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Final stages of massive stars: dust-forming supernovae and the gamma-ray binary system LS 5039

PhD thesis statements

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Scientific background

Evolution of massive (> 8 M_{Sun}) stars, including *core-collapse supernovae* (CC SNe) as the endpoints of their lives and also neutron stars and black holes as the compact remnant objects of these cataclysmic events, is one of the 'hot' topics of today's research in astrophysics. Final stages of massive stars play a leading role in the cosmic nucleosynthesis and the circulation of matter, so they also have significant effects on the birth and evolution of other stars and galaxies.

Owing to their high luminosities, massive stars are visible from large distances. It is especially valid for supernovae, which may shine through a major fraction of the Universe, thus, they are very important in cosmic distance measurements. Another strongly motivating factor in studying supernovae and their remnants is the possibility of processes (particle acceleration, shock waves, etc.) which require extreme physical conditions (e.g. high temperature, pressure, or strong magnetic field). Because of these circumstances, it is very important to observe these objects in all available wavelengths to get relevant information about them.

The type and properties of a CC SN depend mainly on the initial mass of the *progenitor* star. While massive stars go through relatively intense mass-loss processes in the late stages of their lives, most of them preserve large part of the outer H-rich shell. Supernovae originating from such progenitors have a long-term plateau on their light curves, therefore they are classified as type II-P ones (type II means that the spectrum contains H lines). If the initial mass of the progenitor is larger than ~20-25 M_{Sun}, then the stellar wind may expel large part of (in type IIn SNe) or the entire (in type Ib/c SNe) H-rich layer before the core-collapse.

While it is widely accepted that supernovae significantly affect the formation and evolution of other stars, there has been a long-standing argument on whether they also play an important role in the creation of interstellar dust. The large amount of dust observed in high-redshift galaxies and the theoretical models of SN explosions indicate that CC SNe could be the main sources of interstellar dust in the early (and maybe in the present) Universe. The amount and the basic properties of the dust grains formed in the ejecta depend strongly on the type of the progenitor, especially the thickness of its outer H and/or He layers. A thicker outer envelope results in a lower expansion velocity and higher gas density in the deeper layers that contain the condensable elements (C, O, Mg, Al, Si); therefore, larger grains are able to form. This in turn means a larger initial dust mass and also a higher survival rate of the grains.

Based on these theoretical expectations, type II-P SNe are the best candidates for dust formation among CC SNe, in which the models predict 0.1-1 M_{Sun} of newly formed dust grains. However, observations of CC SNe in the local Universe do not support the prediction of intense dust production in these objects. To solve this discrepancy it is necessary to monitor nearby, bright SNe in different wavelenghts and also to develop the dust formation models.

A lot of massive stars can be found in close binary systems, in which the evolution of stars could be very different from the life of single objects. In most of these binaries, one of the components has already gone through the final explosion leaving a compact remnant object (a neutron star or a black hole) behind. If the components are still gravitationally bound to each other, some matter accretes from the hot star to the compact object (or rather to the disk forming around the secondary component). Because the flowing gas is so hot and dense in the accretion disk that it can produce thermal X-rays, these objects are commonly referred to as *X-ray binaries*.

Recently some of these binaries were also observed at very high energies. The general properties of these so-called *gamma-ray binaries* are approximately known, but in the most cases it is still an open question how do the very high-energy (GeV, TeV) photons form. One of the most thoroughly studied but also the most enigmatic members of its class is LS 5039, which consists of a massive O-type primary with a compact companion. In spite of the large amount of data obtained over a wide wavelength range, the nature of the compact object is still unknown. Another motivation for examining LS

5039 is that the observations in X-rays do not show any signs of an accretional disk around the compact object, which indicates a direct wind capture in the system.

Research methods

The main part of my research was to study the signs of dust formation based on publicly available data of type II-P SNe obtained by the *Spitzer Infrared Space Telescope*. In the first part of my work, I focused on SN 2004dj, one of the closest and brightest SNe in the past two decades. I carried out a detailed analysis of mid-infrared light curves and spectra on the SN between +98 and +1381 days after explosion. I calculated the spectral energy distributions (SEDs) from the data, and fit them by blackbodies and several types of dust models, applying the formulae by Meikle et al. (2007) and the 3D radiative-transfer code MOCASSIN. Based on the modeling I was able to determine the basic properties of dust (temperature, composition, grain sizes, spatial distribution) and estimated the epoch of the grain formation.

Using the experience from the study of SN 2004dj, I collected the public photometric and spectroscopic data on 12 other type II-P SNe from the *Spitzer* database. While there are much less data available on these objects, the detailed analysis of mid-IR SEDs allowed me to determine the amount of dust that might be formed in the ejecta after the explosions.

During my doctoral research I also examined the gamma-ray binary LS 5039. As a member of an international collaboration, I took part in obtaining high-resolution optical echelle spectra in 2009 from the Australian National University (ANU) 2.3m Telescope at Siding Spring Observatory, Australia. In total, 118 spectra were obtained that cover almost 40 hours with nearly uniform sampling of the whole orbit (the orbital period is 3.9 days). The dataset was then extended with four spectra taken with the FEROS spectrograph in La Silla, Chile in 2011. These data represent the highest resolution, homogeneous spectral dataset available for LS 5039. Simultaneously, our team carried out high-precision optical photometric observations with the MOST satellite.

First I determined the radial velocities from the Doppler-shifts of the H and He lines of LS 5039. Then I fit a model curve to the He II velocity points using the Wilson-Devinney (WD) code which allowed me to calculate the main orbital and physical parameters of the binary. Using the WD code I also generated light curve models that I could compare with MOST photometry. Based on the radial velocity and light curve models I derived constraints on the mass of the compact object. To get information about the properties of the wind from the O star, I measured the equivalent widths (EWs) of the H and He lines using the IRAF code.

Results

1. Using public data obtained with the *Spitzer Space Telescope* I carried out a detailed analysis of mid-IR light curves and spectra on the nearby, bright SN 2004dj taken between +98 and +1381 days after explosion. I found several pieces of evidence for dust formation after explosion: significant excess flux was detected in all bands between 3.6 and 24 μm, and there was a significant brightening in mid-IR light curves starting after +400 days. My analysis showed that the freshly-formed dust around SN 2004dj can be modeled assuming a nearly spherical shell that contains amorphous carbon grains, which cooled down from ~700 K to ~400 K between +267 and +1246 days. Persistent excess flux was found above 10 μm, which can be explained by a cold (100-120 K) dust component. If this cold dust is of circumstellar origin, it is likely to be condensed in a cool, dense shell between the forward and reverse shocks. An upper limit of $\sim 10^{-3}$ M_{Sun} is derived for the dust mass, which is similar to previously published values for other dust-producing SNe.
   (*Szalai et al., 2011*)

2. I collected the public photometric and spectroscopic data on other 12 type II-P SNe from the *Spitzer* database. I found the data of nine of these objects to be appropriate for a detailed study, which almost doubles the number of type II-P SNe having

detailed, published mid-IR data analysis. I fit the observed SEDs with simplified one- or two-component dust models. In SNe 2005ad and 2005af I found cooling temperatures and decreasing luminosities of the warm component that are similar to the values found in other SNe that are thought to have newly formed dust in their environment. The calculated temperatures for the other SNe do not show strong temporal variation, while the derived luminosities and radii are too high to be compatible with the presence of local dust. The large radius of the warm component may suggest pre-existing dust in these cases, making it unclear if there was new dust formed around these SNe. Nevertheless, theoretical models predict orders of magnitude more freshly formed dust in CC SNe than these observational results suggest ($<10^{-3}$ M_{Sun}). My conclusions support the previous observational results that warm new dust in the environment of SNe contributes only slightly to the cosmic dust content.

(*Szalai & Vinkó, 2013*)

3. I also studied the enigmatic gamma-ray binary system LS 5039. The analysis of high-resolution optical echelle spectra allowed me to find important pieces of information about the system.

3.a

I determined the radial velocities (RV) of the H I, He I and He II lines by fitting two-component functions (a concentric sum of Gaussian and Lorentzian functions) and calculating the shift of the centroids with respect to laboratory wavelengths. I detected systemati blueshifts (15-20 km/s) increasing from the He II lines toward the He I and H Balmer lines. This RV shift may be due to the contamination from the wind of the O star in the profiles of the He I and H lines, so I did not use them to constrain the orbit.

(*Szalai, Kiss & Sarty, 2010; Sarty, Szalai, et al., 2011)*

3.b

The He II radial velocity curve was modeled using the WD code. Based on the fitting I determined the main orbital parameters of LS 5039. In general, my results are close to earlier solutions, but there are some differences. One of the main findings is that the orbital eccentricity of the system (e = 0.24±0.08) is definitely lower than values previously obtained by others. Using the calculated value of the mass function, $f(M_x)$, I determined mass constraints on the compact object as a function of the orbital inclination (i) and the mass of the primary component (M_O). The results imply that the mass of the compact object is at least 1.8 M_{Sun} in the case of the inclination being 60^o or less. Therefore, based on only radial velocity analysis, one cannot decide whether the secondary component is a neutron star or a black hole.

I also repeated the analysis of Casares et al. (2011), in which they fitted an additional sinusoidal component to the radial velocity curve. In contrast to their results I did not find any sign of non-radial pulsations of the O star in our data.

(Szalai, Kiss & Sarty 2010; Sarty, Szalai, et al., 2011; Szalai et al., 2012)

3.c

From EW measurements of the Hα line I derived that the mass-loss rate of the O-type primary due to stellar wind is 3.7 – 4.8 × 10^{-7} M_{Sun} yr^{-1}, similar to the values published by others. Because these EW values show periodic changes, I also checked the EWs of other H and He lines. I found two other lines (Hβ and He I 5875Å) that also showed significant changes during the orbital cycle. The lowest absorption for all of the three lines occurs around phase 0.7 when the compact object is between us and the stellar companion (inferior conjunction). This implies an increased emission strength likely due to the focusing of the stellar wind toward the compact object.

(*Szalai, Kiss & Sarty, 2010; Sarty, Szalai, et al., 2011)*

4. I also analysed the high-precision optical light curve of LS 5039, obtained by the MOST satellite, which indicates a possible variability at the level of 2 mmag, with an apparent broad minimum at phase 0.7 – 0.8. Model calculations of Casares et al. (2005) suggest that if *i* is 30^{o} or less, then photometric variability caused by the distortion of the primary should be of the order of 0.01 mag near periastron. They concluded that if the inclination is less than 30^{o}, then the mass of the compact object is too high (> 3.0 M_{Sun}) to be a neutron star.

To check the conclusions of their light curve simulations, I used the WD code to do my own modeling. Simulations with a fixed mass function give different results than the modeling of Casares et al.: the amplitude of the light curve decreases with increasing total system mass and decreasing eccentricity but do not decrease while lowering the inclination. For fixed total mass and eccentricity, a better inclination diagnostics may be the light curve shape, especially the dip near phase 0, instead of the amplitude. I conclude that one cannot determine the inclination and the mass of the compact object on the basis of the low photometric amplitude alone. At the same time, the low photometric variation is consistent with the lower orbital eccentricity of 0.24 rather than larger values found by others.

(Sarty, Szalai, et al., 2011)

Publications

Publications associated with the thesis

Refereed papers:

- **Szalai, T.**, Vinkó, J.: *Twelve type II-P supernovae seen with the eyes of Spitzer*, 2013, Astronomy and Astrophysics, 549, A79
- **Szalai, T.**, Vinkó, J., Balog, Z., Gáspár, A., Block, M., Kiss, L. L.: *Dust formation in the ejecta of the Type II-P supernova 2004d*j, 2011, Astronomy and Astrophysics, 527, A61

- Sarty, G. E., **Szalai, T.**, Kiss, L. L. et al.: *The gamma-ray binary LS 5039: mass and orbit constraints from MOST observations*, 2011, Monthly Notices of Royal Astronomical Society, 411, 1293

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- **Szalai, T.**, Sarty, G. E., Kiss, L. L., Vinkó, J., Kiss, Cs.: *Mass and orbit constraints of the gamma-ray binary LS 5039*, 2012, Proceedings of the International Astronomical Union, IAU Symposium, 282, 331
- **Szalai, T.**, Kiss, L L., Sarty, G. E.: *Looking into the heart of a beast: the black hole binary LS 5039*, 2010, Journal of Physics Conference Series, 218, 012028

Other conference matters associated with the topic of the thesis

Refereed conference proceedings:

- **Szalai, T.**, Vinkó, J.: *Type II-P supernovae in the mid-infrared*, 2012, Proceedings of the International Astronomical Union, IAU Symposium, 279, 401
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- **Szalai, T.**, Vinkó, J.: *Type II-P supernovae in the mid-infrared*, "Death of Massive Stars: Supernovae & Gamma-Ray Bursts" – IAU Symposium 279 (Nikko, Japan, March 12-16, 2012)
- **Szalai, T.**, Sarty, G. E., Kiss, L. L., Vinkó, J., Kiss, Cs.: *Mass and orbit constraints of the gamma-ray binary LS 5039*, "From Interacting Binaries to Exoplanets: Essential Modeling Tools" – IAU Symposium 282 (Tatranska Lomnice, Slovakia, July 18-22, 2011) – poster and mini-talk
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- **Szalai, T.**: *Dust formation in supernovae - type II-P SNe with the eyes of Spitzer*, "6th Workshop of Young Reasearchers in Astronomy and Astrophysics – The Multi-wavelength Universe from Starbirth to Star Death" (MTA Wigner Research Centre of Physics, Budapest, Sept. 3-6, 2012)
- **Szalai, T.**: *Dust formation in the ejecta of the Type II-P supernova 2004dj*, "Konkoly Workshop: From Dust to Rocky Planets" (MTA Konkoly Astronomical Institute, Budapest, Aug. 28, 2010)

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