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Extragalactic panel
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Probing the explosion mechanism of core collapse supernovae through nebular phase photometric and spectroscopic observations

Abstract

An important unsolved problem in astrophysics is how massive stars explode at the end of their lives as supernovae (SNe). The neutrino heating mechanism is still the favorite, but there are growing theoretical and observational evidences that the energy input generated by a strong magnetic field of rapidly differentially rotating protoneutron star core (magnetar) can contribute significantly. In order to investigate the possible energy input provided by the magnetar in stripped envelope core collapse SNe (SE-SNe), we propose to carry out photometric and spectroscopic observations of 10 SE-SNe in the nebular phase.

Observing Blocks

Instrument/Telescope	Req. time	Min. time	1^{st} Option	2^{nd} Option
CCD Camera/Speculoos	18 nights	9 nights	Any Any	Any Any
TRAPPISTCAM/TRAPI	18 nights	9 nights	Any Any	Any Any
IMACS/Magellan / Baade	2 nights	0 nights	Any Any	Any Any
LDSS3/Magellan / Clay	2 nights	0 nights	Any Any	Any Any

CoIs

Name	Institution	e-mail	Observer?
Bastian Ayala	UNAB	b.ayalainostroza@gmail.com	False
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Mauricio Ramirez	UNAB	m.ramirezvalenzuela@gmail.com	False
Raya Dastidar	UNAB	rdastidr@gmail.com	False

Status of the project

- Past nights: 18
- Future nights: 0
- Long term: False
- Large program: False
- Thesis: False

List of Targets

ID	RA	DEC	Mag
SN2024xxx	12:00:00	00:00:00	V=19.0
SN2024yyy	12:00:00	00:00:00	V=19.0

SCIENTIFIC AIM AND RATIONALE

An important unsolved problem in astrophysics is how massive stars explode at the end of their lives as supernovae (SNe) (e.g. Janka 2012). The neutrino heating mechanism is still the favorite, but the energy input generated by a strong magnetic field of rapidly deferentially rotating protoneutron star core (magnetar) can contribute significantly. Such mechanism has been claimed as the main source of luminosity for superluminous SNe (SLSNe) that are explosion which are 10-100 times brighter than core collapse SNe (CCSNe). Nevertheless, recent theoretical studies have started exploring the role of magnetar energy input also in "normal" stripped-envelope CCSNe (SE-SNe) (Ertl et al., 2019), where the progenitor star has either completely (SNe Ic and SN Ib) or mostly (SN IIb) lost its hydrogen envelope prior to the explosion. For SE-SNe, in a pure neutrino driven explosion, the radioactive decay of ^{56}Ni into ^{56}Co, which has a half time of 6.1 days is the main source of the SN luminosity around maximum light. On the other hand, the radioactive decay of ^{56}Co into ^{56}Fe, which has a half time of 77.1 days, is the main source of the SN luminosity at late phases ($>$ 60 days post explosion) in the so call nebular phase. Currently the most reliable method to estimate ^{56}Ni masses uses the bolometric luminosity at nebular phases, which can be modeled as:

$$L(t) = M_{Ni}((\epsilon_{Ni} - \epsilon_{Co})e^{-t/t_{Ni}} + \epsilon_{Co}e^{-t/t_{Co}})(1 - e^{-(T_o/t)^2}) \tag{1}$$

Where t is the time since the explosion, ϵ_{Ni} and ϵ_{Co} are the specific heating rates of ^{56}Ni and ^{56}Co decay, and t_{Ni} and t_{Co} are their corresponding decay timescales. Finally, T_0 is a time scale that accounts for the fraction of energy of γ-rays and e^+ that is thermalized in the ejecta. The bolometric luminosity $L(t)$ can be estimated from multi-band photometry, therefore the only unknowns in equation (1) are M_{Ni} and T_0 that can be determined by fitting the slope and overall normalization of the radioactive tail of the light curve (see Fig. 1).

Once obtained the value of M_{Ni} from Equation (1), it is possible to estimate the bolometric SN luminosity at peak brightness through the following equation:

$$L_{peak} = \frac{2\epsilon_{Ni}M_{Ni}t_{Ni}^2}{\beta^2 t_p^2}[(1 - \frac{\epsilon_{Co}}{\epsilon_{Ni}})(1 - (1 + \beta t_p/t_{Ni})e^{-\beta t_p//t_{Ni}}) + \frac{\epsilon_{Co}t_{Co}^2}{\epsilon_{Ni}t_{Ni}^2}(1 - (1 + \beta t_p/t_{Co}))e^{-\beta t_p//t_{co}})] \tag{2}$$

Where t_p represents the time elapsed from the moment of the explosion to when the supernova reaches its peak bolometric luminosity, while β is a dimensionless parameter sensitive to several physical effects related to the explosion mechanism. Afsariardchi et al. (2022) calibrated the value of β using Dessart et al.'s (2016) models, which are based on a pure neutrino-driven explosion, obtaining $\beta = 1.125$. By entering the values of β and t_p (which is straightforward to measure from the bolometric light curve) into equation (2) one can obtain the peak bolometric luminosity of the SN in the pure neutrino driven explosions. Therefore, the eventual extra energy input required to reach the observed peak luminosity of the SN should be either due to the energy released by a central engine and/or by the possible interaction of the SN ejecta with the CSM produced by the progenitor system. However, caution should be exercised when interpreting these "excess luminosity" values as they do not account for variations from $\beta = 1.125$ that can be caused by effects such as enhanced nickel mixing and asymmetries in the explosion. Additionally, Equation (2) assumes that the radioactive component peaks at the same time as the observed light curve, which may not always be the case depending on the nature of the excess luminosity source. These shortcomings can be overcame if these excess luminosity values can be computed for a statistically significant sample and correlated with a set of SNe observables such as wideness, rise and decline time of the light curve, and the ejecta expansion velocities as measured from the minimum of the P-Cygni profiles. The latter will also help on disentangle if is the magnetar input or the CSM interaction the main source of the excess luminosity.

It is worth noting that the presence of a central engine should also introduce detectable asymmetries into the SN ejecta (i.e. Soker & Gilkis 2017). The presence of asymmetries in the core of the SN explosion can be estimated from the line profile in the SN nebular spectra, in particular the [OI] $\lambda\lambda$6300,6364 emissions (see Fig. 2) (Taubenberger et al 2009, Fang et al. 2022). We plan to correlate the luminosity excess measured from the light curve with the degree of asymmetry we can estimate from the nebular spectroscopy in the same SN sample. This will provide further insights on the nature of the extra energy source. Summarizing, to carry out the proposed analysis we need:
(1) A well constrained estimation of the explosion time, which we can obtain from the combination of the high cadence $\sim$ 2 days wide field surveys such the Zwicky Transient Facility (ZTF) and the Asteroid Terrestrial-impact Last Alert System (ATLAS).
(2) A well sampled early light curves that we are obtaining through our own and collaborators monitoring programs. Among the latters we can mention the Precision Observations of infant Supernova Explosion (POISE), which is monitoring during a two months campaign every semester a sample of $\sim$20 SNe discovered soon after the explosion with a nightly cadence in the BVugri filters.
(3) Multiple (at least four) photometric measurements covering a wavelength range as broad as possible during the radiative tail of the light curve, (i.e., epochs >60 days). This will enable us to calculate the bolometric luminosity $L(t)$ in the nebular phase and therefore estimate M_{Ni} and T_0. We aim to obtain these data through the proposed observations. The NIR contribution to the bolometric luminosity increase its importance in the radiative tails of the SNe. NIR observations are very time consuming for objects in the magnitude range that we are probing (19-21). Therefore, we plan to use the bolometric corrections (BC) reported in Rodriguez et al. 2022. It is worth mentioning that the uncertainties in the estimation of the SN distance will not affect our calculation of the luminosity excess, because it will impact in the same way the bolometric luminosity of the SN in both the photopheric and nebular phases.
(4) Nebular phase spectroscopic observations to estimate asymmetries in the explosion. We aim to obtain these data through the proposed observations. **It is worth stressing that the spectroscopic observations increase significantly the scientific return of the photometric observations, but photometry is valuable by its own.**
During 2023A 12 SE-SN suitable for the proposed observations were active in the sky reachable by the facilities that we are requesting through this application, therefore, conservatively, we propose to follow-up 10 SE-SN during 2024A. We close stressing the fact that the sample reported in Afsariardchi et al. 2022 consist in 20 SE-SNe (8 IIb, 8 Ib, 4 Ic), therefore with the proposed observation we will increase of 50% the sample for which our study can be carried out. It is worth also mentioning that among these 20 SNe, 16 SNe has nebular spectra.

References:
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Ertl T. et al. 2020, ApJ, 890, id.51
Fang, Q. et al, 2022, ApJ, 928, 151
Janka T. 2012, Annual Review of Nuclear and Particle Science, vol. 62, issue 1, pp. 407-451
Rodriguez, O. et al. 2022, ArXiv:2209.05552
Soker N., Gilkis A. 2017, ApJ, 851, id. 95
Stritzinger M. D., et al. 2018, A&A, 609, A135
Taubenberger, S., et al. 2009, MNRAS, 397, 677

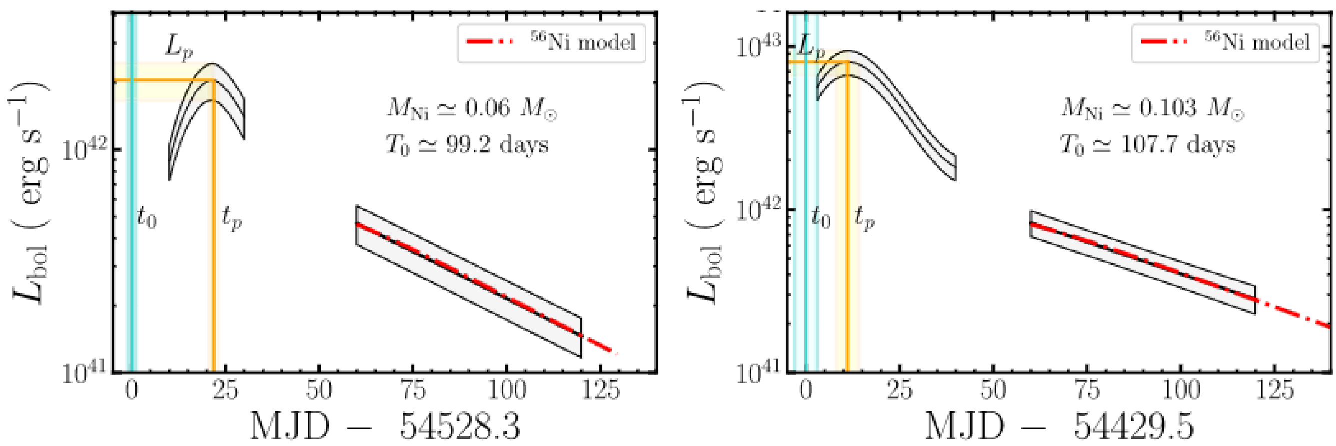

Figure 1: Bolometric light curves for SN 2008ax (left panel) and SN 2007ru (right panel). The cyan vertical line indicates the epoch of explosion, while the vertical and horizontal orange lines denote the peak time t_p and peak luminosity L_p of the bolometric light curves, respectively. The dotted-dashed red curve in the lower panels represents the best-fit ^{56}Ni model of Equation (1) to the bolometric radioactive tails. Figure adapted from Afsariardchi et al. 2022.

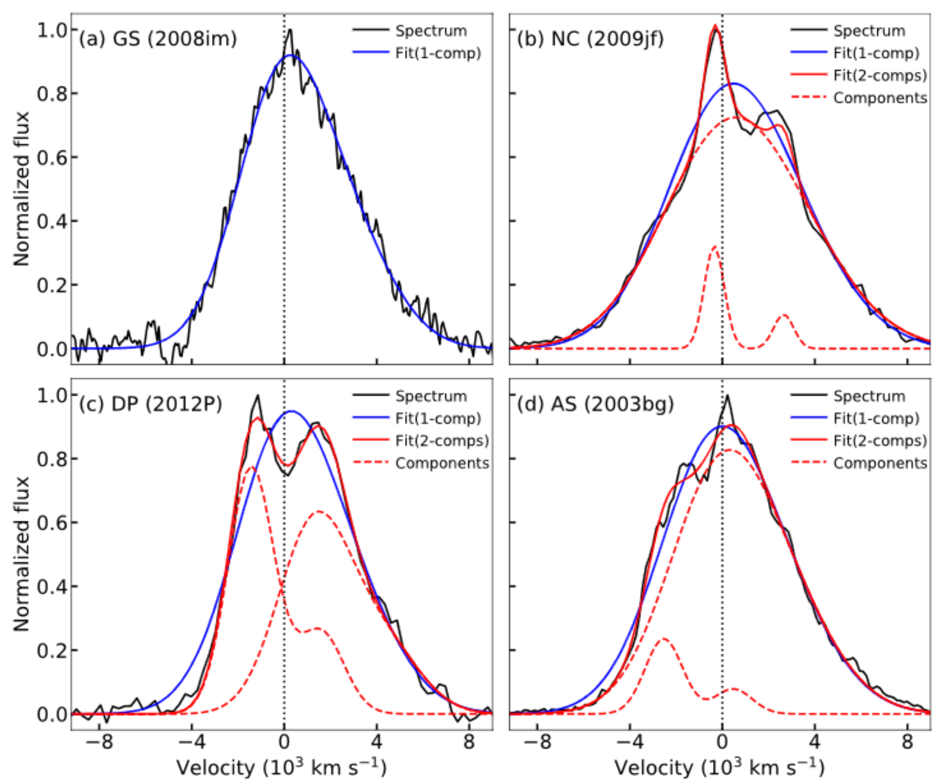

Figure 2: Examples of [OI] $\lambda\lambda$6300,6364 line profiles observable in the nebular spectra of SE-SNe. Figure adapted from Fan et al. 2022.

TECHNICAL DESCRIPTION

The perfect telescope for the photometric part of the proposal would has been the SMARTS 1.0m, but as reported in the call for proposal it will not available during 2024A. We therefore plan to use the combination of two telescopes for the proposed observations: The 1m Speculoos which is equipped with the Sloan griz filters and the 60cm TRAPPIST telescope which is equipped with the Johnson-Cousin BVRI filters. Please note that the BC reported in Rodríguez et al 2022 are computed for several combinations of both the Sloan and Johnson-Cousin bands, therefore having both photometric systems will allow us to keep under control possible systematic errors in the BC calculations. The TRAPPIST time for the Chilean community is scheduled as a night every 10 days (usually the 1st, 10th and 20th of each months). As reported in the document describing the Chilean community access to Speculoos, the time is also scheduled as blocks of 3 nights every ∼10 days. The scheduling of both facilities match well the cadence we need to follow-up SNe in the radiative tail.

To get a reliable photometric measurement we need a S/N∼7.0. Base on the data collected with TRAPPIST in the past, we estimate the following exposure times for the BVRI bands to reach such S/N: 19 mag (V,R,I texp=8.0 min., B, texp=15.0 min), 20 mag (V,R,I texp=20.0 min., B, texp=40.0 min) and 21 (V,R,I texp=50.0 min., B, texp=100.0 min). For Speculoos our estimations are: 19 mag (g,r,i, texp=5.0 min., z, texp=10min), 20 mag (g,r,i, texp=15.0 min., z, texp=30min) and 21 (g,r,i, texp=30.0 min., z, texp=60min). It is worth noting that z band imaging is important to quantify the IR contribution at epochs later then ∼150 days where the BC of Rodríguez et al 2022 are not available. It is very difficult to make a detailed calculations of the time necessary to observe the proposed sample of SNe because at each epoch the magnitude of a SN will depend of its type (i.e. light curve shape), brightness at peak and phase. Nevertheless, through a first order calculation, we estimate that a whole night every ∼10 days will be enough to meet the S/N required.

Summarizing, our request includes 18 nights for both TRAPPIST and Speculoos. Maintaining a 10 days cadence is important to trace the radiative tail evolution, but in the case of telescopes over-subscription a 20 days cadence will be still acceptable. Nevertheless, it is crucial that the allocation spans the entire semester.

For the complementary spectroscopic observations we plan to use either the LDSS3 spectrograph mounted on the Clay telescope, or the IMACS spectrograph mounted on the Baade telescope. This guarantee more flexibility in scheduling our proposed observations. The FWHM of the emission lines in the nebular spectra of SE-SN range between 100Åand 200Å, therefore for LDSS3 we plan to use the VPH-All grism that cover all the wavelength range of interest with a maximum efficiency in the wavelength interval where the [OI] $\lambda\lambda$6300,6364 emissions are present. In the case of IMACS we plan to use the grating Gra-150. For both spectrograph we plan to use a slit of 1" or wider depending of the seeing conditions. Following the recipe of Taubenberger et al. 2009, the nebular spectrum has to acquired later than 100 days after the explosion. At such phase the SE-SNe will have a magnitude ranging between 20 and 21, therefore, base on our experience with both spectrographs, to reach the required signal-to-noise ratio (> 15) to study the line profile, we will need on average $\sim 1.5h$ for each target. To carry out the planned spectroscopy observations for the 10 targets we request two nights of LDSS3 or IMACS in grey/dark time (ideally one in March/April and one in June/July).

CURRENT STATUS OF THE PROJECT

The data obtained so far with TRAPPIST and Speculoos have fully reduced. We also fully reduced and analyzed the spectra we obtained with LDSS3 in August. The second night with LDSS3 is scheduled for January 2024.

STUDENT THESIS

These data represent a relevant contribution to the PhD thesis of Bastian Ayala. The aim of his thesis, in fact, put constraints of the explosion mechanism and progenitor of CCSNe studying the luminosity excess for different types of SE-SNe and explosion possible correlation of such excess with the degree of asymmetry in the SN ejecta.