OTKA/NKFIH PD112325 – Final report (01/01/2015 - 30/06/2018)

As a postdoctoral fellow of the Astrophysical Group at the University of Szeged, I work with the leader of the group, J. Vinkó, as well as with other group members and with a number of Hungarian and international collaborators. Here I present the results of my research work achieved during the full period of the OTKA/NKFIH PD112325 Grant, in order of relevance and grouping by the topics given in the original research plan.

I. DETAILED ANALYSIS OF NEARBY, BRIGHT SUPERNOVAE

a) Investigations on single objects

I have participated in the photometric and spectroscopic observations, data reduction and analyses of several nearby supernovae (SNe) and of some other transient events during the last years. Most of the photometric data have been collected with the 0.6/0.9m Schmidt telescope of the Konkoly Observatory at Piszkesteto Mountain Station, Hungary, while the main source of the spectroscopic data has been the 9.2m Hobby-Eberly Telescope (HET) at McDonald Observatory, Texas. I have played a leading role in the detailed investigation on three objects (SNe 2011ay, 2013df, and 2017eaw), while I have contributed at different scales to other studies.

SN 2011ay belongs to the recently defined class of Type Iax SNe, which are faster evolving and less luminous relatives of the common Type Ia SNe. Photometric and spectroscopic data allowed our team to determine the main explosion parameters (moment of explosion, rise time to light curve maximum, total ejecta mass, mass of the synthesized radioactive Ni), as well as the spectral evolution of the SN during the first month after explosion. We showed that strong blending with metal features (those of Ti II, Fe II, Co II) makes the direct analysis of the broad spectral features (e.g. that of the Si II 6355Å line) very difficult, which can make the 'quick-look' velocity estimates quite uncertain. While the first version of the paper was submitted in 2014, the revision of the spectral analysis gave a lot of work even in the first month of the Grant period; the paper was finally accepted by a Q1 journal in 2015 [1].

I am also the first author of a paper [2] on the complex, multi-wavelength study of the Type IIb SN 2013df, a spectroscopic twin of the well-known SN 1993J. Our goal was to add new understanding of both the early and late-time phases of the object, based on ground-based high-quality optical spectroscopic and photometric measurements completed with mid-infrared (mid-IR) data obtained with the *Spitzer Space Telescope* (hereafter *Spitzer*). I applied the SYNAPPS spectral synthesis code to constrain the chemical composition and physical properties of the ejecta. A principle result is the identification of high-velocity He I lines in the early spectra of SN 2013df, manifest as the blue component of the double-troughed profile at ∼5650Å. This finding, together with the lack of clear separation of H and He lines in velocity space, indicates that both H and He features form at the outer envelope during the early phases.
I also carried out the analysis of the available late-time (~250-830d) *Spitzer* data. The observed mid-IR excess indicates circumstellar interaction starting ∼1 year after explosion, in accordance with previously published optical, X-ray, and radio data. Moreover, I took part in the construction and modelling of the early-time (up to ~50 days) bolometric light curve, which allowed us to determine the main explosion parameters. These results agree well with those we got from the modelling of the late-time optical (r'-band) light curve.

I've been also playing a leading role in the study of SN 2017eaw, one of the most interesting SNe of the last year. This object is a peculiar Type II-P SN showing an early bump in its optical light curves, which suggests ongoing circumstellar interaction; such processes can be rarely observed in this Type of SNe. Shortly after discovery, we published a short telegram about the precise astrometric position of the object [3]. Our colleagues from the Konkoly Observatory (Budapest) have collected and reduced the photometric data using the telescopes at Piszkesteto, and, moreover, our group has also access to a large amount of optical spectra obtained at various sites of the Las Cumbres Observatory. I've been carrying out a comprehensive analysis on both light curves and spectra of this object comparing them to those of other normal or peculiar Type II-P explosions. At the time of writing this report, I'm working on modelling of light curves and spectral energy distributions (SEDs), which is expected to reveal the details of early CSM interaction as well as of the physical details of the explosion. We are planning to submit the research paper, with me as the first author, to a Q1 journal within 2-3 months.

PSN J14021678+5426205, an interesting luminous red nova appeared in the nearby M101 galaxy in 2015, was one of the most interesting cataclysmic events of the last years. I compared mid-IR photometry collected from the *Spitzer Heritage Archive* (SHA) with our nearly contemporaneous optical (BVRI) measurements and calculated the combined SED of the nova from the observed fluxes. The transient shows significant excess flux at 3.6 micron, which might suggest either local dust formation or the heating of some pre-existing dust in the environment of the nova. Although these results were published only in a short telegram [4], it has already received a refereed citation.

Another research project, has been running for a while, has been finished in the last part of the Grant period. In a collaboration with numerous colleagues from Hungary and from the U.S., lead by J. Vinkó, we have carried out a comparative study of absolute distances of some nearby, bright Type Ia SNe derived from high cadence, high signal-to-noise, multiband photometric data. My task was the careful reduction of the BVRI data of two of these objects, SNe 2013dy and 2014J (applying both aperture and PSF photometry). The results of the study shows that the current state-of-the-art light curve fitters (MLCS2k2, SNooPy2, SALT2.4) can provide consistent absolute distance moduli having less than ~0.1-0.2 mag uncertainty for nearby SNe Ia; however, there is room for future improvements to reach the desired ∼0.05 mag accuracy [5].

The study of the nearby, Type II-P SN 2013ej was also published in a Q1 journal [6]. I carried out the reduction of BVRI photometric data obtained at the Konkoly Observatory, which extend up to ~140d after explosion. The study, led by our collaborators at the Southern Methodist University at Dallas, revealed the main explosion parameters of SN 2013ej and allowed us to determine the distance of the host galaxy with a <10% uncertainty.

Additionally, I was a member of a large international collaboration in studying the special SN 2013fc [7]. This SN, appeared in a circumnuclear star-forming ring in a luminous infrared galaxy, was found to be a brighter 'brother' of the famous Type IIn SN 1998S. My contribution to the project was reducing of two spectra obtained with the 9.2m South African Large Telescope (SALT).

b) <u>Studying circumstellar interaction via a ground-based H-alpha imaging survey</u>

Although studying the interaction of SN ejecta and the circumstellar matter (CSM) was not highlighted as a main topic in my original research plan, I have participated in very promising researches in this field. The late-time emission caused by the interaction can be studied in various wavelength regimes (X-ray, mid-IR, radio, H-alpha). These observations offer a chance to reveal information about the type and mass-loss history of the progenitor, the presence of a companion star, and the environment of the SN.

In a U.S-Hungarian co-operation led by our colleagues at the University of Texas at Austin, we have been looking for signs of circumstellar interaction in the late phases (>1 yr after explosion) of various types of SNe. In order to extend our study to as many objects as possible, we started to undertake an H-alpha imaging campaign with the 2.7m Harlan J. Smith Telescope at the McDonald Observatory in 2014; the observations have also been carried out in the next years. Out of 99 SN sites observed to date, net H-alpha emission has been detected in 27 cases after subtracting off the continuum flux. 38 SN sites were observed on at least two epochs, from which 3 objects (SNe 1985F, 2005kl, 2012fh) showed significant temporal variation in the strength of their H-alpha emission in our data. This suggests that the variable emission is probably not due to nearby HII regions unassociated with the SN, and hence is an important additional hint that ejecta-CSM interaction may take place in these systems. Moreover, we successfully detected the late-time H-alpha emission from the Type Ib SN 2014C, which was recently discovered as a strongly interacting SN via multi-wavelength studies. As an extension of this project, our group has received observing time at several nights since 2017 at the Hobby-Eberly Telescope in order to collect complementary spectra on the most promising objects.

In order to collect further complementary data, we applied for observation time at various space and ground-based telescopes (*Chandra*, *Spitzer*, *Swift*, *VLA*) to examine SNe that seem to be interesting. I was the PI of a joint *Spitzer-Chandra* (mid-IR & X-ray) proposal (PID: 12061) in 2015 and of a *Spitzer* (mid-IR) proposal (PID: 13106) in 2016, in which we requested time for observing 10-15 SNe; moreover, our team had a *Chandra-VLA* (X-ray & radio) proposal (PID: 17500536, PI: D. Pooley), a *Chandra* (X-ray) proposal (PID: 19500329, PI: D. Pooley), and a *Swift* (X-ray) proposal (PD: 1215136, PI: D. Pooley) between 2015-2017. While all of these proposals were declined, our latest one for *Chandra-VLA* (X-ray & radio, PID: 20500421, PI: D. Pooley) has been accepted; we can observe eight targets with *Chandra* during 2019 and have received one hour of *VLA* time on each of them.

The paper presents our first results appeared in 2017 [8]. The current results of both the H-alpha and the spectroscopic survey have been presented by our U.S. collaborators at the 230th Meeting of the American Astronomical Society (AAS) in 2017 (IDs 207.01. and 207.02.), while a research paper describe our findings regarding 2004dk has been submitted to ApJ in 2018 [9] and is in the second revision round at the time of writing this report.

<u>c) A comprehensive analysis on Spitzer supernovae</u>

Connecting partly to the research work described in the previous section, I've carried out a comprehensive analysis on far the largest mid-IR dataset of SNe ever studied.

The mid-IR range offers an obvious and advantageous choice in following the late-time evolution of SNe: first, the peak of the SED of these objects shift toward the IR after the photospheric phase; second, mid-IR observations are practically free of interstellar extinction, which is also an important factor in following distant, continually fading objects. Moreover, special astrophysical processes, e.g. dust formation and/or interaction between the SN ejecta and the CSM can be also well traced with mid-IR observations, allowing to reveal the final stages of stellar evolution. In the cases of core-collapse (CC) SNe, we can get information about the pre-explosion mass-loss history of the progenitors, while in thermonuclear explosions, the presence of any CSM could serve as an evidence in a long-term debate on the possible progenitor systems. Recently, *Spitzer* has been the most essential tool to detect mid-IR radiation of SNe and to follow their years-long evolution. Within the framework of targeted surveys, more than 200 SNe have been followed with *Spitzer* to date; however, there can be even more SNe that were captured during non-SN targeted surveys, and whose data have not been analysed and published yet.

My idea was to look for such data in the SHA via creating lists from online SN databases, checking their coordinates in the SHA, and examining the dowloaded *Spitzer*/IRAC images. In total, I have checked the coordinates of more than 4500 objects in the SHA, and have found more than 1100 SN sites captured with *Spitzer* after explosion. After downloading all these data, I have examined in all cases whether there is a mid-IR point source at the given coordinates, and whether it could really connect to the SN (excluding e.g. compact H II regions in the host galaxies); for doing that, I've applied different techniques (searching for flux variations in the cases of multiepoch observations; image subtraction in the cases of available pre-explosion or very late-time images on that the SNe are not detectable).

I have identified in total 125 SNe on *Spitzer*/IRAC images, from which 51 objects have never been reported before with positive mid-IR detections. I have carried out a detailed photometric analysis of the whole studied SN sample including the re-check of the previously published data. The results include the statistical analysis of the mid-IR evolution of the different types of SNe, together with the highlighting of some objects show interesting behavior in this wavelength-range. I've also fitted blackbodies (BBs) and simple dust models to the SEDs calculated from the mid-IR data of SNe, combined them with optical data in some cases. Modelling of SEDs allows to disentangle between the possible scenarios of the mid-IR radiation (dust formation in the ejecta or in the region between forward and reverse shocks, radiative/collisional heating of pre-existing dust, IR echo), and, in some cases, to determine the main physical parameters of dust. It can be also stated that every SN with known late-time CSM interaction is bright in mid-IR; thus, *Spitzer* or other future mid-IR, large FoV detectors could be ideal "tracers" for even more special devices (e.g. JWST) in observing these processes.

I have involved a few international collaborators and one of my students to the analysis of the data. I presented preliminary results on posters at the 227th Meeting of the AAS (Kissimmee, FL, USA, January 2016) and at the *"AGB-Supernovae Mass Transition Conference"* (Rome, Italy, March 2017), as well as in the related journal volume of the conference proceedings of the latter event [10]. The extended results were presented by me in a contributed talk at the *"Deciphering the Violent Universe"* conference (Playa del Carmen, Mexico, December 2017), and on posters at the "*Supernovae - From Simulations to Observations and Nucleosynthetic Fingerprints"* workshop (Bad Honnef, Germany, January 2018) and at the *"Shocking Supernovae: surrounding interactions and unusual events"* conference (Stockholm, Sweden, May 2018).

The paper contains all the details of the research, and is ~60 pages long (in one-column style, including tables and figures), has been submitted to ApJ [11]. Although the opinion of the referee was positive, he/she suggested a moderate revision with a whole list of specific comments; at the time of writing this report, our team is ~1-2 weeks from re-submission.

It is also worth mentioning that I have been asked by J. Guillochon (Harvard-Smithsonian Center for Astrophysics), main developer of the Open Supernova Catalog, for sharing the results of mid-IR photometry of the studied SNe, which are now available at http://sne.space site.

II. COMPARATIVE SPECTROSCOPIC STUDY OF SUBLUMINOUS SNe

Based on the results on SN 2011ay described in Section I/a, I have carried out a comparative analysis of early-time (< 50 days) spectra of several Type Iax SNe using the SYNAPPS code. One of the main goals has been to find the reason of the differences between the spectra of these subluminous events and those of 'normal' Type Ia SNe. Another aim has been to find a method that enables the reliable determination of the ejecta velocities of Type Iax SNe, which is very challenging because of the strong blending caused by metal features. Since my first-author paper about SN 2011ay was among the first ones described this problem in detail, I got the chance to present my results as a contributed talk at one of the most important conferences of the SN community in the last years (*"Supernovae Through the Ages"*, Easter Island, Chile, August 2016).

As an extension of this project – with the lead of B. Barna (a PhD student of our group), and in a co-operation with several foreign researchers from ESO Garching bei München, the Queen's University Belfast, and the University of Heidelberg –, it has been aimed to find spectral solutions that give consistent chemical composition for all the observed epochs and to check the validity of the different explosion scenarios. We have been working on this problem using TARDIS, a recently developed Monte Carlo radiative-transfer spectral synthesis code. As our analysis of the spectra of SN 2011ay shows, the well-mixed atmospheric model, predicted by the so-called 'pure deflagration' explosion scenario of the white dwarf star, cannot reproduce the spectral features of the earliest epochs and causes too strong Fe lines. Therefore, the abundance profile can be separated in two different regime: a well-mixed region under 10,000 km/s and a stratified region with decreasing abundances of iron group elements above 10,000 km/s. The preliminary results of this project have been presented on a poster at the conference held on the Easter Island (Barna, Szalai et al.), while a paper containing the detailed analysis appeared in 2017 [12].

After that, we have started to carry out a first-of-its-kind comparative spectroscopic analysis of several members of the heterogeneous group of Type Iax SNe. Based on the results, similarly to our previous conclusions according to SN 2011ay, the spectral models do not fully support any of the existing explosion scenarios. On the other hand, despite the observed heterogeneity in peak brightnesses and ejecta velocities, the results suggest that all the studied SNe Iax have similar internal structures, which is an argument for their common origin. The related research paper [13] has been submitted in March 2018, and, after a very positive, second-round referee report, is expected to be accepted within days (at the time of writing this report).

I was also involved in a comparative spectroscopic analysis of Type Ia SNe led by our collaborators at the UT Austin [14]. The main result of the study is the identification of high-velocity Ca and Si features. Although I played only a minor role in this project, the professional experiences I gained have become very useful during my later work.

III. DISCOVERY, CLASSIFICATION AND STATISTICAL STUDIES OF NEW SUPERNOVAE DURING THE HETDEX SPECTROSCOPIC SURVEY

Our group is involved in the HETDEX[1] spectroscopic sky survey, which has been carrying out in test mode using the upgraded Hobby-Eberly Telescope since the end of 2015. In this phase, the main project of our group is to operate a supporting imaging survey using the 0.6/0.9m Schmidt telescope at Piszkesteto. I have been playing a leading role in the reduction and analysis of these images. Moreover, I have developed an automatic image subtracting method using HOTPANTS code, which is expected to be an important step in verifying the near-future spectroscopic discoveries of transients within the HETDEX program.

1 http://hetdex.org/

Although the HETDEX survey has finally started in 2017, it is still not operating at full capacity, which does not really support our planned SN survey in this phase. Up to now, we were able to firstly classify only a single SN, AT 2017byx, using HETDEX data [15]. Nevertheless, we have been continuing both the development of image reduction algorithms and the operation of a supporting imaging survey from Piszkesteto.

In the next years, sky surveys of great dimensions (e.g. ZTF, LSST, WFIRST) are expected to raise SN researches at an even higher level. In order to get an overview about the methodology of these surveys and to build professional relationships, I participated at several workshops and sections at the AAS#227 Meeting, as well as at the *"Preparing for Supernova Science in the LSST Era"* workshop in Pittsburgh (USA), both held in 2016.

FINAL REMARKS

a) Scientific performance

During the Grant Period, I have been the co-author of 8 papers accepted by Q1 journals (first author: 2 papers, second/third author: 2 papers), of 3 papers submitted to Q1 journals (first author: 1 paper, second/third author: 1 paper), of a single-author conference proceeding, and of 3 short telegrams (first author: 1). I participated at 6 international conferences, at which I presented 2 contributed talks and 5 posters (first author: 4, second author: 1). These numbers satisfy the expected level of scientific performance presented in my original research plan.

b) Future perspectives

Since January 2018, I have been employed by the GINOP-2-3-2-15-2016-00033 project (“Transient Astrophysical Objects”) as a postdoctoral fellow of the University of Szeged. Up to the end of this Grant (31/12/2020), I can surely continue my work at the field of supernova research, build seriously upon the results of the OTKA/NKFIH Grant period.
In the last years, I've build a strong collaboration with several foreign researchers, highlighting J.C. Wheeler (head of the Supernova Group at University of Texas at Austin), O. D. Fox (a leading expert of space astronomy at STScI, Baltimore), as well as D. Pooley (Trinity University, San Antonio, TX), O. Pejcha (Charles University in Prague), W. Kerzendorf (ESO at Garching bei München), and M. Krömer (University of Heidelberg). I have ongoing research projects with all of the listed colleagues, which is expected to guarantee further high-level results and publications.
I would like to highlight that, mainly thanks to the results described in Section I/b and I/c, I've got an invitation to a group (including some of the leading SN researchers in the U.S.) forming to write space telescope proposals for observing CSM interacting SNe in the next years. As a first success, our group has received observing time of ~25 hours with *Spitzer* in order to observe 35-40 SNe of various types in 2018/19 (PID: 14098, PI: O. Fox).

c) Involving students to research work

I have involved Sz. Zsíros, a talented BSc (now MSc) student, in the research work described in Section I/c. She received a I. prize at the Young Scientists' Conference at the University of Szeged (TDK) in 2016 under my supervision, and a V. prize at the National Conference (OTDK) in 2017. She has been a co-author of a submitted Q1 paper [11] as well as of two conference posters. Currently, she has been working on a new TDK project and on her MSc thesis work under my supervision.

As a consultant and colleague, I have been also working with B. Barna, a PhD student of our research group at the University of Szeged (now a pre-doctoral fellow at ESA Garching bei München) in the field of research described in Section II, see also publications [12] and [13].

d) Dissemination of the results

During the Grant period, I had several seminar talks at the University of Szeged, and I was also an invited speaker at the Konkoly Observatory, Budapest in February 2016 and April 2018. I have given a number of talks to high-school students and teachers in Szeged (e.g. on Researcher's Night programs, or at schools), but also in Gyöngyös, and Újvidék (Novi Sad).
I have published several articles regarding SN research at http://csillagaszat.hu website and I have an accepted paper (with J. Vinkó and Sz. Zsíros) by *Természet Világa,* a prestigious Hungarian journal in scientific dissemination, regarding research fields described in Sections I/b and I/c [16].

e) Fellowships & awards

In 2017, I received the fellowship of the UNKP-17-4 New National Excellence Program (5 months, 2018/02/01-2018/06/30, postgraduate I. Category) connecting to the fields of research described in Sections I/a (SN 2017eaw), I/b, and I/c.
Mainly thanks to the research work supported by this NKFIH/OTKA Grant, I received in 2017 the Scientific Grant of the Faculty of Science and Informatics of the University of Szeged, as well as the prestigious national "Junior Prima Prize" in the category of Hungarian Science.

LIST OF PUBLICATIONS

[1] Szalai T., et al. 2015, MNRAS, 453, 2103 (Q1)
[2] Szalai T., et al. 2016, MNRAS, 460, 1500 (Q1)
[3] Sárneczky K., … Szalai T. 2017, ATel, #10381 (short telegram)
[4] Szalai T., et al. 2016, ATel, #8891 (short telegram)
[5] Vinkó J., Ordasi A., Szalai T., et al. 2018, PASP, 130, 4101 (Q1)
[6] Dhungana G., …, Szalai T., et al. 2016, ApJ, 822, 6 (Q1)
[7] Kangas T., …, Szalai T., et al. 2016, MNRAS, 456, 323 (Q1)
[8] Vinkó J., …, Szalai T., et al. 2017, ApJ, 837, 62 (Q1)
[9] Pooley D., …, Szalai T., et al. 2018, submitted to ApJ (Q1)
[10] Szalai T. 2017, MmSAI, 88, 459 (conference proceeding)
[11] Szalai T., et al. 2018, submitted to ApJ (Q1), https://arxiv.org/abs/1803.02571
[12] Barna B., Szalai T., et al. 2017, MNRAS, 471, 4865 (Q1)
[13] Barna B., Szalai T., et al. 2018, submitted to MNRAS (Q1)
[14] Silverman J.M., …, Szalai T., et al. 2015, MNRAS, 451, 1973 (Q1)
[15] Vinkó J., …, Szalai T., et al. 2017, ATel, #10350 (short telegram)
[16] Szalai T., Zsíros Sz. & Vinkó J., *"Kölcsönhatások és porképződés a szupernóvák környezetében",* Természet Világa, 2018/08 (in press, in Hungarian)

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