-time LCs are not correlated for most objects. Thus, scaling the R-band light curve is not usually a plausible solution. For quantitative analysis, I fit both the R-band and bolometric data and compare the ejected masses, which indicates a significant (up to 30%) difference in the derived results. However, the ratio between Mej gained from early and late-time fits show no notable differences. Thus, this approximation is not fully adequate to estimate the physical properties of the individual supernovae, but it does not make a considerable effect on solving the mass discrepancy problem (Nagy, submitted to ApJ).
- *The density profile of the ejecta is constant.* It is a generally used approach that seems to work well for normal Type IIP SNe. However, it might not be a good approximation

for SNe with low-mass ejecta such as Type Ib/c and Type Ia SNe. However, we should keep in mind that a self-similar density profile is needed to solve the equations of models analytically. Thus, I tested a power-law density profile to fit the observable light curves of several supernovae (Barna et al. 2023; Szalai et al., submitted to A&A), including SESNe. For stripped-envelope supernovae, I found that without any extra energy source, a barely non-constant density profile is not able to result in better light curve fits. Moreover, it terminates lower ejecta masses, which deepens mass discrepancy.

- *The opacity of the ejecta is constant*. In analytical models, this is one of the most crucial approximations, because the opacity is correlated with other physical parameters (such as ejected mass or progenitor radius). In literature, a generally used assumption is that the constant opacity is equal to the Thomson-scattering opacity. But this simplification may cause large uncertainties in supernova properties. Thus, applying lower average opacities instead of Thomson- scattering opacity or using κ as a fitting parameter during light curve modeling can reduce the mass difference between early- and late-time calculations. So, with proper chose of the constant opacity, we can moderate the mass discrepancy problem.

- *Only radioactive nickel and cobalt have an effect on the late-time light curve.* Late-time (or post-maximum) LCs are usually assumed to follow the decay of radioactive nickel and cobalt. However, from the observation of SN 1987A, we already know that at long-time time-scales, titanium isotopes could also be important. To test this statement, I implemented titanium-decay in my code and analyzed the light curve of SN 2019va with it (Zhang et al. 2022). Nevertheless, titanium can only play an important role hundreds of days after the explosion, when stripped-envelope supernovae are too faint to be observable. Thus, neglecting titanium does not cause any considerable effect on fitting SESN light curves.

- *Only the radioactive energy input affects the late-time light curve.* In literature, two possible progenitor scenarios exist for SESNe. One of them prefers a binary system containing two massive stars, while the other one favors a single Wolf-Rayet as the progenitor star. Apart from the actual progenitor, we assume that these SN explosions are related to the collapse of the nickel-iron core. If the progenitor has a strong magnetic field, the core-collapse may form a highly magnetized neutron star (a.k.a. magnetar), which releases its energy via magnetic spin-down providing a power source for the ejecta. In this case, besides radioactive decay, the magnetar energy input could be also a viable component for LC modeling. My results show that using magnetar energy input help to fit properly the entire LC of SESNe (Fig. 1.), except in some cases, where a re-brightening occurs in the late-time light curve (Nagy, submitted to ApJ).

- *The ejected mass can be calculated from the rise time to maximum brightness*. Here, we assume that the rise time of the supernova LC corresponds with the effective diffusion time-scale that can be derived from ejected mass, kinetic energy, and opacity (Arnett 1980). This is a valid approximation until the mean free path of the photons is much shorter than the size of the ejecta (e.g., in Type IIb SNe). For Type Ib and Ic SNe, the difference between these two features causes large uncertainties in the calculation of the ejected mass (Nagy, submitted to ApJ).

- *Late-time (partial) leakage of the positrons can be neglected.* Gamma-rays and positrons are generated via the radioactive decay of Co, and some of them can carry out energy from the ejecta. Thus, gamma-ray and positron leakage determine the main slope of the late-time light curve of CCSNe. Despite this fact, it is a generally used approach to neglect the effect of positrons during model calculations, which is a valid approximation as far as the ejected mass is high enough to trap most of the gamma-rays. For SESNe, the ejecta mass is far too low, thus, the contribution of positron trapping cannot be discarded. However, our results show that taking into account both gamma-ray and positron-leakage somewhat reduces the derived ejecta masses as well as giving more reasonable nickel masses. But, this scenario still results in higher masses compared to the values gained form the fitting of the entire light curve, regardless of the used velocity definition (Nagy, submitted to ApJ). I also discovered that the previous studies made a mistake when they fit the late-time light curve without the positron-trapping. Namely, when they neglect the effect of the positron, they determine the characteristic time-scale of the gamma-ray trapping (T_0) as the characteristic time-scale of both the positrons and the gamma-ray are the same. However, as I noticed, from a modeling point of view using both gamma-ray and positron-trapping does not just add an extra energy source at very late times, but also reduces T_0. Thus, the proper solution for this computation is the fitting of T_0 as the characteristic time-scale of the positrons is zero.

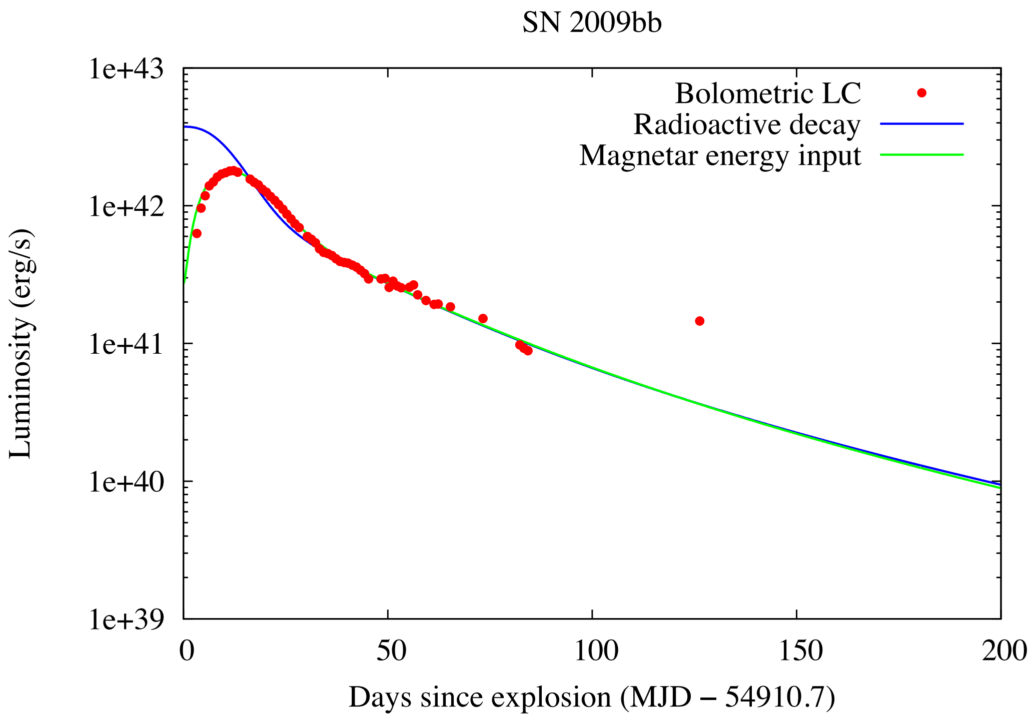

Fig. 1. Comparison of the bolometric LC of SN 2009bb (dots) with the best model fits with only radioactive (blue line) and radioactive + magnetar energy input (green line).

During this systematic study, I found an interesting phenomenon related to the generally used velocity calculations. As velocity definition significantly alters the calculated ejecta masses, I thought it worth investigating further. The problem is that for these calculations we need to know the scaling velocity. At first glance, it seems obvious, but the scaling velocity is not related directly to any observable properties. Thus, we freely choose a reasonable velocity approximation to estimate the scaling velocity. Nevertheless, in the literature, only one solution has been stated. Namely, that the photospheric velocity is approximately equal to the scaling velocity. However, in practice, the photospheric velocity could be diverse for different chemical elements or spectral synthesis codes, and it can also be affected by the density distribution as well as the opacity. Hence, this assumption does not describe the fixed scaling velocity. So, I determine two other velocity definitions that can be plausible for ejecta mass calculations. One is a characteristic average expansion velocity for each SESN subtype that can be used for supernovae with no spectroscopic data. The other plausible solution is the deriving of the scaling velocities from LC modeling. However, for the method, we need to fit the entire supernova light curve properly, which could be challenging for some striped-envelope supernovae (Nagy, submitted to ApJ).

As a by-product of this systematic study, another interesting feature was revealed, namely, that according to their global light curve properties, 30% of the examined SESNe show increasing or bumpy late-time bolometric light curves. This phenomenon is most probably generated by the IR-band contributions that may be the trace of a circumstellar interaction. One such object is SN 1993J, which I investigated in more detail within a joint research study with Szanna Zsíros and Tamás Szalai (Zsíros et al. 2022).

2.2. Studying CSM interaction around SESNe

Besides modeling issues, mass discrepancy problem may also caused by real physical processes that we neglect during light curve fitting. For example, the explosion may occur within a circumstellar matter formed throughout stellar evolution. The circumstellar matter could play an important role in generating the light curve of some superluminous SNe, even if there are no obvious spectral signs of the interaction (Moriya & Maeda 2012; Mazzali et al. 2016; Wheeler et al. 2017). Moreover, as Kuncarayakti (2022) revealed, normal Type Ic supernovae may show similar spectroscopic features to interacting Type Ibn and Icn SNe at late phases. So, it seems reasonable to suggest a possible circumstellar interaction for Type Ib/c supernovae as well.

To test the effect of a CSM interaction, I started with a simple solution. Creating a combined semi-analytic model is capable of taking into account circumstellar interaction. The test subject for this project was SN 2004gq (Type Ic supernova), which is quite peculiar for a core-collapse supernova as it does not follow the nickel-cobalt decay rate at late times, not even we take into consideration gamma-ray leakage. Namely, the initial, steady luminosity decline of the LC tail seems to re-brighten a bit after 60 days. To convert these qualitative LC features into quantitative considerations, we assume that the observable light variations in different bands and, as follows, the quasi-bolometric LC are generated by three different energy inputs: photo-diffusion, magnetar spin-down, and CSM interaction.

In this estimated progenitor configuration, we have a spherically symmetric ejecta and a CSM shell. While both regions have a common center, they are separated from each other. Hence, the generated shock wave needs some time to reach the circumstellar matter. This configuration has two advantages: self-consistency with the radio data and general light curve properties, and it also allows separating the differential equations of both components as the photon diffusion time scale is much lower in one of the regions (Kumar 2013). Thus, we could simply add up the generated luminosities at late times.

Besides, detailed light curve modeling, one of my Ph.D. students, Boróka Hanga Pál, analyzed the radio observations of SN 2004gq as an independent data source to trace the signs of circumstellar interaction. If the ejecta interacts with its surrounding CSM, a forward and a reverse shock forms, and the movement of these shock fronts generates synchrotron emission (Chevalier & Fransson 2006; Maeda 2012; Matsuoka et al. 2019).

As a result, we did not just create a reasonable modeling solution to fit the peculiar late-time LC feature of SN 2004gq with a delayed circumstellar interaction, but we also were able to determine the basic physical properties of the CSM that estimate the most important features of a previous episodic mass-loss of the progenitor. Both the radio analysis and the analytical LC modeling results lead to the same conclusion according to the average mass-loss rate. Moreover, calculating the distance of the CSM also shows self-consistency (Nagy, Pál & Szalai, submitted to A&A).

However, numerical studies could be crucial to reveal the nature of this early CSM interaction and expose a possible mass-loss episode shortly before the supernova explosion. Thus, with the help of my other Ph.D. student, Zsófia Bodola, we apply one-dimensional hydrodynamic calculations to generate the bolometric light curves from SESN progenitor models interacting with circumstellar matter. To do so, we first needed non-interacting progenitor models. However, there is some debate about it in the literature. Some studies suggest (e.g., Cao et al. 2013) a massive single star (possibly Wolf-Rayet) progenitor that loses its outer envelope due to extreme stellar wind or irregular eruption phases. However, others (e.g. Sana et al. 2012; Woosley et al. 2021) assume binary interaction before the explosion that strips away the outermost layers of the massive donor star. The commonality in both scenarios is that they suggest circumstellar matter around the progenitor star. So, I created a total of 14 single-star models, while Zsófia Bodola generated about the same amount of massive binary configurations.

Here, we performed complete hydrodynamical modeling and analytic approximations to create the unique physical configuration, self-consistent with a supernova explosion that occurs in a close circumstellar matter caused by an extreme mass-loss event just a few days or weeks before the cataclysm. We calculate both single star and binary progenitor models using the Modules for Experiments in Stellar Astrophysics (MESA version r-12778), which is a 1-dimensional, numerical hydrodynamic stellar evolution code (Paxton et al. 2011, 2013, 2015, 2018, 2019). Then, we generate different thin ($R_{CSM} \leq 10\ R_p$) and relatively low-mass ($M_{CSM} \leq 2M_\odot$) CSM configurations with a power-law density profile analytically and add them to the MESA models. As a final step, we calculate the bolometric light curves of our progenitor models with and without the attached circumstellar matter using the 1D spherical Lagrangian SuperNova Explosion Code (SNEC, Morozova et al. 2015).

We have investigated the effect of close, thin CSM shells around stripped-envelope supernova progenitors interacting with the SN ejecta by analyzing their bolometric LCs. As a result, we found that the evolution of the bolometric light curves of our interacting single-star models is different than that of the binary progenitors (Fig. 2.). It seems, that the overall light curve features mainly depend on the compactness of the progenitor star, which results in major differences between the LCs of the distinct progenitor scenarios, regardless of their similar maximum luminosity. Thus, this may indicate that the pre-supernova evolution of the exploding star can be estimated from the general physical properties of Type Ib/c light curves (Nagy & Bodola, submitted to A&A).

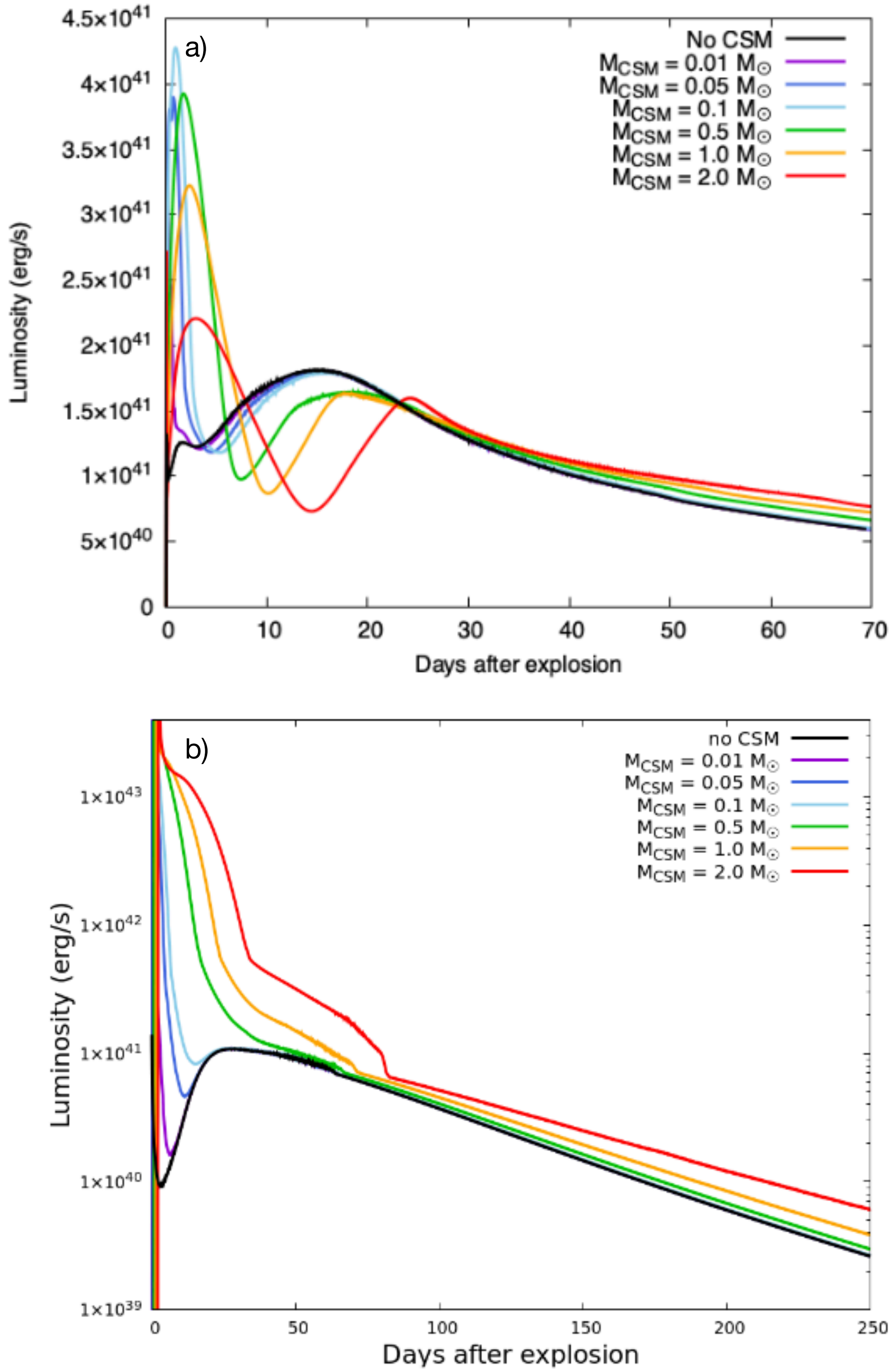

Fig. 2. The effect of different CSM mass on the bolometric light curves of single-star (panel a) and binary (panel b) models. The black line represents the non-interacting reference models, while the violet, dark blue, light blue, green, orange, and red illustrate the effect of circumstellar matter with a mass of 0.01, 0.05, 0.1, 0.5, 1, and 2 $M_\odot$, respectively.

3. Issues

Unfortunately, the first year of this project overlapped with the lockdown of the COVID-19 pandemic. Thus, the preparation for the study related to numerical CSM models had to be postponed as it was nearly impossible to keep contact with my Japanese collaborator due to his unexpected educational and other duties. Moreover, due to the strict post-COVID restrictions of Japan, I only had a chance to visit him and intensively work on this part of the project this August. Nevertheless, the paper related to this work (Nagy & Bodola, submitted to A&A) has already got a referee report asking for minor revisions.

However, some of the other publications had some problems getting referee reports during the past two years. For example, the first referee report for the SN 2004qg paper (Nagy, Pál & Szalai, submitted to A&A) arrived 5 months after the submission. Nevertheless, it is a major revision, but the referee seems interested in our result. So, I hope that after finishing the correction of this paper, it will be accepted.

On the other hand, the publication mentioned in my last year's report (Nagy 2022, arXiv:2210.10458), was not that lucky. First, I received the referee report with several months delay. Then, the referee rejected the paper. However, for his report, it was obvious, that he did not bother to read the paper in detail (e.g. asking for technicalities was already in the paper). Thus, I asked for a new referee, but after a few months of waiting, the editor suggested to withdraw the paper instead. So, I expanded this paper with the results gained during this whole process and submitted this improved version in ApJ at the end of this November. So, I still waiting for the first referee report.

4. Project Summary

Overall, most of the proposed goals were achieved: 7 scientific papers were submitted or published; analytical model approximations were systematically tested; spherical CSM structures were created and analyzed. The only exception is the 2-dimensional interacting models that should have been prepared to study the asymmetric structure of the circumstellar matter. The cause of this is the previously mentioned unexpected phenomena (such as different velocity definitions) that arose during the systematic examination of the analytical models, and testing these consumed considerable extra time. Thus, did no time left to create models showing asymmetry.

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