Studying cosmic dust formation in the environment of supernova explosions

PhD thesis statements

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Scientific case

Core-collapse supernovae (CCSNe) are the explosive deaths of massive stars (M > 8 $M_\odot$, see, e.g., Woosley et al. 2002). These cataclysmic events provide an opportunity to investigate the final evolution stages of massive stars and their mass-loss processes. They also play a significant role in the cosmic matter cycle including interstellar dust formation. Cosmic dust grains are detected throughout the Universe and are the primary elements of forming molecules and planets. However, their origins are not yet fully understood.

The physical conditions required for dust formation are typically present in the extended atmospheres of asymptotic giant branch stars (AGBs). Nevertheless, recent breakthrough discoveries suggest that a large amount of dust could be present in young galaxies (see, e.g., Watson et al., 2015) that do not contain AGBs due to their age. Owing to their rapid evolution and a presumed large number in young galaxies, CCSNe may have been a primary dust source in the early Universe (see, e.g., Gall et al., 2011). Nevertheless, only a few young extra-galactic SNe and older SN remnants show direct observational evidence for dust condensation (see, e.g., Szalai et al., 2019; De Looze et al., 2019). Thus, there are still numerous unanswered questions regarding the parameters and origin of dust grains in the environment of CCSNe.

CCSNe have an extremely complex environment where dust grains could be:

- newly-formed in the ejecta or the contact discontinuity behind the reverse shock (called the cold, dense shell);
- or pre-existing and heated by collision/radiation of the shocked or unshocked circumstellar medium. Light scattering from interstellar matter that is much farther away produces an infrared echo.

Hence, the spatial distribution of grains and the geometry of the dust-containing region play an important role in determining the origin of the dust.

One efficient and widely used method for studying dust grains in the environment of CCSNe is modeling their thermal emission. Dust grains absorb and scatter light in ultraviolet, optical, and near-infrared regimes and emit the absorbed energy as thermal emission at mid-infrared and sub-millimeter wavelengths. A less widespread but successful method for obtaining dust parameters is modeling the optical and near-IR emission-line profiles (see, e.g., Bevan & Barlow, 2016; Niculescu-Duvaz et al., 2022). As far as we know, newly-formed dust grains in the ejecta can explain the asymmetries of emission lines at these wavelengths. Furthermore, simultaneously applying both modeling approaches, it is possible to disentangle pre-existing and newly-formed SN dust components.

In the past two decades, the *Spitzer Space Telescope* was the primary source of mid-infrared data. With its three detectors, the telescope carried out photometric and spectroscopic observations. However, the *James Webb Space Telescope* (JWST), launched in 2021, opened a new perspective on cosmic dust research and revolutionized the field with its groundbreaking first results.

In the *JWST* era, statistical methods, which are applied more widely in astrophysics, are expected to become more significant. Statistical data analysis, including the Bayesian framework, enables fast and efficient problem-solving in the case of non-analytical physical systems. This approach allows us to map the broad parameter space of relevant models and describe the relationship between given parameters. Within the Bayesian framework, we can derive the most probable solutions of a system from the probability distribution. The exceptional datasets provided by the *JWST* present an opportunity to exploit the benefits of the Bayesian framework.

Objective and research methods

In the work presented here, I studied the dust formation in the environment of core-collapse supernovae via multi-wavelength datasets using analytical and numerical models and a statistical approach. Throughout the analysis, I used data from the *Spitzer Space Telescope*, the *JWST*, and the *Keck Telescope* and investigated in detail the SN 1993J and SN 1980K.

I carried out a photometry on all available data of the *Spitzer* IRAC and MIPS detectors regarding both SNe and obtained the late-time mid-IR lightcurves. Based on mid-infrared observations, the cooling ejecta alone cannot account for the observed mid-infrared flux excess, suggesting the presence of dust grains. To obtain the dust parameters, I used analytical and numerical dust models. I computed numerical dust models with the MOCASSIN (Ercolano et al., 2003, 2005, 2008) radiative transfer code.

Furthermore, I thoroughly investigated the possibility of newly-formed dust and pre-existing dust heated by collision/radiation. I estimated the size of the ejecta and the cold dense shell mainly using blackbody models, the expanding velocity of the ejecta, and radio observations. I compared these findings with the results of optical line profile modeling, considering both my analysis and previously published research. I investigated the pre-existing and collisionally heated dust scenario with the standard interacting model (which describes the interaction of the SN-shock wave and the circumstellar matter). Moreover, I studied the pre-existing and radiatively heated dust grains by applying a widely-used infrared echo model. Finally, based on the dust properties derived from different approaches, I was able to make constraints on the origins of the grains.

In the case of SN 1980K, we have a late-time optical spectrum obtained with the *Keck* telescope around the same time as the *JWST* observations. The spectrum exhibits strong, asymmetric emission lines, which also implies the presence of dust grains. I modeled the asymmetries in optical and near-IR emission-line profiles with the DAMOCLES (Bevan & Barlow, 2016; Bevan, 2018) radiative transfer code and derived the properties of the newly-formed dust grains.

In the other part of my research, I examined numerical dust models of CCSNe and interpreted the results using a statistical approach. I fit analytical dust models to the spectral energy distributions to estimate the model parameters. In order to investigate the parameters further, I computed numerical models with the MOCASSIN code. To interpret the numerical models, I applied a Bayesian data inference framework coupled to a Markov chain Monte Carlo (MCMC) algorithm. I achieved the sampling utilizing an affine invariant ensemble sampler implemented through the ”emcee” package (Foreman-Mackey et al., 2013) in Python, which uses random walks of a collection of walkers. I examined the degree of convergence of the sampling, the relationship between the model parameters, and possible parameter degeneracies (in a context where many different parameter configurations can result in a given solution).

The objective of the presented work is to carry out a detailed analysis of cosmic dust – which is one of the significant components of the Universe – in the vicinity of core-collapse supernovae using high-quality multi-wavelength datasets and systematically applying several modeling techniques and also a statistical approach.

Results

T1. I studied the late-time mid-infrared evolution and dust grains in the environment of the nearby Type IIb SN 1993J based on data from the *Spitzer* telescope IRAC and MIPS detectors and a late-time IRS spectrum, using analytical dust models and blackbody models.

T1./A Based on my modeling the detected late-time mid-infrared emission cannot be explained by one-component analytical dust models with amorphous carbon or silicate-based composition. I found that the late-time mid-infrared emission of SN 1993J can be described by two-component dust models with a dust mass of $\sim 3.5\text{-}6.0 \cdot 10^{-3}$ $M_{\odot}$ in case of a partly silicate-based dust composition. Furthermore, the IRS spectrum of the supernova supports the presence of silicate dust in its environment.

T1./B Our research group investigated the local dust formation and the heating of pre-existing dust grains by collision/radiation in the environment of SN 1980K.

During the analysis, I estimated the size of the ejecta and the cold, dense shell, fitted the late-time integrated mid-infrared light curve, and examined the presence of a possible light echo.

Based on the above findings, we found that the mid-infrared emission excess detected by *Spitzer* can be explained by the presence of:

- newly-formed dust grains located both in the unshocked inner ejecta and the outer cold dense shell;
- or pre-existing dust grains heated primarily radiatively by ongoing interaction with the circumstellar matter (in accordance with previous studies).

This thesis statement is based on: **[S1]**.

T2. I studied the late-time mid-infrared evolution and dust grains in the environment of the Type IIL SN 1980K based on data from the *Spitzer Space Telescope*, the *Keck* ground-based telescope, and the *James Webb Space Telescope* (*JWST*) MIRI detector, using analytical and numerical dust models.

T2./A Based on my modeling the detected late-time mid-infrared emission excess cannot be explained by one-component analytical dust models with amorphous carbon or silicate-based composition. I found that the late-time mid-infrared emission of SN 1980K can be described by two-component dust models with a dust temperature of ~ 150 K and a dust mass of $\sim 2 \cdot 10^{-3}$ $M_\odot$ in case of a partly silicate-based dust composition, accompanied by a dust/gas component of a temperature at least 400 K.

T2./B I computed numerical models with the MOCASSIN radiative transfer code describing the late-time mid-infrared spectral energy distributions of SN 1980K calculated from the MIRI data. I found that the *JWST*/MIRI data of SN 1980K can be described by the presence of a dust shell with an outer radius of $1{,}5 \cdot 10^{17}$ cm and a ratio of the inner and outer radii of $R_{\mathrm{inner}}/R_{\mathrm{outer}} \approx 0.08$.

T2./C Our research group investigated the local dust formation and the heating of pre-existing dust grains by collision/radiation in the environment of SN 1980K. During the analysis, I examined the pre-existing and radiatively heated dust scenario in detail with a light echo model.

Based on the above findings and the modeling of the optical emission lines profiles, we found that the emission excess detected by *JWST*/MIRI can be explained by the presence of:

- pre-existing dust grains heated by collision (or partly radiation);

- or presumably the mid-infrared component of newly-formed dust grains,

accompanied by a much colder dust component in the ejecta.

This thesis statement is based on: **[S2]**.

T3. I investigated the dust grains in the vicinity of SN 1980K based on the late-time spectrum of the *Keck* telescope using the state-of-the-art radiative transfer code DAMOCLES. In agreement with previous studies, strong asymmetric emission lines are present in the spectrum, strengthening dust formation in the environment of the supernova. I modeled the Hα and [O I] 6300, 6363 Å emission lines in the late-time optical *Keck* spectrum and found that they can be described by the presence of even two orders of magnitude higher dust masses ($\sim$ 0.24-0.58 $M_{\odot}$) with probably very low temperature in the ejecta.

This thesis statement is based on: **[S2]**.

T4. I studied models describing the thermal emission of dust grains in the environment of core-collapse supernovae with a statistical approach. To efficiently and systematically explore and interpret the models computed with the MOCASSIN radiative transfer code, I applied a Bayesian data inference framework linked to an MCMC algorithm. I investigated a sample of three different types of core-collapse supernovae. Based on my results, this method can be applied to efficiently describe the parameter space of MOCASSIN models of core-collapse supernovae, and the shell-like numerical dust models of the examined supernovae are consistent with analytical dust models.

This thesis statement is based on: **[S3]**.

Publications

I. Publications associcated with the thesis:

List of peer-reviewed papers in English:

[S1] **Zsíros, Szanna**; Nagy, Andrea P.; Szalai, Tamás: *Rescued from oblivion: detailed analysis of archival Spitzer data of SN 1993J*, Monthly Notices of the Royal Astronomical Society, Volume 509, Issue 3, pp.3235-3246, 2022.

[S2] **Zsíros, Szanna**, Szalai, Tamás; De Looze, Ilse; Sarangi, Arkaprabha; Shahbandeh, Melissa; Fox, Ori D.; Temim, Tea; Milisavljevic, Dan; Van Dyk, Schuyler D.; Smith, Nathan; Filippenko, Alexei V.; Brink, Thomas G.; Zheng, WeiKang; Dessart, Luc; Jencson, Jacob; Johansson, Joel; Pierel, Justin; Rest, Armin; Tinyanont, Samaporn; Niculescu-Duvaz, Maria; Barlow, M. J.; Wesson, Roger; Andrews, Jennifer; Clayton, Geoff; De, Kishalay; Dwek, Eli; Engesser, Michael; Foley, Ryan J.; Gezari, Suvi; Gomez, Sebastian; Gonzaga, Shireen; Kasliwal, Mansi; Lau, Ryan; Marston, Anthony; O'Steen, Richard; Siebert, Matthew; Skrutskie, Michael; Strolger, Lou; Wang, Qinan; Williams, Brian; Williams, Robert; Xiao, Lin: *Serendipitous detection of the dusty Type IIL SN 1980K with JWST/MIRI*, Monthly Notices of the Royal Astronomical Society, Volume 529, Issue 1, pp.155-168, 2024.

Refereed proceeding in English:

[S3] **Zsíros, Szanna**; De Looze, Ilse; Szalai, Tamás: *Numerical modeling of IR SEDs of dusty CCSNe within a Bayesian framework*, accepted for publication in the Proceedings of the International Astronomical Union, DOI: 10.1017/S1743921322002897.

II. Other peer-reviewed papers in English:

- Shahbandeh, Melissa; Sarangi, Arkaprabha; Temim, Tea; Szalai, Tamás; Fox, Ori D.; Tinyanont, Samaporn; Dwek, Eli; Dessart, Luc; Filippenko, Alexei V.; Brink, Thomas G.; Foley, Ryan J.; Jencson, Jacob; Pierel, Justin; **Zsíros, Szanna**; Rest, Armin; Zheng, WeiKang; Andrews, Jennifer; Clayton, Geoffrey C.; De, Kishalay; Engesser, Michael; Gezari, Suvi; Gomez, Sebastian; Gonzaga, Shireen; Johansson, Joel; Kasliwal, Mansi; Lau, Ryan; De Looze, Ilse; Marston, Anthony; Milisavljevic, Dan; O'Steen, Richard; Siebert, Matthew; Skrutskie, Michael; Smith, Nathan; Strolger, Lou; Van Dyk, Schuyler D.; Wang, Qinan; Williams, Brian; Williams, Robert; Xiao, Lin; Yang, Yi: *JWST observations of dust reservoirs in type IIP supernovae 2004et and 2017eaw*, Monthly Notices of the Royal Astronomical Society, Volume 523, Issue 4, pp.6048-6060, 2023.

- Barna, B.; Nagy, A. P.; Bora, Zs.; Czavalinga, D. R.; Könyves-Tóth, R.; Szalai, T.; Székely, P.; **Zsíros, Szanna**; Bánhidi, D.; Bíró, I. B.; Csányi, I.; Kriskovics, L.; Pál, A.; Szabó, Zs. M.; Szakáts, R.; Vida, K.; Bodola, Zs.; Vinkó, J.: *Three is the magic number: Distance measurement of NGC 3147 using SN 2021hpr and its siblings*, Astronomy & Astrophysics, VOL(677), id.A183, 16 pp., 2023.

- Szalai, Tamás; **Zsíros, Szanna**; Fox, Ori D.; Pejcha, Ondřej; Müller, Tomás: *A Comprehensive Analysis of Spitzer Supernovae*, The Astrophysical Journal Supplement Series, Volume 241, Issue 2, article id. 38, 35 pp., 2019.

III. Conference talks in English:

- *Serendipitous detection of the dusty Type IIL SN 1980K with JWST/MIRI*, ”SuperVirtual 2023”, (06-10 November 2023, online)

- *Serendipitous detection of the dusty Type IIL SN 1980K with JWST/MIRI*, ”The First Year of JWST Science Conference”, (11-14 September 2023, Baltimore, USA, participating online)

- *Comparative analysis on dust properties in core-collapse supernovae*, ”Wheel of Star Formation”, (12-16 September 2022, Prague, Czech Republic)

- *Looking for dust in core-collapse supernovae with a Bayesian approach*, ”Astrophysics with Radioactive Isotopes”, (12-17 June 2022, Budapest, Hungary)

IV. First author conference posters in English:

- **Zsíros, Szanna**; Szalai, Tamás; De Looze, Ilse és mtsaik.: *Serendipitous detection of SN 1980K with JWST/MIRI*, ”Origin and Fate of Dust in our Universe”, (25-29 September 2023, Gothenburg, Sweden)

- **Zsíros, Szanna**; Szalai, Tamás; Fox, Ori D. és mtsaik.: *Serendipitous detection of SN 1980K with JWST/MIRI*, ”First Science Results of JWST”, (12-15 December 2022, Baltimore, USA, participating online)

- **Zsíros, Szanna**; Szalai, Tamás; De Looze, Ilse: *Numerical modeling of IR SEDs of dusty core-collapse supernovae with a Bayesian approach*, ”IAU Symposium 361: Massive Stars Near and Far”, (08-13 May 2022, Ballyconnell, Ireland)

- **Zsíros, Szanna**; Szalai, Tamás; Nagy, A. P.: *Rescued from oblivion: detailed analysis of archival Spitzer data of SN 1993J*, ”SuperVirtual 2021 - From Common to Exotic Transients”, (15-19 November 2021, online)

- **Zsíros, Szanna**; Szalai, Tamás; Nagy, A. P.: *Rescued from oblivion: detailed analysis of archival Spitzer data of SN 1993J,* ”IAU Symposium 366 on The Origin of Outflows in Evolved Stars”, (01-05 November 2021, online), https://doi.org/10.5281/zenodo.5820077
- **Zsíros, Szanna**; Szalai, Tamás; Nagy, A. P.: *Circumstellar interaction and dust in the environment of Type IIb Supernova 1993J,* ”The Rise of Metals and Dust in Galaxies through Cosmic Time”, (26-30 October 2020, participating online)
- **Zsíros, Szanna**; Szalai, Tamás; Nagy, A. P.: *Study of Type IIb Supernova 1993J evolved from a binary progenitor,* ”International meeting on variable stars research - KOLOS 2019”, (05-07 December 2019, Stakčín, Slovakia)

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