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Determining the ejecta mass and other physical parameters in supernova explosions

PhD thesis statements

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Scientific background

The astrophysics of brightest stellar explosions, called supernovae (SNe) is an intensively studied field of research from the past century. The "traditional" SNe are divided into two main groups by their explosion mechanism: core collapse and thermonuclear or Type Ia supernovae.

The members of the former group are the explosions of massive stars, having initially more than 8 solar masses. Such a star develops an iron core inside the onion-skin structure. Since the iron cannot fuse into heavier elements, the iron core grows until it reaches the Chandrasekhar mass, then becomes unstable and collapses into a neutron star. The outer envelope falls onto the neutron star, then bounces back, because the neutron star is practically incompressible. After the bounce, a shock wave develops and travels through the envelope toward the surface of the star. This shock wave compresses and heats up the stellar material, which starts expanding outward.

The progenitors of SNe belonging to the thermonuclear group are thought to be carbon/oxygen white dwarfs, where the explosion is caused by spontaneous fusion of C and O to Ni after reaching the Chandrasekhar mass. As the material of the white dwarf is degenerate, the object cannot start an adiabatic expansion to cool down, and therefore the energy released by the fusion is used to start new fusion explosively, leading to a nuclear burning flame that engulfs the entire star. However, the physical cause of the photometric and spectroscopic diversity, the way to reach the Chandrasekhar mass, and the start of the fusion are still debated.

There are two main proposed progenitor scenarios: single-degenerate (SD) and double-degenerate (DD). The SD scenario presumes that a carbon/oxygen white dwarf has a non-degenerate companion star, for example a red giant, a subgiant or a He-star, which, after overflowing its Roche-lobe, transfers mass to the white dwarf. When the white dwarf approaches the Chandrasekhar mass, spontaneous fusion of C/O to ^{56}Ni develops that quickly engulfs the whole white dwarf, leading to a thermonuclear explosion.

The details on the onset and the progress of the C/O fusion is still an issue, and many possible mechanisms have been proposed in the literature. The most successful one is the delayed detonation explosion (DDE) model, in which the burning starts as a deflagration, but later it turns into a detonation wave to produce the observed amount of iron-group elements. A variant of that is the pulsational delayed detonation explosion (PDDE): during the initial deflagration phase the expansion of the white dwarf expels some material from its outermost layers, which pulsates, expands and avoids burning. After that, the bound material falls back to the WD that leads to a subsequent detonation. The third theoretical possibility is the sub-Chandrasekhar double-detonation (DUDE) scenario, where the progenitor accretes a thin layer of helium onto its surface, which is compressed by its own mass that leads to He-detonation. This triggers the thermonuclear explosion of the underlying C/O white dwarf. In the double degenerate (DD) scenario two white dwarfs merge or collide that results in a subsequent explosion.

A new subclass of SNe, the so-called superluminous supernovae (SLSNe) having outstandingly bright peak magnitudes in all bands of the optical wavelengths (M < -21 mag) was discovered in the past decades. Currently only a few hundreds of these intrinsically rare stellar explosions are known, thus the explosion mechanism, the heating source and the progenitor itself are still uncertain. Since the observations show that they prefer metal-poor galaxies as host environments, there is a high probability that they are originated from the death of very massive stars.

Although many theoretical hypotheses were proposed to explain their physics and extremely high luminosity, none of them was validated directly by observations. According to the magnetar scenario, the vast amount of energy observed in SLSNe is released by the spin-down of a hot neutron star having strong magnetic field. Another theory suggests that the fallback accretion onto a newly formed black hole created by the gravitational collapse of an initially very massive star can power SLSNe as well, as the black hole accretes the remaining material of the progenitor during a few days after the core collapse. A third hypothesis, called pair-instability supernova (PISN) presumes a very massive progenitor (M $\sim$ 140-160 $M_{\odot}$) having extremely hot core that contracts swiftly after the pressure-loss due to the e^- and e^+ pair production, resulting in a thermonuclear explosion that destroys the star. Last but not least, the interaction with a massive circumstellar medium (CSM) can produce the required amount of energy as well. In some cases, the observed features of a SLSN can be fitted properly with the combination of the above mentioned models. Since the study of SLSNe is still in its infancy, and raises more and more issues instead of answering questions, their investigation may open a door to explore and become acquainted with yet unknown phenomena.

Therefore the study of the astrophysics of supernovae plays a major role in the development of our view of the Universe. By using them as "standard candles", one can determine the distances of high-redshift extragalaxies, prove the accelerating expansion of the Universe and the existence of dark energy, refine the value of the Hubble constant, explain the dust-gas ratio in different galaxies, get a deeper insight into the interior of stars differing from our Sun, study the formation of the elements heavier than iron and the monumental explosions of dying stars releasing enormous amount of energy in a really short time.

Research methods

During my PhD research, I concentrated on the determination of physical parameters in supernova explosions, with a special attention to the ejecta mass. These results were obtained using three different research methods: distance measurement, photometry and spectroscopy.

Distances were estimated in the case of one core-collapse supernova (SN 2017eaw) using the expanding photosphere method, and for 17 Type Ia SNe via multi-color light curve modeling. For the latter group of objects, the `SNooPy2` code (Burns et al., 2011, 2014) was applied to fit the observed $BVRI$ light curves. The fitted parameters were the color excess due to interstellar extinction in the host galaxy ($E(B-V)_{\mathrm{host}}$), the moment of maximum light in the B-band (T_{max}), the extinction-free distance modulus (μ_0) and the decline rate parameters (either s_{BV}, or Δm_{15}).

Photometric methods were used to study the sample of Type Ia SNe. Observations of these objects were carried out (partly by myself) with 0.6/0.9 m Schmidt-telescope at Piszkéstető station of the Konkoly Observatory, Hungary between 2016 and 2018 utilizing the Johnson-Cousins B, V, R_C, and I_C filters. A self-developed pipeline was applied for the reduction and the PSF photometry of the studied SNe. Then, the bolometric light curves were constructed by integrating the observed fluxes along wavelength using the trapezodial integration rule. The fluxes of the missing UV- and IR-bands were estimated by extrapolations. The `Minim` code (Chatzopoulos et al., 2012; Li et al., 2019) was used to fit the radiation diffusion model of Arnett (1982) to the bolometric light curves. The optimized parameters were the followings: the moment of first light (t_0), the LC time scale (t_{lc}), the γ-ray leakage time scale (t_γ), and the initial nickel-mass (M_{Ni}).

Finally, **spectroscopic** methods were applied to determine the chemical composition and the physical parameters for the studied sample of superluminous supernovae. The reduced observational data of 28 Type I SLSN were downloaded from the publicly available Open Supernova Catalog (OSC)[1] (Guillochon et al., 2017), while the spectra of SN 2010kd and SN 2019neq were measured by two American collaborators, and reduced by my supervisor. After correcting these spectra for redshift and interstellar extinction, they were fitted utilizing the `SYN++` code (Thomas et al., 2011) written in C++. Instead of the complex NLTE physics, model spectra are calculated using the Sobolev approximation assuming Boltzmann excitations, and the P Cygni profiles of the individual elements are fitted individually and interactively. The fitted global parameters (referring to the whole wavelength-range of the model spectrum) are the scaling factors of the flux (a_0, a_1, and a_2), the velocity at the photosphere ($v_{\rm phot}$), the velocity corresponding to the top of the SN-atmosphere ($v_{\rm outer}$) and the photospheric temperature ($T_{\rm phot}$). The local parameters (to fit the lines of individual elements) are the logarithm of the optical depth ($\log\tau$) of each ion, the velocity of the lower and upper border of their line-forming region ($v_{\rm min}$ and $v_{\rm max}$), the line width and the excitation temperature ($T_{\rm exc}$).

Results

1. Distance estimates of a Type II-P supernova, SN 2017eaw, using the expanding photosphere method

Expanding photosphere method (EPM) is a widely used technique to derive the distance of expanding gas clouds, thus it is ideal for a Type II-P SN having a thick, expanding H-shell around its collapsing core. To apply this method, the angular size and the expansion velocity must be known in different epochs. I developed a C code in order to calculate the distance of a Type II-P supernova, SN 2017eaw, from the mentioned

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[1] https://sne.space/

values. The result was 7.22 ± 0.41 Mpc, which matches within the error the distance calculated from the so-called "standard candle method" formula published by Takáts & Vinkó (2012). Thus the distance of Type II-P SNe can be estimated reliably using the presented C code.

Related publication:
Szalai, T., Vinkó, J., **Könyves-Tóth, R.**, et al. 2019, ApJ, 876, 19.

2. Constraints on the physical properties of Type Ia supernovae using photometric methods

From light curve modeling of 17 Type Ia SNe observed at Piszkéstető, I presented estimates on the physical parameters of the explosions, which allowed me to give constraints on the progenitor properties, the ejecta masses and the possible correlation between the inferred parameters.

- The observations and the reduction of the studied SNe was partly done by myself. Then, from modeling the multi-color light curves I determined the distance modulus, the moment of maximum light, the interstellar extinction and the decline rate parameters of the studied SNe. Based on these parameters I estimated their peak absolute magnitudes, and assembled their bolometric light curves.

- I fitted the bolometric light curves with an Arnett model assuming radiative diffusion, utilizing the `Minim` code. I derived the light curve timescales (t_{lc}, t_γ), the moment of explosion (t_0) and the initial amount of synthesized radioactive nickel ($M_{\rm Ni}$).

- I derived upper and lower limits for one of the most critical parameter of the Arnett model, the optical opacity by using the same method as in Li et al. (2019). After averaging the resulting opacity values, I inferred the expansion velocity ($v_{\rm exp}$) and ejected mass ($M_{\rm ej}$) for each SN. I found that my calculations are generally consistent with conclusions of previous studies (e.g. Scalzo et al., 2014; Li et al., 2019).

- I examined the early-phase $(B-V)_0$ color evolution of the SNe in order to classify them into the early red or early blue group created recently by Stritzinger et al. (2018). Since the observational data from sufficiently early epochs was sparse, only two of the studied SNe, the early red SN 2017erp and the early blue SN 2016bln could be classified.

- I compared the pre-maximum $(B - V)_0$ colors to the predictions of delayed detonation (DDE), pulsational delayed detonation (PDDE) and some other explosion models. I revealed that the Ni-masses of DDE models are the most similar to values obtained from the bolometric light curve modeling.
- I searched for possible correlations between the inferred explosion parameters (e.g. S_{BV} vs M_{ej}, S_{BV} vs M_{Ni}, S_{BV} vs τ_γ, M_{Ni} vs M_{ej} and τ_{lc} vs τ_γ). I found that even though all four parameter combinations showed sort of a correlation, their Pearson coefficients proved that only the S_{BV} vs M_{Ni} and the S_{BV} vs τ_γ correlations are statistically significant. These results are consistent with the results by Scalzo et al. (2019) and the predictions of the formulae created by Khatami & Kasen (2019).

Related publication:

Könyves-Tóth, R., Vinkó, J., Ordasi, A., et al. 2020, ApJ, 892, 121.

3. Comparative spectroscopic analysis of SLSN 2010kd and SLSN 2019neq

I have done a comparative study between the photospheric-phase optical spectra of the recently discovered fast-evolving Type I SLSN 2019neq and the slow-evolving Type I SLSN 2010kd. The aim of this work was to find whether the different timescales of the spectroscopic evolution were related to different spectroscopic characteristics as well.

- After correcting the spectra for redshift and extinction, I modeled them using the `SYN++` code (Thomas et al., 2011). In the case of SN 2010kd, I had access to spectroscopic data at 4 observed epochs: −27, +11, +129 and +174 days relative to the moment of the maximum light. By the last observed phase SN 2010kd has already reached its nebular phase, thus, I identified the features of forbidden transitions of the ions in the spectrum based on Inserra

(2019). In the case of the first 3 epochs, I determined the chemical composition of the object, the model parameters and the number densities of each identified ion at the observed phases. I found that during these phases the photospheric temperature decreased from 15000 K to 10500 and then to 6500 K, while the photospheric velocity declined from 15000 km s^{-1} to 10000, then 4000 km s^{-1}. The line identification was sometimes ambiguous, for example the spectrum taken at +11 days could be fitted equally well with three different models: one containing carbon, another one having helium instead, and a third one having both C and He.

- I modeled the spectra of SN 2019neq at 3 observed epochs as well (−4 d, +5 d, +29 d phases) applying the `SYN++` code. The photospheric velocity determined at the first two epochs was roughly constant at 21000 km s^{-1}, but steeply declined to 12000 km s^{-1} by the moment of the third epoch (+29 d). This behavior is consistent with the observed properties of other fast SLSNe-I. Over the same period of time, the photospheric temperature declined from 15000 K to 12000 K, then to 6000 K.

- I revealed that the W-shaped absorption feature usually seen as a tracer in the pre-maximum spectra of Type I SLSNe between 3500 and 4500 Å can be modeled with the combination of C III, O III and Si IV as well, instead of the widely used and accepted O II.

- By the examination of the +5 day phase spectrum of SN 2019neq, I pointed out that the wavelength region between 4000 and 5000 Å is unlikely to correspond to the line of Fe II λ5169, which was extensively used to estimate the photospheric velocity of Type I SLSNe in previous studies. I showed that this wavelength range is dominated by the blending of numerous, weak Fe II lines. Therefore, the modeling of the whole optical spectrum is required to determine the photospheric velocity accurately.

- I showed that SN 2019neq (that was unclassified previously) belongs to the fast-evolving subgroup of Type I SLSNe by comparing its +29 day phase spectrum to the +85 day phase spectrum of the slow-evolving SN 2010kd. Since the two spectra are quite similar, SN 2019neq belongs unambiguously to the fast-evolving type.

This statement is strengthened by the high photospheric velocity measured at the moment of maximum light of SN 2019neq and its steep decline.

- By comparing the evolution of the photospheric velocities and the optical depth of ions having strong features (C II and Fe II) in the spectra of SN 2010kd to those of SN 2019neq, I suggested that SN 2019neq has somewhat smaller total ejecta mass and different density profile than SN 2010kd.
- I estimated the ejected masses of the two objects from the modeled optical depths around maximum light, and obtained $M_{\mathrm{ej}} \sim 23$ and $\sim 48\ M_{\odot}$ for SN 2019neq and SN 2010kd, respectively. These values are in agreement with the ones estimated from light curve modeling, and they exceed the typical SN Ia ejecta mass by at least one order of magnitude.
- I proposed the presence of a possible correlation between the evolution timescale and the ejecta mass of Type I SLSNe similarly to normal Type Ia SNe: slower evolving SLSNe may possess larger ejecta masses. (The validation of this hypothesis was my main goal in the fourth thesis of my PhD work.)

Related publications:

- **Könyves-Tóth, R.,** Thomas, B. P., Vinkó, J., et al. 2020, ApJ, 900, 73
- Kumar, A., Pandey, S. B., **Könyves-Tóth, R.**, et al. 2020, ApJ, 892, 28
- **Könyves-Tóth, R.**, Vinkó, J., Thomas, B. P., Wheeler, J. C. 2019, The Astronomer's Telegram, 13083, 1
- Thomas, B. P., **Könyves-Tóth, R.,** Vinkó, J., et al. 2019, The Astronomer's Telegram, 13184, 1

4. Photospheric velocity and ejecta mass calculation of Type I SLSNe

I estimated the value of the photospheric velocities and the ejecta masses of a sample containing 28 Type I SLSNe having publicly available photometric and spectroscopic data in the Open Supernova Catalogue (Guillochon et al., 2017). My main goal was to search for the physical differences between the fast- and the slow-evolving groups, and the validation of the proposed connection between the evolution timescale and the ejected mass.

- I developed a method combining SYN++ modeling with the cross-correlation technique in order to obtain quick and reliable estimates of the photospheric velocities of the studied SLSNe.

- I revealed that the W-shaped O II absorption blend, typically present between ~ 3900 and ~ 4500 Å in the pre-maximum spectra of Type I SLSNe is absent from the spectra of 9 SLSNe in the sample. These objects were found to be spectroscopically similar to SN 2015bn. Therefore, I divided the examined 28 SLSNe into two subgroups by the presence or absence of the W-shaped absorption blend: the "Type W" and the "Type 15bn" types.

- I classified the studied SLSNe into the spectroscopically fast or slow-evolving SLSN-subgroup by the gradient of the photospheric velocity measured at the maximum and at +30 day phase. I concluded that spectroscopically slow-evolving objects tend to have nearly constant photospheric velocities through the mentioned epochs, while the fast-evolving ones show a steep decline of the photospheric velocity. My findings are in agreement with the classification scheme of Inserra et al. (2018).

- I confirmed that fast-evolving SLSNe in general have higher photospheric velocities close to the moment of the maximum light, compared to the slow-evolving events. Therefore one pre-maximum spectrum is sufficient to classify the SLSNe with no post-maximum data into the spectroscopically fast/slow-evolving subtype. Thus, I considered the objects showing $v_{\rm phot} \geq 20000$ km s^{-1} near maximum as fast, and the SLSNe with $v_{\rm phot} \leq 16000$ km s^{-1} as slow events.

- For the studied events I revealed that the fast evolving SLSNe defined by the photospheric velocities have rapidly evolving light curves with short rise times as well. On the contrary, slow evolving SLSNe having lower photospheric velocities show more diverse light curve rise time scales, ranging from the shortest (a few weeks) up to the longest (∼150 days). I also found that all "Type 15bn" events belong to the Slow evolving SLSN-I subgroup defined by the photospheric velocity, while "Type W" objects were represented in both the fast and the slow evolving subtypes.

- From the inferred rise times and photospheric velocities, I calculated the ejecta masses of the 28 SLSNe using the formalism of Arnett (1980), resulting in a mean of $\langle M_{\rm ej} \rangle = 42.96 \pm 12.50\ M_\odot$ ranging between 2.9 (±0.8) and 208 (±61) $M_\odot$. These values exceed significantly the ejecta masses derived by Nicholl et al. (2015), who obtained $\langle M_{\rm ej} \rangle \sim 10\ M_\odot$ between 3 and 30 $M_\odot$ for another sample of Type I SLSNe. The difference is most probably caused by the different method for the derivation the light curce rise time scales and the photospheric velocities. With this analysis, I partly confirmed my previous hypothesis suggested by the study of SN 2010kd and SN 2019neq.

Related publication:
Könyves-Tóth, R. & Vinkó, J. 2021, ApJ, 909, 24J

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Publications

I. Publications associated with the thesis

Refereed papers

- **Könyves-Tóth, R.**, & Vinkó, J. "Photospheric Velocity Gradients and Ejecta Masses of Hydrogen-poor Superluminous Supernovae: Proxies for Distinguishing between Fast and Slow Events" The Astrophysical Journal, 909, 24 (2021)
- **Könyves-Tóth, R.,** Thomas, B. P., Vinkó, J., & Wheeler, J. C. "Comparative Spectral Analysis of the Superluminous Supernova 2019neq" The Astrophysical Journal, 900, 73 (2020)
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III. Other publications

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