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Abundance tomography of thermonuclear supernovae

Ph.D. thesis statements

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Scientific background

The Type Ia supernovae (SNe) are one of the most important objects of astronomy and cosmology. These supernovae originate from carbon-oxygen white dwarfs (C/O WD), which do not produce energy anymore, and the degenerated electron gas holds against the gravitational collapse. If the WD is a member of a binary system, it may gain mass from its companion star. According to the classical explanation, the mass gaining stops at the Chandrasekhar-mass (in the case of a non-rotating C/O WD, $M_{Ch} = 1,44M_{\odot}$), when the fusion of carbon starts in the inner core. The fusion rate increases rapidly because the pressure, hence the equilibrium condition of the degenerate matter does not depend on the temperature. As a result, the released energy completely disrupts the WD. However, there are some contradictions between the observations and the single-degenerate model. This issue may be solved with the so-called double-degenerate scenario, in which two WDs merge together via accretion or collision.

The importance of SNe Ia lies in the correlation between their peak luminosity and the characteristic timescale of the post-peak decline.. Since the decline rate can be easily measured, these objects can be used as distance estimators even on the cosmological scale. The method helps to measure not only the distances of the galaxies but also the value of the Hubble-Lemaitre parameter and its evolution in the past. Based on this correlation, two research groups independently found in 1999 that the Universe expands with an accelerating rate - their work was honored with Nobel prize in 2011 (Riess et al., 1998; Perlmutter et al., 1999). The SNe Ia are also excellent astrophysical laboratories because of their extreme physical properties.

Despite several decades of intensive research, the exact origin of thermonuclear SNe is still unclear. The most important questions to be clarified is the scenario of the mass gaining (simple or double degenerate system), the propagation of the fusion flame (deflagration or detonation) and the possible interaction with the circumstellar or interstellar matter. The investigation of the chemical abundances produced in the explosion could be the key to answer all these questions. The several hundred Angström-wide spectral lines caused by the expansion of the SN ejecta challenge any form of the spectroscopic analysis. The spectral features overlap each other, which makes the line identification and profile distinction ambiguous. Thus, the individual line profiles are usually not modeled independently, instead, the whole spectral range is analyzed.

As the SN ejecta expands, its density and temperature decrease. The photosphere, which separates the optically thick inner- and optically thin outer regions, draws back and we can get insight into deeper and deeper layers. The newly emerged layers contribute to the formation of the spectral lines, while the outermost, low-density regions lose their impact on the spectrum. As a result, the supernova spectra sample through the ejecta in time, from outside to inside. If not only one spectral epoch but the whole spectral time series is fit with the same self-consistent model structure, the physical and chemical properties of the ejecta can be mapped (Stehle et al., 2005). The method called abundance tomography increases the number of fitting constraints more than the number of free parameters, so it makes the spectrum fitting better constrained.

Although the abundance tomography is a powerful tool, the spectral features of the normal SNe Ia challenge the method. However, one of the subclasses of the thermonuclear SNe called Type Iax SNe are ideal subjects for the analysis. These types of explosions show extremely various luminosities and expansion velocities ranging from extremely low (SN 2008ha: $M_V = -14,5$ mag; $v_{fot} = 2.500$ kms^{-1}; Foley et al., 2010a) up to the values close to those of normal SNe Ia (SN 2011ay: $M_V = -18,4$ mag; $v_{fot} = 9.500$ kms^{-1}; Szalai et al., 2015). The Type Ia SNe are born from the explosions of WDs, but the mechanism of their explosions obviously differ from those of SNe Ia. According to the literature, it is probable that these objects originate from pure deflagration explosion scenarios. The hydrodynamical simulations proved that the diverse properties, as well the main spectral features of SNe Iax can be explained by scaling the strength of deflagrations. The deflagration models predict a nearly constant abundance profiles, in which the radioactive ^{56}Ni, oxygen and carbon show the highest mass fractions (Fink et al., 2014).

Research methods

During my PhD research, first, I analyzed the spectral time series of normal SNe Ia. The main motivation of this study was the survey of the high-velocity features (HVF) and studying their velocity evolution. I used the spectral synthesis code called SYN++ (Fisher et al., 1997; Thomas et al., 2011) for the fitting, which is based on the elementary supernova model. The code assumes pure blackbody function as flux-continuum and P Cygni line profiles as a result of resonant scattering. The SYN++ models are not suitable for complete abundance tomography, because the code constraints only the observed line profiles. Thus, spectral line identification and the velocity estimation of the line forming regions can be done, but the structure of the SN ejecta (density profile and chemical abundances) cannot be studied directly. Despite the limitations of the code, SYN++ is a widely used and accepted tool for the spectral analysis of supernovae.

In the publication of Silverman et al. (2015), I fit the pre-maximum spectra of six normal SNe Ia, focusing on the wavelength ranges of Ca II and Si II showing HVFs. The goal of that study was the test of the Gauss-fitting algorithm, which was written by the first author to identify the HVFs and estimate their velocities. As a second project, I studied the extremely strong and blueshifted HVFs of the SN 2010kg via fitting its whole spectral time series with SYN++ (Barna et al., 2016). I identified the spectral lines of ten ions and studied their velocity evolutions. Beyond the expected HVFs and the line forming regions close to the photosphere, the O II and the Fe II lines showed detached velocities between the two groups. Based on the velocity functions of the ions, the stratified nature of the chemical elements can be constrained in the studied velocity range of the SN atmosphere.

Complete abundance tomography analysis made with the Monte Carlo radiative transfer code TARDIS (Kerzendorf és Sim, 2014) was also part of my PhD research. TARDIS allows the user to adjust the model structure directly, thus, the chemical abundances is constrained in the SN ejecta. The computational volume, which models the SN atmosphere, is split into radial cells, whose properties are defined by the model structure. The bottom boundary of the computational volume is the photosphere, which can be assumed as a layer emitting blackbody radiation. The TARDIS samples a Planck-function according to the adjusted parameters (luminosity, time since explosion, photospheric velocity) and initializes a large number of photon packages. The propagation of these packages are followed by the code from the inner boundary to the model surface. In each radial cell, the packages can move through, scatter on electrons or interact with ions according to the result of a Monte Carlo simulation (Lucy, 2002). The energy represented by the photon package remains the same during the interactions, but the direction and the wavelength may change. The TARDIS modifies the temperature profile of the model according to the emitted photon packages from the computational volume and the adjusted luminosity, and a new iteration cycle begins. After the last iteration, the code estimates the synthetic spectrum based on the flight history of the emitted photon packages,

For the abundance tomography with TARDIS, I chose the peculiar Type Iax SNe, which were not analyzed with similar methods before. I fit the spectral series of the relatively bright Type Iax SN 2011ay (Szalai et al., 2015) in the first publication of this project (Barna et al., 2017). The synthetic spectra of the resulted model were in a good agreement with observed data, and the fitting strategy was suitable for mapping the physical and chemical properties of the ejecta. As the main result, the chemical abundance profiles of the best-fit model were not constant as it was predicted by the pure deflagration scenario (Fink et al., 2014). The stratified nature of the Type Iax SN 2011ay made further investigations necessary.

In a follow-up study (Barna et al., 2018), I applied the method to a small sample of five SNe Iax, which were collected according to the requirements of the abundance tomography technique. The 30 spectra of the five spectral series were fit with five individual TARDIS models. I changed the fitting strategy to test the predicted model structures of pure deflagration simulations directly. The best-fit models confirmed the conclusions of the previous Iax abundance tomography (Barna et al., 2017) and further correlations were revealed between the physical properties. Since the sample well represents the more luminous half of the whole subclass, these conclusions are probably general for the more energetic Type Iax SNe. Although the best-fit models share several similarities with the predictions of the pure deflagration scenario (e.g. density functions, presence of chemical elements, abundances of the inner layers), the found discrepancies (e.g. abundances of the outer layers, lack of carbon) indicate the reconsideration of the possible explosion mechanism of the Type Iax SNe.

Results

1. I fit the spectra of normal SNe Ia using the SYN++ synthesis code based on the elementary supernova model and estimated the spatial distribution of the photosphere and the line forming regions.

1.a. I fit the pre-maximum spectra of six SNe Ia and compared my SYN++ models to the results of the automatic Gaussian-fitting code of (Silverman et al., 2015), which was developed for the detection and velocity estimation of the HVFs of the Ca II and Si II lines. The two methods showed a good agreement within the uncertainties.

1.b. I fit the spectral time series of SN 2010kg showing extremely strong and blueshifted HVFs. The fitting of spectral series within a month after the explosion allowed a more precise line identification. I detected the contribution of ions, whose spectral lines were previously not identified in the literature.

1.c. Based on the best-fit SYN++ models, I studied the evolution of the line forming regions in the ejecta of SN 2010kg. The analysis showed that some of the chemical elements form spectral components both at and above the photosphere, but below the line forming regions of the HVFs. These elements appear throughout the whole ejecta continuously. The line forming regions of the photospheric and HVF components of the Ca II and the Si II do not overlap each other, thus, the distribution of these elements are probably stratified.

2. I fit the spectral time series of the peculiar Type Iax SNe using the Monte Carlo radiative transfer code called TARDIS. Adapting the method of abundance tomography, I mapped the profiles of the physical properties and the distributions of the chemical elements.

2.a. I studied one of the most luminous Type Iax SN 2011ay and I showed that TARDIS is suitable to reproduce all the main spectral features of any epochs within a month after the explosion.

2.b. There are only a few examples of using the abundance tomography method on SNe, and there is only a single study on a Type Iax SN (Sahu et al., 2008). Adopting a precise fitting strategy, I studied the presence of more chemical elements and their contributions to the spectra, thus, my work is the most detailed spectral analysis of SNe Iax so far.

3. The results from the best-fit TARDIS models of SNe Iax were compared with the hydrodynamical simulations of pure deflagrations, which are able to broadly reproduce the observables.

3.a. One of the main results of the deflagration models that the mass fractions of the chemical elements are nearly constant throughout the whole ejecta. The synthetic spectra calculated from these abundances showed systematic differences compared to the observed spectra. The models predict too strong iron lines at the earliest epochs and too blueshifted absorptions around the maximum light. Both of these discrepancies suggest that the pure deflagration scenario cannot describe outer regions of the ejecta of SNe Iax.

3.b. I varied the density profiles of the deflagration simulations and I showed that the discrepancies mentioned in IV.a. could only be explained partially. In order to fit the line profiles at each epoch, the chemical abundances have to be also changed at the outermost layers in the ejecta. Thus, the predicted constant abundances are not suitable at high velocities.

3.c. The abundances of the best-fit models in the inner region, especially those of IGEs, show a good agreement with the predictions of the deflagration scenario. Moreover, the density profiles are also compatible with the results of hydrodynamical simulations. The discrepancies affect only the outermost layers, while the deflagration models can explain the inner regions of the Type Iax SNe.

3.d. The only exception of the similarities mentioned in IV.c. is the lack of carbon in the best-fit TARDIS models. The deflagration scenarios predict that 10-20% of the SN Iax ejecta consists of carbon depending on the strength of the explosion. However, my results show that carbon cannot appear with significant (>1%) mass fraction in the inner region. In the case of the outer regions, I could estimate only an upper limit for carbon.

4. I extended the abundance tomography method to a smaller sample of SNe Iax, whose objects represents well the more luminous half this subclass. The mapping of their physical- and chemical parameters highlighted the common attributes and possibly the common origin of these SNe Iax.

4.a. The density profiles of the SNe Iax were well described by exponential functions with cut-offs at high velocities. The two fitting parameters of these functions were the value of the central density and the velocity, above which the density profile starts to deviate from the pure exponential function.

4.b. The SNe Iax of the sample had highly different expansion velocities, however, their abundance profiles showed similar features. I created an abundance template by averaging the mass fractions of the individual SN models in each layer relative from a reference velocity. This abundance template can effectively reproduce the inner structure of the studied SNe Iax by adjusting only one free parameter, the velocity shift of the template.

4.c. As it was reported by several publications about SNe Iax, there is a weak correlation between the peak luminosity and the expansion velocity at the moment of maximum light. My study showed that this correlation is much stronger in the case of the five SNe in the sample, and it also expands for the density structure and abundance profile as well.

Hivatkozások

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Publications

I. Publications associated with the thesis

Refereed papers:

- Silverman, J. M.; Vinkó, J.; Marion, G. H.; Wheeler, J. C.; **Barna, B.**; Szalai, T.; Mulligan, B. W.; Filippenko, A. V.: *High-velocity features of calcium and silicon in the spectra of Type Ia supernovae*, 2015, MNRAs, 451, 1973
- **Barna, B.**; Vinko, J.; Silverman, J. M.; Marion, G. H.; Wheeler, J. C.: *Possible detection of singly ionized oxygen in the Type Ia SN 2010kg*, 2016, MNRAS, 457, 3225
- **Barna B.**, Szalai, T.; Kromer, M.; Kerzendorf, W. E.; Vinkó, J.; Silverman, J. M.; Marion, G. H.; Wheeler, J. C.: *Abundance tomography of Type Iax SN 2011ay with Tardis*, 2017, MNRAS, 471, 4865
- **Barna B.**, Szalai, T.; Kerzendorf, W. E.; Kromer, M.; Sim, S. A.; Magee, M. R.; Leibundgut, B.: *Type Iax supernovae as a few-parameter family*, 2018, MNRAs, 480, 3609

II. Other conference matters associated with the topic of the thesis

Conference posters:

- Szalai, T.; Vinkó, J.; **Barna**, B., Silverman, J. M., Marion, G. H.; Wheeler, J. C.: *Measuring expansion velocities in Type lax SNe*, Type Ia supernovae progenitors, explosions and cosmology (Chicago, USA, 2014.09.15-19.)
- **Barna, B.**; Vinkó, J.; Silverman, J. M.; Marion, G. H.; Wheeler, J. C.; *Detection of C lll in the Type la SN 2010kg*, F.O.E. Fifty-One Erg workshop (Raleigh, USA, 2015.06.01-05.)

- **Barna, B.**; Szalai, T.; Vinkó, J.; Silverman, J. M.; Marion, G. H.; Wheeler, J. C.; Kerzendort, W. E.: *Comparative spectroscopic analysis of Type lax SNe*, Supernovae Through the Ages (Easter Island, Chile, 2016.08.08-13.)
- Camacho-Neves, Y.; Jha, S. W.; **Barna, B.**; Foley, R.; McCully, C.: *Spectral divergence of the Type Iax Supernova SN 2014dt*, 233rd AAS Meeting (Seattle, USA, 2019.01.06-10.)

Conference talk:

- **Barna B.**; Szalai, T.; Kerzendorf, W. E.: *Abundance tomography of Type Iax SNe*, Supernovae - From Simulations to Observations and Nucleosynthetic Fingerprints (Bad Honnef, Germany, 2018.01.21-24.)