Semester: 2023b
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Project No. 1: Precision Observations of Infant Supernova Explosions

Priority: 1

Co-Investigators: Phillips, Morrell, Piro, Polin (Carnegie) + an international team of collaborators (see footnote on page 3 of Scientific Justification)

Observing Runs:

No.	Blocks	Nights	Max Moon	Telescope	Instr. One	Instr. Two	Service	In Person	Observers
1	2023_D10 (2023_D10-2023_D11)	3	|10|	Baade	IMACS f/2	FIRE	No	Yes	Burns, Hsiao, Morrell, Phillips, Polin
2	2023_D11 (2023_D11-2023_D12)	3	|10|	Baade	IMACS f/2	FIRE	No	Yes	Burns, Hsiao, Morrell, Phillips, Polin
3	2023_D10 (2023_D10-2023_D12)	60	|14|	Swope	Direct		No	Yes	Burns, Morrell, Phillips, Polin, Students

Conflicts:

None

Special or Additional Requirements:

We ask that the 6 Magellan Baade nights be scheduled as individual nights spread evenly between Oct.15 and Dec. 9, avoiding the dates closest to full moon. We request to be scheduled on the Swope from Oct. 15 to Dec. 9. Swope is used to validate targets, so it is crucial that the Baade nights be scheduled during our Swope run.

Abstract:

Project 1

We request time on the Baade and Swope telescopes in the months of 2023 October-December to obtain an unprecedented data set of early-time spectra and photometry to investigate the progenitors of supernovae (SNe) and how they explode. With the advent of improved wide-field transient searches, a machine-learning-based alert broker, and multi-color pre-screening with the Swope telescope, we can ensure a high likelihood of very young SNe for our optical and near-infrared follow-up observations. Very early-time observations will allow us to measure the conditions at the outermost layers of the ejecta and distinguish between the explosion and progenitor scenarios across multiple types of SNe. These data can help determine the cause of the early color diversity in Type Ia SNe. For stripped-envelope SNe, very early spectral data will reveal the chemical structure of the outer layers of the progenitor star, and allow us to distinguish between mass loss mechanisms. In the case of Type II SNe, these early-time data can reveal three early fronts: the light flash, the reionization phase, and the hydrodynamical shock and provide details of the physical conditions of the progenitor star. Our successful observing runs during the 2021A to 2022B semesters show that we can find and confirm roughly 10 early candidates a month within 3-4 days of last non-detection. The advent of new ATLAS facilities in Chile and South Africa will increase this number.

Target List:

1- The main spectroscopic targets of this proposal are ~4-5 as yet undiscovered supernovae. Most Swope targets are yet to be discovered.

2- Follow-up Swope observations of previous POISE SN fields for galaxy template images and photometric calibration:

SN	Coordinates
2022aacn	00:44:26.44 +07:22:28.11
2022ywf	01:22:12.20 +00:57:23.59
2022abvt	01:30:43.44 -31:30:51.92
2022abic	02:59:09.29 -04:28:16.29
2022acko	03:19:38.97 -19:23:42.87
2022zkc	04:47:58.58 -16:39:37.00
2022aanx	05:35:05.15 -66:07:21.60
2022zlz	05:43:05.38 +00:37:13.90
2022abwj	05:56:41.50 -26:33:41.35
2022aaxy	08:30:48.42 -30:35:44.90
2022abdh	08:39:08.04 -08:51:47.66
2022esa	16:53:57.60 -09:42:10.08
2022aagp	09:10:41.91 +07:12:20.44
2022acwj	09:14:24.34 -33:20:14.80
2022aatx	09:15:15.32 +11:53:04.62
2022abzc	10:20:20.98 -40:23:43.10
2022abgs	11:03:00.19 -16:17:19.79
2022zkg	21:25:02.22 -39:49:07.80
2022aaah	22:11:41.50 -35:22:47.79

Precision Observations of Infant Supernova Explosions (POISE)

1. Science Justification

Supernovae (SNe) are the cataclysmic end points of massive stars and white dwarfs. As cauldrons of nucleosynthesis, they provide the interstellar medium with most of the metallic mass while their enormous kinetic energies (~10^{51} ergs) drive galaxy evolution. With their high intrinsic peak luminosity, SNe serve as excellent cosmological distance indicators and can be used to map out the expansion history of the universe. Yet much of what we know about the physics of SNe and their progenitors is based on observations of objects obtained well past explosion. To expand our understanding of SN origins, we need rapid-cadence observations obtained in the first few hours-to-days after explosion. From these very early phase observations, we can estimate key explosion parameters, distinguish between leading explosion models, and study the local environment of these cosmic explosions. Early observations can also provide information on the mixing processes during the explosion. Catching SNe as early as possible requires triggering observations of objects that have yet to be classified. However, there is much to learn about all classes of SNe, as we outline below.

Early Type Ia Supernovae (SNe Ia) -- Only a dozen published normal SNe Ia have been caught within 3 days of explosion. Their early light curves reveal significant diversity (Stritzinger et al. 2018) that cannot be investigated with photometry alone. Possible explanations of this diversity include: the collision of SN ejecta with a non-degenerate companion, interaction between the SN ejecta and circumstellar material, composition/opacity differences between explosions, different distributions of high-velocity ^{56}Ni, and different progenitor scenarios. Obtaining spectra immediately after explosion enables us to study the outer (10^{-5}–10^{-2} $M_{\odot}$) ejecta to make precise kinetic energy measurements (see Fig. 1, left panel), detect its chemical structure, and ascertain the nature of the accreting surface layer. For example, the explosive He burning in the double detonation scenario may leave traces of He and produce 44Ti and 56Ni, while leaving little unburned C (Fink et al. 2010; Jiang et al. 2017). On the other hand, the delayed detonation scenario predicts C, O, and possibly Si at early times with accreted burning products detectable up to 2 days post-explosion (Mazzali 2001; Blondin et al 2013; Hoeflich et al. 2017). The addition of NIR spectra can provide a more sensitive tool for detecting He and the recombination of C (Hsiao et al. 2019).

Early Stripped Envelope Supernovae (SESNe) -- It is still highly uncertain how SE-SNe lose their envelopes. For SNe Ic in particular, it is unclear how the star is stripped of its hydrogen and helium layers or if the helium is mixed into a layer where it can be burned. Detecting residual He in SNe Ic immediately after the explosion could differentiate between different mass loss scenarios (e.g., Smith 2006, Smith & Owocki 2006, Hachinger et al. 2012). Early observations of Type Ib SNe can catch flash features, indicating the presence of CSM that would be evidence of a period of enhanced mass loss. Our study of the near-infrared (NIR) spectral features suggests that the He I 2.0581 micron line can be a distinguishing feature between the He-rich and He-poor groups (Shahbandeh et al. 2022). Early spectra can also reveal clues about the “shock cooling emission,” a poorly-observed phenomenon seen in some Type Ib/c and IIb (Bersten et al. 2018). Our proposed observations can be a powerful tool for studying asymmetries and progenitor radii. We can also investigate rare objects that have extreme characteristics and push models in new areas of parameter space (see Fig. 1, right panel).

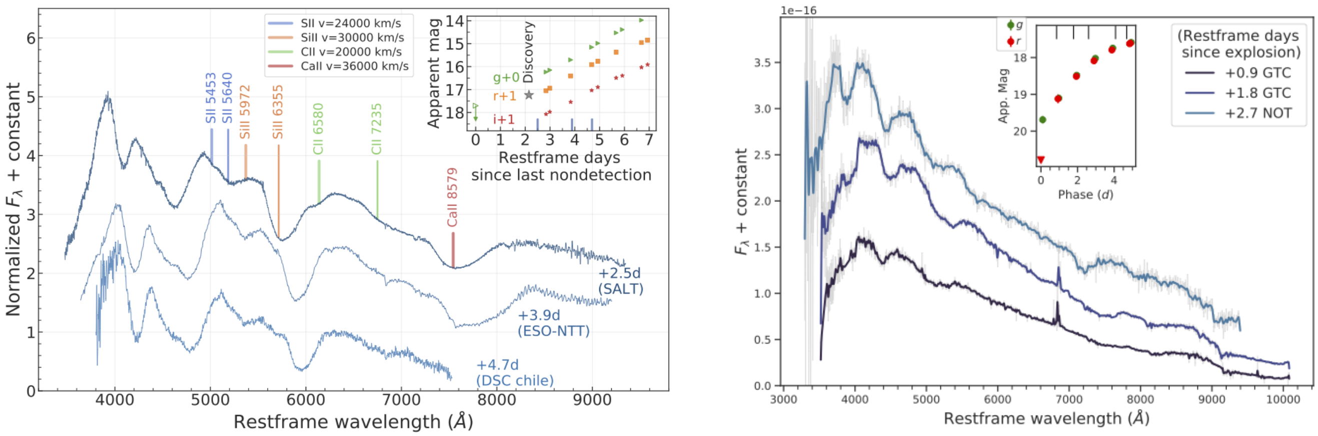

Figure 1: (Left) Early-time spectra of SN 2021aefx. The extreme velocity shift in the outermost layers can be observed. Early-phase spectra of this quality allows the chemical fingerprints of the outermost layers to be quantified and measured. High-precision multi-band light curves are also shown at early phases. The first spectrum was taken on the South African Large Telescope (SALT). (Right) Very early phase observations of SN 2020lao, a ZTF target from ALeRCE discovered within one day of the last non-detection. Observations at GTC and NOT provided multiple high-quality spectra within the first 48 hours, revealing SN 2020lao to be one of the highest velocity Ic-BL SNe ever observed with ejection velocity near 10% the speed of light and the youngest Ic-BL without an associated GRB. In both panels, insets show the light curves with vertical lines denoting epochs at which spectra were taken.

Early Type II Supernovae (SNe II) -- SNe II are the explosions of massive stars (> 8 $M_\odot$) that have retained a significant portion of their hydrogen envelope. Early photometric (Morozova et al. 2017; Förster et al. 2018) and spectroscopic (Yaron et al. 2017) data indicate that many SNe II are surrounded by dense circumstellar material which is connected with increased winds and outflows of massive stars near the end of their lifetimes. The origin of this increasingly violent activity is unknown, with possible sources being unstable burning (Smith & Arnett 2014) or convection driven gravity waves (Fuller 2017). Multiple spectra within the first 4-5 days after explosion are necessary to investigate: i) the shock breakout flash, which probes the shallowest layers of material; ii) flash spectroscopy features, which measure the composition, density and extent of low density circumstellar material; and iii) the subsequent shock cooling emission, which teaches us about the radius of the progenitor and dense circumstellar material close to the star. There is very sparse data at these early phases and spectra are needed, both in the optical and NIR (Davis et al. 2019) to understand the outer structure, kinematics, and composition of these progenitor stars to provide constraints on the origin of the surrounding circumstellar material, and help develop a more complete picture of how the interiors of massive stars near the end of their lives affect the outer surface layers.

Rapid Transients This broad category of heterogeneous objects sits in an area of the time scale-brightness space that is difficult to routinely get comprehensive observations for, until now. When these observations are obtained, they often point to novel mechanisms that are shown to be possible in nature (e.g., Kasliwal et al. 2010). Our strategy will be effective at identifying these objects (3 objects per semester) and obtaining comprehensive data, even for objects with rapid light-curve declines as extreme as 1 mag per day. These data are scarce, and the proposed observations will provide the sorely needed spectra which will reveal details of the chemical structure and explosion kinematics.

Our program's objective is to obtain rapid-cadence early-phase photometric and spectroscopic observations to gain a better understanding of supernovae and their progenitors. We are part of an international collaboration of supernova researchers in Argentina, Chile, Europe, and the USA[1] who share the goal of combining telescope resources in Chile, Hawaii, and La Palma to study supernovae discovered within hours of explosion. In the following, we describe the experimental design, with emphasis on the central role of the proposed observations with the Swope and Magellan telescopes within this collaboration.

2. Experimental Design

Candidate supernovae will come primarily from the Zwicky Transient Facility (ZTF; Bellm et al. 2019) and ATLAS (Tonry et al. 2018) transient surveys. The ATLAS project currently has two telescopes in Hawaii that scan the whole sky to magnitude 20 with a 2-day cadence, and have added telescopes in Chile and South Africa that will improve the cadence to twice per night. A machine-learning-based alert broker "ALeRCE" (Automatic Learning for the Rapid Classification of Events), developed by a team at the Center for Mathematical Modelling (CMM) of the Universidad de Chile and the Instituto Milenio de Astrofísica (MAS), will sift through the alert streams to categorize and rank the candidates. To limit the number of evolved SNe, each candidate will be required to have a last non-detection limit within 72 hours of discovery and a rapid increase in brightness of > 0.2 mag per day since the last non-detection. These new candidates ranked by ALeRCE are ingested into the 1-m Swope queue via the CSP marshal to obtain *ugriBV* images. This step of Swope pre-screening confirms a candidate, providing early colors and magnitudes for a preliminary classification, and generates an up-to-date finding chart. Only candidates with greater than 0.3 mag per day rise or decline remain in the queue. Candidates that pass the Swope screening will be observed spectroscopically with the IMACS and FIRE spectrographs on Baade, providing high S/N spectra covering optical to NIR during the same night.

During our previous POISE runs (2021A - 2022B), we performed follow-up photometry on the Swope for 81 objects that were deemed real and caught early enough for further follow-up observations. The majority of them were caught 3-4 days after their last non-detection. Approximately 70% of candidates

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[1] Many of the participants in this international collaboration have their roots in the Carnegie Supernova Project (CSP). In Argentina, our principal collaborators are Melina Bersten, Kaila Ertini and Gastón Folatelli (Instituto de Astrofísica de La Plata); in Chile, Alejandro Clocchiatti (Universidad Católica), Francisco Förster (Center for Mathematical Modeling, Universidad de Chile), Priscila Pessi (Stockholm University), Giuliano Pignata (Universidad Andrés Bello), and Joe Anderson (ESO); in Europe, Maximilian Stritzinger (Aarhus University), and Lluís Galbany (Institute of Space Sciences); and in the USA, Willem Hoogendam, Dahvil Desai, Ben Shappee, and John Tonry (University of Hawaii), Eddie Baron (University of Oklahoma), Peter Hoeflich, Eric Hsiao, Sahana Kumar, and Jing Lu (Florida State University), Peter Brown, Kevin Krisciunas, and Nicholas Suntzeff (Texas A&M University), Chris Ashall and James DerKacy (Virginia Tech), Melissa Shahbandeh (STSci), and Syed Uddin (USNO).

were rejected as bogus or faint, evolved objects. This highlights the need for Swope pre-screening before committing our spectroscopic resources.

Most of our SNe have photometry that is contaminated with host galaxy light and require follow-up observations after the object has faded. Some of these objects (especially the nearby ones) take years to fade from sligh. There are also a handful of SN fields that require additional calibration on photometric nights. A small fraction of the 2023B time on Swope will be used to obtain these observations.

To obtain the earliest spectra and supplement the optical and NIR spectroscopy (see Fig. 2) that we propose to acquire with the Magellan Baade telescopes, our collaboration has obtained ToO time on the GTC 10.4m.. Other optical resources to which we have preferred access include the UH 2.2 m + SNIFS, the ARC 3.5 m telescope at APO, ToO time on the 2-m Liverpool telescope, and the Nordic Optical 2.54 m telescope + ALFOSC for optical photometry and spectroscopy from the NOT-Unbiased Transient Survey (NUTs).. We are also using the robotic 0.8m telescope at Montsec Observatory and Telescope Joan Oró (TJO) for optical followup between POISE runs. We have applied for time on the Isaac Newton Telescope (INT) with IDS and the Calar Alto 3.5 m telescope with Omega2000 for NIR photometry. Our collaboration plans to request target of opportunity observations for UV/optical photometry with Swift's Ultraviolet/Optical Telescope. Lastly, we have been awarded JWST time for late-time follow-up of POISE objects.

This is a new and significant opportunity in supernova observations, and one that points to the future of transient astronomy.

3. Prior Results

This proposal has been awarded a total of 288 nights on the Swope and 29 nights on Magellan Baade in semesters 2021A through 2023A.. Nearly all nights on the Swope have been successful, allowing us to follow a little over 80 supernovae with an almost daily cadence (see Fig. 2). ToO spectroscopic observations of these targets were obtained by our collaborators on the facilities mentioned above. The real-time Swope photometry allowed us to weed out false positive detections as well as evolved SNe. The Baade time was used to obtain follow-up spectra of the 81 SNe that were deemed of most interest, adding to the rich dataset for each object. Unfortunately, FIRE was offline most of our run and IMACS is currently experiencing reduced throughput, so our spectroscopic follow-up was greatly reduced. We have also been able to use our 2022 and 2023 time to obtain imaging of the 2021 objects that require host galaxy subtractions as well as photometric calibration, which will allow us to publish our first photometric data release, led by PI Chris Burns.

A paper on the peculiar type Icn SN 2021csp has been submitted for publication and is available on the ArXiv (Fraser et al., 2021). The high cadence Swope photometry over a wide range of filters allowed us to model the early emission using the work of Piro et al. (2021) and measure the mass and radius of dense circumstellar material around the SN, while the IMACS spectra were used to measure the early evolution of ionized Carbon. Another paper led by Keila Ertini, a graduate student at Universidad

Nacional de la Plata, modeling the early data of SN2021gno (a type IIb SN caught early) has been submitted for publication . A unique stripped-envelope SN, 2021bxu, which shows low velocity features of H and He and a 10-day plateau in its light curve, was modeled by Tony Piro and Chris Ashall (University of Hawaii) and has been submitted to MNRAS (Dhavil et al., 2023). Figure 3 shows the modeling of the early light-curve. A nearby type Ia supernova, 2021aefx, was caught very early by our team and showed early excess blue flux. The early spectra have been analyzed and presented in an ApJ Letter (Ashall et al., 2022). 2021aefx has also been observed extensively by JWST (Jha et al, 2023, Ashall et al., in pre) A paper on 2021fxy, an example of an emerging class of type Ia SNe with suppressed UV flux, has been submitted to MNRAS(DerKacy et al, 2023).

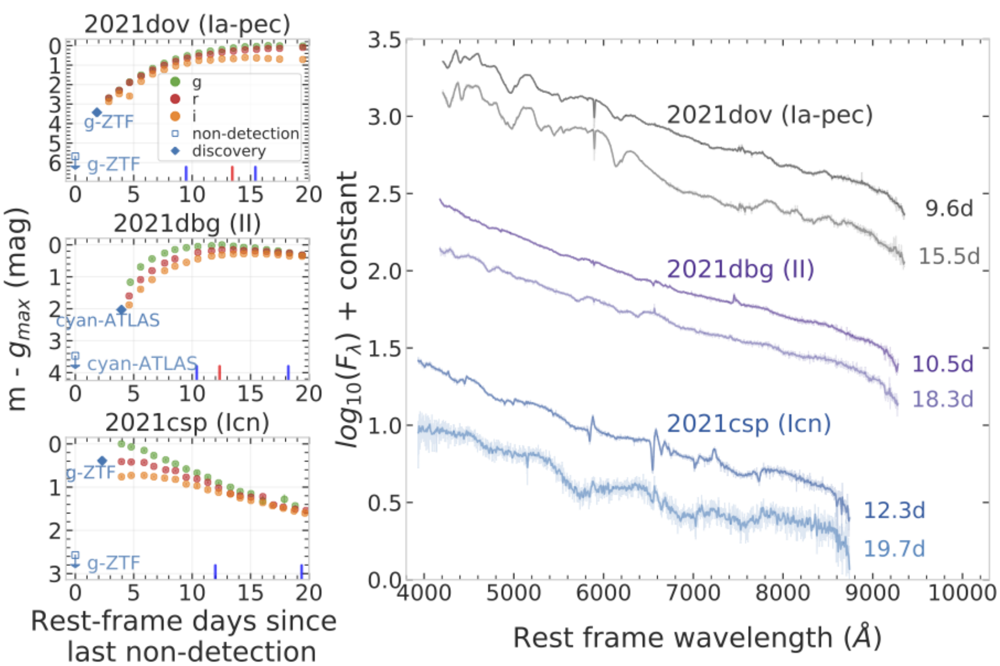

Figure 2: (Left Panels) A sample of Swope photometry (filled circles) of several types of SNe observed during our pilot POISE run between February and April of 2021. Last non-detections and first detections are plotted as blue open and filled symbols, respectively. (Right panels) Sample optical spectra of these SNe, labeled with days since last non-detection. Swope confirmed new targets and began precision photometry within hours, but lack of RToO access delayed spectroscopic observations.

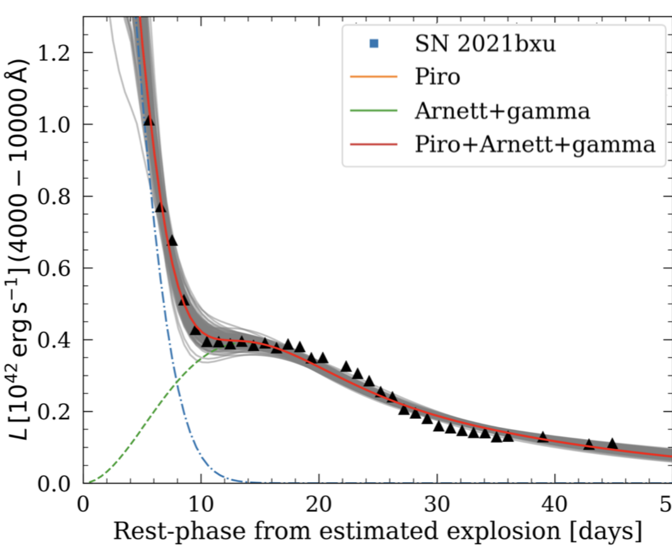

Figure 3: Pseudo-bolometric light curve of SN 2021bxu fit using a two component model: shock cooling and 56Ni decay including γ-ray leakage. Shock cooling is fit with the model from Piro et al. (2021) and 56Ni decay comes from the model from Arnett (1982) with additional correction for γ-ray leakage (Wheeler et al., 2015). Figure to appear in Desai et al. (2023).

4. Request for Las Campanas Telescope Time

We request time on the Swope and Baade telescopes to carry out a 2-month campaign from mid October to mid-December 2023. Details of our request are as follows:

Swope Telescope: To succeed, this campaign requires nightly access to the Swope telescope to carry out pre-screening of candidates and *ugriBV* follow-up imaging of those SNe discovered at early epochs (which is a unique feature of this project). Ideally, the SNe will be followed to at least 20-30 days past maximum light, providing a full record of the optical photometric evolution. Observations at later phases will be obtained through the facilities of our collaborators. Note that during the requested 60-day period, we are willing to carry out limited imaging for other Carnegie staff members.

Baade Telescope: The Baade telescope will be used to obtain optical and NIR spectroscopy of the infant SNe. We request 6 nights as evenly distributed through the campaign period as possible.

Note that we are more than willing to obtain observations of any high-priority target discovered by LIGO that requires optical and NIR data during the 2-month period of our project.

This project is the top research priority for Phillips, Burns, Piro, and Morrell in the 2023A semester, and follows upon the legacy of the CSP-I and CSP-II projects that have produced 120 refereed publications and 8,989 citations in 4,205 refereed papers to date. A list of CSP refereed papers is available at: https://ui.adsabs.harvard.edu/public-libraries/RAA6co_WQmeqrxq3EqE9fg

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