Final report (category: FK-20, Nr.: 134432)

Supernovae and their environments

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Research summary

Here we present the results of our research work achieved during the full period of the OTKA/NKFIH FK134432 Grant (01/12/2020–30/11/2024), in order of relevance and grouping by the topics given in the original research plan.

Topic I: The origin of Type Iax and other (peculiar) thermonuclear supernovae

One of our main research goals was to extend the abundance tomography method, which we previously applied successfully for analyzing the spectra of the special type of thermonuclear supernovae, SNe Iax, for further objects covering the whole luminosity range of the class. Optical and near-IR spectra (just as UV and optical photometry) of the nearby, intermediate-luminosity SN 2019muj, collected by a world-wide international team, offered a good chance for that. Detailed analysis of the object, led by our Group members, showed that our previous stratified abundance template based on brighter SNe Iax provides a good match with SN 2019muj. Moreover, SN 2019muj provides a unique opportunity to link extremely low-luminosity SNe Iax to well-studied, brighter ones [1].

As a highlighted result of our Team during the grant period, two of our group members – B. Barna and T. Szalai – have been co-Is of several approved JWST programs in Cycles 1,2, and 3 (GO 2072, 4516, 6580, PI: S. Jha; GO 5232, PI: L. Kwok), during which we obtain nebular near and mid-IR spectra of thermonuclear SNe belong to various subtypes. Research paper on our first target, SN 2021aefx, was accepted and published in 2023 [2]. Later, the second target, SN 2022pul (a special subluminous Type Ia explosion) was also observed with JWST. This object turned to be highly interesting, producing peculiar spectral features and signs of ongoing circumstellar interaction; the peculiarity of the object, combined with a unique dataset, led to a couple of interesting results presented in two consecutive manuscripts in ApJ [3, 4].

Some further results connecting to the topic of thermonuclear SNe:

- We carried out UV/optical spectral and light-curve analysis (partly based on HST data) of the normal SN Ia ASASSN-14lp for testing various explosion scenarios. The observed ultraviolet suppression can be explained either by presence of radioactive material in the outer layers of the ejecta, or by assuming that the radiation at the photosphere is significantly lower in the UV regime than the pure Planck function [5].
- We have continued our studies on both early- and late-time data on objects belong to the peculiar Iax class of thermonuclear SNe. Our Team members have also contributed to the comparative analysis of two overluminous SNe Iax SN 2018cni and 2020kyg [6]. We also took part in the late-time spectral analysis of the unique SN Iax 2014dt showing late-time optical and mid-IR excess [7]. The complex photometric and spectroscopic analysis of the nearby SN 2022xlp was also finished and submitted to A&A (leading by our Team members D. Bánhidi and B. Barna).
- We also contributed to two thorough analyses on revealnig the initial ^{56}Ni masses, ejecta masses, and on other physical parameters for a larger set of Type Ia SNe inferred from multiband photometric and optical spectroscopic data [8, 9].

We have also been active in writing telescope proposals for collecting either early- or late-time spectra of thermonuclear SNe. Beyond the listed JWST proposals, i) we approved DDT time on VLT/FORS2 on SN 2021aefx in September 2022 (with T. Szalai as PI); the analysis of the spectrum is in progress; and, ii) B. Barna and T. Szalai have been co-Is of an approved HST proposal (C29, id 16693, PI: S.Jha). Additionally, B. Barna has been the PI (with T. Szalai as co-I) of three unapproved VLT-XShooter proposals (P108, P109, P111), and one unapproved HST proposal (C29).

Topic II: Supernovae and circumstellar matter

Comprehensive study of very late-time IR evolution of various types of interacting SNe (based on Spitzer data obtained by an international team including T. Szalai), together with their detailed multi-wavelength analysis was a specific goal in our first-year workplan. We successfully finished the project and published its results in a first-author paper by T. Szalai [10]. Our main conclusion was that, practically, all observed interacting SNe are detectable during years (or even decades) in mid-IR, which offers unique chances to follow their late-time evolution and to reveal still hidden details of underlying physical processes (collisional/radiative interaction of SN explosions with their ambient matter; formation/destruction of dust grains in SN environments).

Inspired by these and previous results, we and our collaborators have submitted a number of JWST proposals in the topic of SN-CSM and SN-dust connections, and many of them have been approved. As a great local success, the approved proposals include Cycle 3 program GO 6049 led by T. Szalai (the number of JWST program PIs from Central Europe is very limited)! Moreover, T. Szalai has also been the co-PI of Cycle 1 program GO 2666 (PI: O.D. Fox). The goal of both of these programs is to constitute the mid-IR SEDs of dusty core-collapse (basically Type II-P) SNe using MIRI imaging with 8 filters between 5-25 microns, in order to reveal large amount of - potentially - newly-formed dust in the remnants of the explosions at various ages (∼5-25 years after explosion). Our Team members have been taking part in the modeling of both the mid-IR SEDs and of contemporaneous optical spectra (obtained by Keck Telescopes).

Regarding our GO 2666 program, we targeted 5 SNe and have positive detections for all of them. In our first paper [11], we showed that both of our famous targets appeared in NGC 6946 (SNe 2004et and 2017eaw) contain significant amount of dust (the amount found in SN 2004et, ~ 0.014 $M_{\odot}$, is the second larger mass ever detected based on the infrared excess of a SN). Similar examinations, leading by our Team members - Sz. Zsíros, T. Szalai -, have been obtained on the Type II-L SN 1980K (located in the same galaxy), which has been serendipitously observed by JWST. In the paper published in 2024 [12], we present the complex analysis of JWST/MIRI and contemporaneous optical Keck data and showed that the spectral energy distribution and dust-heating mechanisms seem to be quite similar to what can be seen in the famous SN 1987A, just at a higher dust mass. All the other targets of our JWST Cycle 1 programs have been positively detected (8-filter MIRI photometric dataset, MIRI spectra, and NIRSpec+MIRI spectrum for 3, 5, and 1 object, respectively); analysis and writing of research papers for every single object SNe 2005af, 2011ja, 2013ej) is still in progress.

Beyond these two proposals, several further JWST proposals have been approved for studying SN-dust and SN-CSM connections involved Team members T. Szalai and Sz. Zsíros as co-Is. These proposals include data (have been / will be) obtained during MIRI Imaging (SURVEY 3921), MIRI/NIRSpec spectroscopy (GO 1860, 2348, 4217, 6583; DD 4436, 4520), or, combined imaging + spectroscopy (GO 5290, 6213). Three manuscripts based on these data have been already submitted to Q1 journals: MIRI imaging on SNe 1993J (T. Szalai et al.) and 2017gci (Gomez et al.), and MIRI spectroscopy on SN 2005ip (Shahbandeh et al.); a number of further papers are in preparation. Moreover, in connection with our ongoing JWST programs, we also approved observation time on VLT for obtaining late-time optical spectra of two SNe (P111, PI: T. Szalai, with B. Barna as co-I). Furthermore, our collaboration also submitted HST proposals; three of them (IDs 15834, 17195, 17814, PI: O.D. Fox) were approved for obtaining UV spectroscopic signatures from fast evolving transients.

Some further results connecting to Topic II:

- T. Szalai was involved into the analysis part of a Spitzer survey for dust-obscured supernovae in luminous infrared galaxies. We reported the detection of 9 SNe (five of which were not discovered by optical surveys) and found that the number of detections is consistent with the theoretical SN rates [13]. These results were also promoted by a NASA JPL Press Release on August 4, 2021.

- T. Szalai was also involved in another JWST study on the dust formation observed in Type II SN 2021afdx appeared in the spectacular Cartwheel Galaxy; he contributed to the near-IR + mid-IR SED analysis of the object [14].

- We took part in the multiwavelength analysis of the special object AT 2019krl; its source was probably a giant eruption of a luminous blue variable (LBV) or of a heavily dust-enshrouded (blue) supergiant, or, maybe a massive-star merger event [15].

- A large international team, involved T. Szalai, published a research study (Low-Mass Helium Star Progenitor Model for the Type Ibn SN 2020nxt) based on unique HST UV spectroscopy and a large set of ground-based data [16].

- We also have a joint project with colleagues from the Czech Academy of Sciences aiming to run hydrodynamic simulations for seeing the effects of assumed SN explosions in nuclear star clusters close to the center of our Galaxy. Results of this project appeared in two Q1 research papers: one of them - presenting the general methodology - with the lead of our Team member, B. Barna [17], and another one - revealing the past of SN remnant Sgr A East - with his co-authorship [18].
- Moreover, a study written by three of our Team members on modeling the circumstellar interaction around radio-bright SN 2004gq has also been submitted to A&A (Nagy, Pál & Szalai).

Topic III: Pre-explosion mass-loss processes of massive stars

Regarding this Topic, our main goal for the first year was the pre- and post-explosion analysis of the famous Type IIb SN 1993J. We analyzed the long-term IR evolution of the object and its connection with further multi-wavelength data and pre-explosion mass-loss history. We have provided evidence that the observed late-time mid-IR excess of SN 1993J can be described by the presence of two-component local dust, which source could be either newly-formed or pre-existing dust (if latter, it may be heated by ongoing CSM interaction also detected at other wavelengths). The paper containing our results was published in MNRAS [19].

A highlighted event of the year was the appearance of SN 2023ixf, one of the closest SNe of the past few decades (Type IIP, located in the M101 galaxy). T. Szalai and S. Van Dyk (Caltech) successfully identified the progenitor star on the archival images of Spitzer Space Telescope within a day after discovery and published a short Astronomer's Telegram [20] on that. We also determined the luminosity of the progenitor star and detected signs of its infrared variability in the past years before explosion. Cooperating with further researchers, we published two research papers; one on the pre-explosion infrared variability of the progenitor [21], and one on the physical parameters and environmental properties of the exploding star [22]. Importance of these studies can be shown with the number of citations received within a short time: based on ADS, our short ATel has received 13 citations since 2023 May (most of them are Q1 papers), while papers [21] (published in 2023 November) and [22] (published in 2024 June) have received 49, and 31 citations to date, respectively. Very recently, with T. Szalai as the second author, a further study was published on SN 2023ixf. In this paper [23], we analyzed the pre- and post-explosion NEOWISE-R infrared data on the object, combined with ground-based optical and near-IR photometry and spectra. Using a very-well sampled dataset obtained during the first ∼12 days after explosion, we can strengthen the previous results how and when SN shockwave just pass the very dense ambient circumstellar matter.

Furthermore, we have been working with I. de Looze (Ghent University) in order to carry out Bayesian dust modeling on existing optical-IR SEDs of various types of dust-forming SNe. This kind of examinations is expected to give a more detailed picture on the physical properties and geometry of dust in SN environments and, thus, on the pre-explosion mass-loss processes of massive stellar progenitors. Preliminary results of this project were presented on a poster on the IAU Symposium 361 ("Massive Stars Near & Far"; Dublin, May 8-13, 2022) and appeared in the Conference Proceedings [24]. We plan to continue this promising project in the future.

Moreover, we have also started to work on studying late-time mass-loss processes of massive stars and the influence of binary companions on that. We generated different sets of MESA codes and examine how the wind parameters and presence of a binary companion affect late-time stellar evolution. The first results of this study have been submitted to a Q1 journal (Nagy, Bodola et al.)

Topic IV: Follow-up studies of nearby supernovae and other extragalactic transients

A very important goal of our OTKA Grant project has been to maintain an effective and routinary way of local follow-up observations of (extra)galactic transients using our recently installed 0.8m robotic telescope (BRC80) at Baja Observatory of the University of Szeged. Regular scientific observations with BRC80 started in February 2021 (in a strong cooperation with its "twin" facility at the Piszkéstető Mountain Station of the Konkoly Observatory). Up to now, we have collected multi-color photometric (BVg'r'i'z') datasets on ∼100 SNe and some other transients (galactic novae, AGNs); regarding some of them, we started to carry out own analyses and also joined in some collaborative projects.

The first few papers partially based on BRC80 data have already been accepted and published in Q1 journals. The first one has been written about the calcium-rich SN 2021gno in a large international collaboration [25]. The second paper is a comprehensive analysis on SN Ia 2021hpr and on its two siblings appeared in the same galaxy - this latter project is led by our Team members [26]. Moreover, our Team also published a work on the combined photometric/spectroscopic analysis of the peculiar Type II SN 2021aatd led by T. Szalai [27]. This event seems to be the first identified object that belong to a transient group between 1987A-like exploding blue supergiants and slowly-evolving SNe with multi-peaked light curves. Furthermore, we have also contributed to the data analysis of the Type Ic SN 2021krf [28], and of the Ca-rich SN 2022oqm [29].

Beyond all that, our Team member R. Könyves-Tóth led two papers on the premaximum diversity and postmaximum homogeneity of H-poor superluminous (SL) SNe [30, 31] and also contributed to a study focusing on SLSNe 2021bnw and 2021fpl [32], as well as to creating the most comprehensive catalogue of Type I SLSNe to date [33].

Moreover, Team members T. Szalai and R. Könyves-Tóth acted as co-authors of an invited review paper on space-based SN researches appeared in the MDPI Q2 journal Universe [34].

Final remarks

Scientific performance

During the Grant period, our Team members have worked in various top-level SN collaborations, playing a leading role in several projects that based on data of e.g. the James Webb, Spitzer, and Hubble space telescopes, as well as of local or the largest-aperture ground-based telescopes. Combining the observational results with a strong theoretical background (including the application of various modeling codes), we have led or contributed to top-quality research projects: we have examined e.g. the role of SNe in the cosmic dust formation, the late-time evolution of massive stars, and the fundamental open questions in the field of exploding white dwarfs.

Between December 2020 and November 2024, we published **31 Q1 research papers** (in 11 papers, one of our local Team members is the first author) and we have submitted a few more manuscripts. Since, originally, we expected to take part in writing at least 4 Q1 research papers per year, we can say that we successfully fulfilled the criteria. There is also a conference proceeding, a short telegram, and a Q2 review paper on our list of publications.

We also presented our results at various international conferences and seminars:

- IAU Symposium 366: The origin of outflows in evolved stars (2021.11.01-05, online): poster (Sz. Zsíros et al.)
- SuperVirtual 2021 - From Common to Exotic Transients (2021.11.15-19, online): contributed talk (T. Szalai), 3 posters (A Nagy; Sz. Zsíros et al.; Camacho-Neves, ... B. Barna et al.)
- Supernovae and Dust Tele-talks (11 Febr, 2021): **invited talk** (T. Szalai)
- IAU Symposium 361 ("Massive Stars Near & Far"; Dublin, 2022.05.08-13): poster + proceeding (Sz. Zsíros et al.)
- Cosmic cycles (Symposium of the Hungarian Academy of Sciences, 2022.05.16): contributed talk (T. Szalai)
- Supernovae and Dust Tele-talks (2022.05.26): **invited talk** (Sz. Zsíros)
- "Wheel of Star Formation" conference (Prague, Czech Republic, 2022.09-16): 4 contributed talks (B. Barna, A. Nagy, B.H. Pál, Sz. Zsíros)
- "First Year of JWST Science" conference (Baltimore, USA, 2023.09.11-14): contributed talk (Sz. Zsíros)
- "SuperVirtual 2023" conference (online, 2023.11.06-10): 2 contributed talks (B. Barna, Sz. Zsíros)
- "JWST First Science Results" conference (Baltimore, USA, 2022.12.12-14): 3 posters (with T. Szalai and Sz. Zsíros as co-authors)
- "AAS 241 meeting" (Seattle, USA, 2023.01.08-12): poster (with T. Szalai and Sz. Zsíros as co-authors)
- "Cosmic Dust" conference (Göteborg, Sweden, 2023.09.25-29): poster (Sz. Zsíros et al.)
- "SN 2023ixf, The Decadal Supernova in M101" workshop (Garching bei München, Germany, 2024.06.04-07): **invited talk** (T. Szalai)
- “Supernova Remnants III: An Odyssey in Space after Stellar death” conference (Chania, Greece, 2024.06.09-15): contributed talk (T. Szalai), 4 posters (B. Barna, Sz. Zsíros, Zs. Bodola, B.H. Pál)

Involving students to research work

Team Member Szanna Zsíros was a PhD student at the beginning of the Grant period. Her PhD research work has strongly connected to Topics II and III. She had a successful PhD defense in 2024 December. Other involved PhD students – István Csányi, Pál H. Boróka and Zsófia Bodola – have been also effectively contributed to the scientific goals via data reduction and analysis. We also involved Dominik Bánhidi, a talented BSc (now PhD) student, in the research work. He received a I. prize at the Young Scientists' Conference at the University of Szeged (TDK) and took part at the National Conference (OTDK) two times (2021, 2023).

Dissemination of the results

During the Grant period, we had several seminar talks at the University of Szeged, and at the Konkoly Observatory, Budapest. We gave a number of talks to high-school students and teachers in Szeged (e.g. on Researcher's Night programs, or at schools), but also e.g. in Kiskunhalas, Orosháza, Hódmezővásárhely, or in Sopron. We published several articles regarding SN research at http://csillagaszat.hu website and also two papers in the "Fizikai Szemle", a prestigious Hungarian journal in scientific dissemination.

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