# Astrophysics of supernova explosions

## NN 107637 project final report

This document summarizes the most important results obtained during the course of the project. The originally proposed timeframe was 2 years (from 2013-01-01 to 2014-12-31), which was later extended by 8 months, until 2015-08-31. The number of original participants was 6, including the PI, which was also increased later by adding 3 new research fellows and 5 students. In the followings the results are presented in the same order as they were proposed in the original work plan.

## 1. Discovery of new supernovae

**We participated in the discovery of 3 new supernovae** (SNe) made with the ROTSE-III telescope at McDonald Observatory, Texas in 2013. This was less than we expected and proposed based on the previous performance of the telescope (at least 10 SNe per year). The reason for this were the persistent technical issues that prevented continuous observing, and (mainly) the temporal termination of the regular operation of the 10m Hobby Eberly Telescope (HET) in 2014, which we planned to use extensively for spectroscopy of new SNe. The HET has not started to operate since then, which was a major loss in our instrumental resources. Still, before the termination of HET operation, **we contributed to the spectroscopic classification of 13 new SNe** discovered by other programs. Moreover, our international team made pre-discovery detection of two newly discovered, nearby SNe, which turned out to be very useful in constraining their moment of the explosion. Table 1 lists the details of our new discoveries, pre-discovery detections and spectroscopic classifications.

| SN | Type | Instr. | Action | Ref. | SN | Type | Instr. | Action | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| 2013X | Ia | ROTSE+ HET | discovery | CBET 3413 | 2013cp | Ia | HET | classification | CBET 3528 |
| 2013ag | Ia | ROTSE+ HET | discovery | CBET 3428 | 2013cr | II-P | HET | classification | CBET 3532 |
| 2013ah | Ia | HET | classification | CBET 3432 | 2013dk | Ic | SALT | classification | CBET 3566 |
| MASTER OT* | Ia | HET | classification | ATel 4932 | 2013dz | IIn | ROTSE+ HET | discovery | CBET 3589 |
| 2013be | Ia | HET | classification | CBET 3470 | 2013ej | II-P | ROTSE | pre-discov. detection | arXiv:1509.01721 |
| 2013bf | Ia | HET | classification | CBET 3471 | 2014W | Ia | SALT | classification | CBET 3819 |
| 2013bv | Ic-BL | HET | classification | CBET 3499 | ROTSE OT** | PSN | ROTSE | detection | ATel 5832 |
| 2013bx | Ia | HET | classification | CBET 3501 | 2014J | Ia | ROTSE | pre-discov. detection | CBET 3792 |
| 2013ca | II | HET | classification | CBET 3508 | 2014ao | Ia | SALT | classification | CBET 3863 |
| 2013co | Ic | HET | classification | CBET 3527 | 2015C | II | LCOGT | classification | CBET 4049 |

***Table 1**: List of SNe discovered / classified in this project*

* MASTER OT J122114.34+472950.7

** ROTSE-III OT J115442.29+440118.1

We also proposed discovery of SNe among the data flow of the HETDEX sky survey. HETDEX suffered a two-year delay with respect to its originally proposed starting date, which was absolutely unexpected, and totally prevented the successful completion of this part of our proposed work. Nevertheless, we continued the built-up of our reference database (including object lists and CCD frames) using the 60/90 cm Schmidt telescope at Konkoly Observatory, Piszkéstető. Weather permitting, we performed regular imaging of the HETDEX areas (the 245 sq. degree "Spring field" and the 150 sq. degree "Fall field"). By the end of this project we covered 224 sq. deg. of the Spring field (91 %, Fig.1a) and  143 sq.deg. of the Fall field (96 %, Fig.1b). With a few additional CCD frames we will be able to reach 100 % coverage in both fields by December 2015, which is the actual proposed starting date for the HETDEX survey.

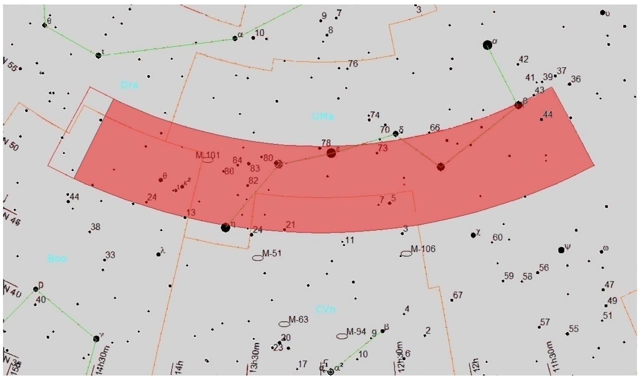

***Fig.1a**: HETDEX Spring field coverage (2015 Sept.)*

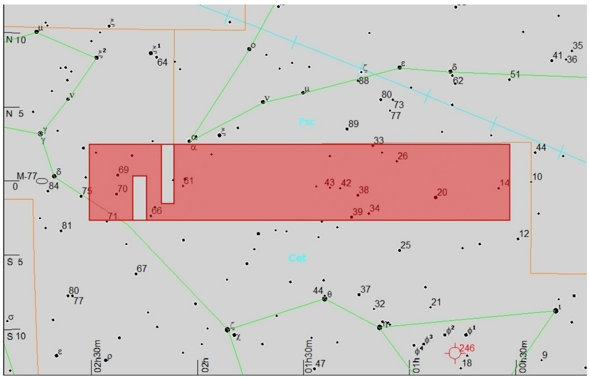

***Fig.1b**: HETDEX Fall field coverage (2015 Sept.)*

## 2. Spectroscopic and photometric monitoring of nearby SNe

Table 2 lists the SNe that were followed up using the available telescopes at Baja Observatory (BART telescope), Konkoly Observatory (Schmidt telescope), Hungary, and McDonald Observatory (ROTSE, HET), Texas. Filtered photometry was performed with BART and Schmidt telescopes using SDSS *griz* and Johnson-Cousins *BVRI* filters, respectively. Spectra were taken mostly with the 10m Hobby-Eberly Telescope. We were also allowed to apply for telescope time at the 10m South Africa Large Telescope (SALT) as part of the HET Consortium, which resulted in additional spectra for some southern hemisphere objects.  Beside these new data, we also worked on the analysis of our existing datasets on other nearby SNe taken previously.  Here we briefly summarize the most important scientific results, most of which have been already published. Details can be found in the cited papers.

### 2.a. Type Ia Supernovae:

We investigated the statistics of the appearance of the high-velocity features (HVFs) of ionized calcium and silicon (CaII and SiII) using a unique dataset containing more than 400 spectra for 210 Type Ia SNe (Silverman et al. 2015). **We found that 91 % of the studied Ia SNe showed early HVFs of CaII, and the remaining 9 % SNe all belonged to the underluminous Ia/91bg subclass. On the other hand, only 20 - 30 % of the sample showed the HVF of SiII.** At present there is no consensus on the physical cause of the HVFs, thus, our empirical results can provide important constraints for new physical models of Ia SNe. In particular, we also made detailed studies on the HVFs of SNe 2009ig (Marion et al. 2013) and 2010kg (Barna et al. 2015). **For 2009ig** we pointed out that two weeks before maximum (at -14 day) several ions may show detectable HVFs, namely SiII, SII, CaII and FeII, but after -6 days most of these disappear, or become blended with increasing photospheric-velocity features (PVFs). **We also presented observational evidence that the velocities of all HVFs, including the CaII H&K and near-IR triplet features, are consistent with each other, all being 7 - 8000 km/s above the photosphere.** This resolves the long-standing debate in the literature on whether the high-velocity component of

CaII H&K feature could be due to blending with SiII instead of being a real HVF.

| SN | Type | Instrument | Data | Reference |
|---|---|---|---|---|
| 2012ht | Ia | BART, Schmidt, HET | light curve (griz, BVRI), spectra | Vinkó et al. Chicago poster 2014 |
| 2013bh | Ia-pec | SALT | spectra | Silverman et al. 2013 |
| 2013cs | Ia | SALT | spectra | -- |
| 2013df | IIb | BART, Schmidt, ROTSE, HET | LC (griz, BVRI), spectra | Szalai et al. 2015b |
| 2013dk | Ic | SALT | spectra | CBET 3565 |
| 2013dy | Ia | BART, Schmidt, HET | LC (griz, BVRI), spectra | Zheng et al. 2013; Pan et al. 2015; Vinkó et al. Chicago 2014 |
| 2013ej | II-P | BART, Schmidt, ROTSE, HET | LC (griz, BVRI), spectra | Dhungana et al. 2015 |
| 2013fc | IIn | SALT | spectra | Kangas et al. 2015 |
| 2013fs | II-P | BART | LC (griz) | -- |
| iPTF13bvn | Ib | HET, SALT | spectra | ATel 5142 |
| iPTF13ebh | Ia | BART | LC (griz) | -- |
| 2014J | Ia | BART, Schmidt, ROTSE | LC (griz, BVRI) | Vinkó et al. Chicago 2014; Marion et al. 2015a |
| 2014dg | Ia | BART | LC (griz) | -- |
| 2014G | II-L | BART | LC (griz) | Jager, OTDK 2015 |
| ASN-14eu | Ia-pec | SALT | spectra | -- |
| PSN(M101) | LRN | BART, Schmidt | LC (griz, BVRI) | ATel 7079 |
| SNHunt275 | IIn | Schmidt | LC (BVRI) | ATel 7541 |

***Table 2**: Follow-up observations taken for nearby SNe*

**For 2010kg** we derived similar separation between the velocity of the photosphere and the HVFs. We identified several ions that produce features in between the photosphere and the HVF layer in velocity space. These "detached" features form in the SN ejecta, but definitely above the photosphere, which could provide interesting constraints for Ia ejecta models. In particular, **we detected doubly-ionized carbon (CIII) as a "detached" feature in 2010kg, which is the first convincing evidence for the presence of this ion in a SN Ia.** This may give further support for the Ia explosion model that assumes the detonation of a thin He-layer on top of the C/O white dwarf as a triggering mechanism.

**We presented observational evidence for a fading excess blue light in the very early light curve of SN 2012cg (Marion et al. 2015b). The most likely explanation for this excess luminosity is the interaction between the SN ejecta and a non-compact companion star.** Our data are consistent with recent models of such an interaction, and suggest a moderately massive companion of ~ 6 $M_{solar}$ mass.

We also built parametrized models for the spectra of several Ia SNe, including 2011ay, 2013bh and 2014J, using the public modeling code SYNAPPS. **For 2011ay (Type Iax; Szalai et al. 2015) we pointed out that early appearance of strong FeII obscures other photospheric features,** which prevents the construction of a unique physical model having a sharp photosphere. Both low-velocity (~ 5000 km/s) and higher-velocity (~ 9000 km/s) models can give adequate description of the observed spectra, which is different from the case of "normal" SNe Ia. **This might suggest**

**either different ejecta properties (maybe an asymmetric, jet-like explosion), or a different progenitor, or both.** 2013bh belonged to the extremely rare "2000cx" subclass, and our modeling showed that the spectra of such SNe are dominated by iron-group elements (Fe, Co, Ni), and doubly-ionized ions like FeIII and SiIII imply high photospheric temperatures (T > 12 000 K). Our data suggest that 2013bh synthesized ~ 1 $M_{solar}$ radioactive nickel during the explosion, which is significantly higher than the Ni-yield of most other "normal" SNe Ia (Silverman et al. 2013). On the other hand, **2014J appeared to be a relatively "normal" Ia SN**, although heavily extinguished by dust in its host galaxy (M81). We contributed to the spectrum modeling of this SN, which resulted in the possible detection of neutral carbon (CI) in the earliest near-IR spectrum. We also pointed out that **features due to MgII and OI evolve differently from other ions: the velocities of MgII and OI stay constant at ~ 14 000 km/s while the velocities of heavier elements (SiII, SII, CaII, FeII) continue to decrease toward 10 000 km/s up to 10 days after maximum.** This suggests a spatial separation of the "light" (O, Mg) and heavier (Si and others) ions, which must be connected with the (yet unknown) details of the explosive nucleosynthesis in Ia SNe (Marion et al. 2015a) .

**In the case of SN 2013dy**, a Ia discovered a few hours after explosion, we contributed to the analysis of the spectroscopic data collected by many other groups using several instruments including the Hubble Space Telescope (Pan et al. 2015). The main goal was to find any changes in the high-resolution spectra of the narrow NaD features, which are formed outside the SN ejecta. **Careful inspection of the spectra revealed no such variation in the NaD profiles, which suggests that there were no significant amout of circumstellar matter (CSM) around the explosion site**, and the observed NaD features should be formed in the interstellar medium (ISM) in the host galaxy and the Milky Way.

SN 2013dy, together with 2012cg, 2012ht and 2014J, was also followed up photometrically with BART and the Schmidt telescope at Baja and Konkoly Observatories (see Table 2). We have assembled fairly complete light curves in 8 photometric bands (griz and BVRI) from pre-maximum epochs up to ~100 days after maximum. We analyzed these light curves using the public light curve fitting codes MLCS2k2, SALT2 and SNooPy in order to test and compare the different methods and calibrations for measuring photometric distances to Ia SNe. **We found reasonable agreement between the distances derived by the different codes for 2012cg, 2012ht and 2013dy**, i.e. those SNe that were not significantly reddened by interstellar dust. However, 2014J was heavily extinguished by non-standard dust in M81, which strongly compromised the photometric analysis of that event. We are still working on modifying the treatment of non-standard reddening in the MLCS2k2 code, which will hopefully result in more reliable distance for 2014J. These preliminary results were presented as a poster contribution on the *Type Ia Supernovae* conference in Chicago in September, 2014, the final results will be published in a regular paper.

### 2.b. Core-collapse Supernovae:

Our motivation for studying nearby core-collapse (i.e. Type II and Ib/c) SNe was twofold: determining reliable distances to them, and getting new information on the possible progenitors of Type Ib/c ones. SN 2011dh (Type IIb) seemed to be a good test case, as its progenitor was identified on pre-explosion images. Our study (Marion et al. 2014) revealed that **SN 2011dh had much lower amount of hydrogen in its envelope that most other Type II SNe**: from the analysis of the H and HeI features we pointed out that the H-rich envelope became transparent (optically thin) by 11 days after explosion, while in most Type II events the H-rich ejecta remain optically thick for ~ 100 days. Surprisingly, the presence of HeI was also found in the spectrum of SN 2012ap (Milisavljevic et al. 2015), which was a broad-lined Type Ic SN, i.e. an event where He was not supposed to be present. Further analysis of the He features, involving both optical and near-IR spectra, may provide interesting new details for the enigma of the progenitors of stripped-envelope SNe. As a prelimiary example, **our in-depth spectroscopic analysis of SN 2013df (another Type IIb SN, having**

**thinner H-rich envelope) revealed the appearance of high-velocity HeI features that are clearly formed above the He-rich core, in the shock-heated cooling envelope (Szalai et al. 2015b).**

**We successfully applied the Expanding Photosphere Method to measure distances to the Type II-P SNe 2009N and 2013ej** (Takáts et al. 2014; Dhungana et al. 2015). In the latter case we combined our new data with pre-existing measurements for SN 2002ap (broad-lined Ic) which appeared in the same host galaxy as 2013ej. Using this technique we could further improve the reliability of the calculated distances (22 ± 1 Mpc and 9 ± 0.5 Mpc for 2009N and 2013ej, respectively).

## 3. Super-luminous supernovae: explosion mechanisms and ejecta properties

Our original workplan proposed the study of 1-2 newly discovered Super-luminous SNe (SLSNe). However, the loss of the availability of HET and SALT in 2014 prevented the study of such new events. We took spectroscopic observations on SN 2013fc with SALT, which was originally thought as a Type II SLSN, similar to 2006gy. However, it turned out that this SN was of a regular Type IIn that did not brighten up to the peak brightness level of SLSNe (-21 mag). Nevertheless, we contributed our SALT spectra to an international collaboration led by the PESSTO group (Kangas et al. 2015). That study pointed out the spectroscopic similarity between 2013fc and other Type IIn SNe.

**We used our pre-existing data to investigate the likely input power mechanism of 10 SLSNe.** Three different physical models were fit to the light curves of these SLSNe: the traditional radioactive decay of Ni and Co (#1), the spin-down of a highly-magnetized neutron star (#2) and shock-wave heating of the surrouding CSM (#3). We found (Chatzopoulos et al. 2013) that model #1 alone can be ruled out, because the necessary Ni-masses are larger than the ejecta masses derived from the light curves. However, both the magnetar- and the CSM-interaction model can account for the observed light variations. **Our study favored the CSM-interaction as the more likely mechanism that powers most (maybe all) SLSNe**, but a simultaneous presence of either (or all) mechanism cannot be ruled out.

**We developed a new modeling code which computes the bolometric light curve of a supernova by taking into account recombination processes in the outer part of the ejecta** (Nagy et al. 2014). This code uses various input power mechanisms, like the Ni-Co radioactive decay or magnetar spin-down, which were used in the fitting of SLSNe light curves described above.

The P.I. also contributed to the study led by another international team to observe host galaxies of previous SLSNe (Leloudas et al. 2015). That study revealed that H-poor SLSNe tend to appear in metal-poor galaxies which show extremely strong emission lines, in contrast to H-rich SLSNe that occur in galaxies with much softer radiation fields. There seems to be a likely correlation between the extreme environment and the (yet unknown) progenitors of H-poor SLSNe.

## 4. Other interesting transient objects

In January, 2009, ROTSE discovered a mysterious transient object, nicknamed "Dougie", that looked very similar to a young SLSN, showing blue, featureless spectra and reaching -22 absolute magnitude at its light curve peak. We completed the analysis of the extensive dataset collected on this transient and its host galaxy. **By examining four types of different physical models, we found that "Dougie" was most probably a Tidal Disruption Event (TDE), i.e. a ~ 2 $M_{solar}$ star torn apart by a moderately massive ($M < 10^5$ $M_{solar}$) black hole** (Vinkó et al. 2015).

We also contributed our SALT spectra, collected on the known supernova impostor (i.e. a Luminous Blue Variable, LBV) SN 2009ip during its big outburst in 2012, to an international collaboration led by our partners at CfA, Harvard. These spectra were useful to reveal that, despite reaching the brightness range of real SNe in its light curve, SN 2009ip did not experience a terminal explosion, and the massive LBV star very probably survived the giant outburst (Margutti et al. 2014).

In 2015, during the extension of our project, we started to monitor two similar events from Baja and Konkoly Observatories. The first object, PSN J14021678+5426205 in the M101 galaxy (Fig. 2), turned out to be an "Intermediate Luminosity Red Transient" (ILRT). We assembled a well-sampled light curve in 8 photometric bands (Vinkó, Sárneczky & Szing, ATel 7079) and also collected good-quality pre-outburst measurements on the progenitor star from public archives. The analysis of these data is still underway, the preliminary results point toward a massive binary progenitor having two nearly ~20 $M_{solar}$ stars. The final results will be published in a regular paper. The other object, named SNHunt275, was classified as a supernova impostor in 2013. This object showed a giant outburst in 2015, which we observed with the Schmidt telescope at Piszkéstető. Our team was the first who pointed out that this object reached -17 absolute magnitude in its light curve (Vinkó, Sárneczky & Vida, ATel 7541) which makes it likely that it finally exploded as a real SN. We plan to continue collecting data on this transient, after emerging from solar conjunction later this year, which will hopefully result in more published results.

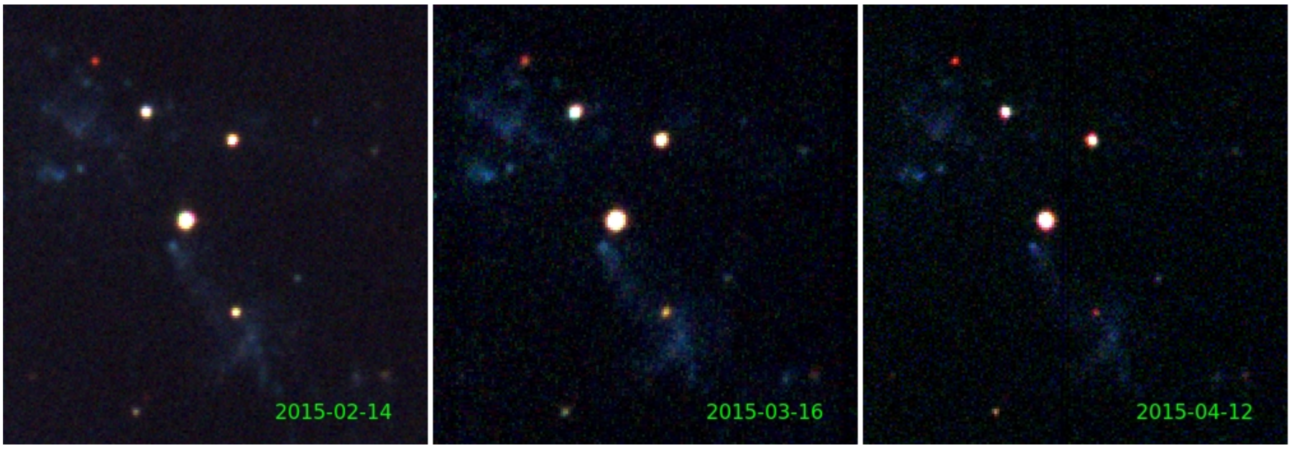

***Fig.2***: *The fading of the red transient in M101 as seen from Piszkéstető, Hungary*

## Conferences, traveling

The team members have actively participated on international conferences and meetings, where the results from the project were presented.

In 2013 Vinkó, Sárneczky and Szalai attended the annual HETDEX meeting in Potsdam, Germany, where Vinkó gave an oral presentation on the planned program of discovering supernovae in the HETDEX data flow.

In 2014, Szalai gave a poster presentation on the Nuclei in the Cosmos XIII meeting in Debrecen, Hungary, while graduate student A. Nagy took part in the graduate school of the same NIC conference. Székely presented a poster containing some additional results on the CAASTRO Annual Meeting at Coffs Harbour, Australia. Vinkó and Szalai also participated on the "Type Ia Supernovae" meeting at University of Chicago, IL with two posters.

In 2015 graduate student B. Barna made a very successful poster contribution on the "51 Erg (FOE)" meeting in Raleigh, NC showing his results of C III detection in a Ia SN.

Vinkó, Szalai and Sárneczky were involved in some of the observations taken at McDonald Observatory, Texas, in 2014 and 2015.

The project attracted many students, who were working very actively during the project. A.

Nagy and A. Ordasi participated in the 2014 MESA Summer School in Santa Barbara, CA. A. Szing and A. Soltész took part in the regular observing with the telescopes at Hungarian institutes. Z. Jäger used our data taken with the BART telescope at Baja Observatory for his student project that he presented on the XXII National Scientific Student Conference (OTDK) at Cluj-Napoca, Romania.

In addition to the group members, we also would like to express our thanks to the staff at Konkoly Observatory, Hungary, who actively participated as volunteer observers in completing our excessive observational program. Their contribution was essential in obtaining the massive amount of new data collected during this project.

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