CATCHING THE EARLY LIGHT OF ZTF SUPERNOVAE

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1. SUMMARY

The dawn of deep, high-cadence, wide-field surveys opens up the opportunity to study one of the final frontiers in supernova (SN) science: the first hours after the single star or binary system exploded. The early evolution is highly sensitive to circumstellar material in the proximity of the SN progenitor (pCSM), the elusive final evolutionary history of progenitor just before the explosion, and how the star exploded. After a few days, these signatures get wiped out by the expanding SN ejecta (Gal-Yam et al. 2014; Yaron et al. 2017).

The high-cadence experiment of the Zwicky Transient Facility (ZTF) plays a distinct role in this frontier field. ZTF can detect one-day old SNe every week. Such infant SNe can be identified based on their rise time of a few tenths of a mag every 3–4 hours (Fig. 1), faster than most known transients. However, spectroscopic observations are needed to confirm candidates and secure spectroscopic information of this elusive phase. We propose to secure spectroscopy and photometry of *up to* ~ 53 infant SNe with SEDM during the first six months of ZTF. These data will allow us to answer key questions not only why but also how stars explode as SNe.

2. SCIENTIFIC CASE

This proposal has no false positives. Any extragalactic astrophysical transient discovered within < 1 day of explosion would be of interest for the greater ZTF community.

2.1. *Core-collapse Supernovae*

Spectroscopic observations of infant H-rich CCSNe have revealed transient, narrow Balmer emission-lines and emission lines from highly ionized species, such as carbon, nitrogen, and oxygen. These features can be attributed to a confined CSM shell, ejected through an enhanced pre-explosion mass loss episode just months to years before the SN explosion (Gal-Yam et al. 2014; Khazov et al. 2016; Yaron et al. 2017). This proximate CSM carries invaluable information about the surface composition and mass-loss history of massive stars, the SN progenitors, at their very final stages. In addition, the evolution of these features traces the temperature evolution of the explosion shock, which is critical in understanding the shock physics. Since ZTF will routinely detect such young SNe (Fig. 2), we envision to build a sample to get a systematic view of the pCSM and the pre-explosion evolution of massive stars for different types of SNe and progenitors.

Early light-curves of CCSNe that have massive envelopes are dominated by shock-cooling. The bolometric luminosity of the early UV and optical emission from

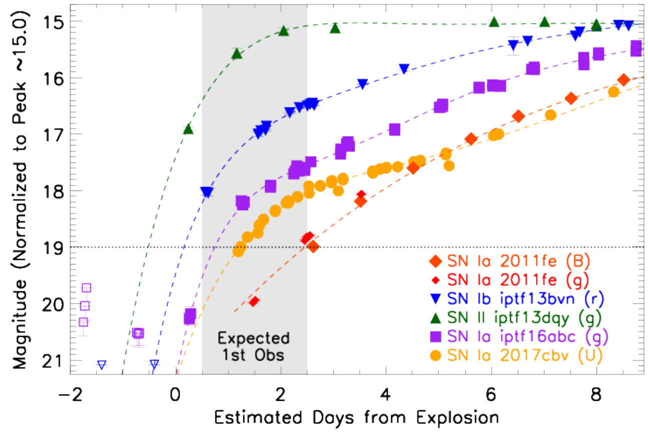

Figure 1. Early light curves of infant SNe. Extremely energetic explosions discovered by hours-cadence ZTF survey with significant rising over short time scales would be the key criteria for target selection. Note the diversity in different types of SNe. The brightness limit of $g = 19$ mag is indicated by the horizontal line. Non detections are displayed by empty markers.

the SN remains roughly constant, and the temperature of the ejecta drops due to the expansion. The color observed in the outer envelope is mainly determined by the stellar radius and the composition of the ejecta. Hence, we can infer the radii of the progenitors by measuring the color evolution of CCSNe (Rabinak & Waxman 2011; Ganot et al. 2016). That puts additional strong constraints on stellar evolution models. For stripped-envelope CCSNe, the early light curve is dominated by the degree of mixture of radioactive ^{56}Ni in the ejecta (Nakar & Piro 2014), providing a strong probe of the explosion model: strong/weak mixing is favored by jet-driven/spherical models.

2.2. *Type Ia Supernovae*

Theoretical models by Kasen (2010) showed that the ejecta-companion interaction may be detected up to a few days after the explosion, and it is found to be supported by a UV light curve excess (Cao et al. 2015) and a clearly-resolved blue bump in the light curve of SN 2017cbv (Hosseinzadeh et al. 2017). This early and fast evolving bump can only become resolvable in at least every-few-hour photometry. In addition, many type Ia SNe show detached, high-velocity features in their spectra (Silverman et al. 2015). Those features indicate significantly higher velocities, i.e., > 6000 km s^{-1} than the photosphere velocity and can be explained by the ejecta-CSM collision. The broadened-feature can be resolved even with the $R \sim 100$ ($\Delta v \sim 3000$ km s^{-1}) SEDM. The presence and evolution of such features can be revealed only in the earliest data.

Some well-observed individual SNe such as SN 2011fe as well as composite light curves Hayden et al. (2010) showed an initial rise well described by a t^2 power-law. However, Piro & Nakar (2013) argued that this model is too simplistic. Indeed, a wide range of the rise index n in the t^n power-law has been found in the first days of many type Ia SN light curves (Fig. 1; Zheng et al.

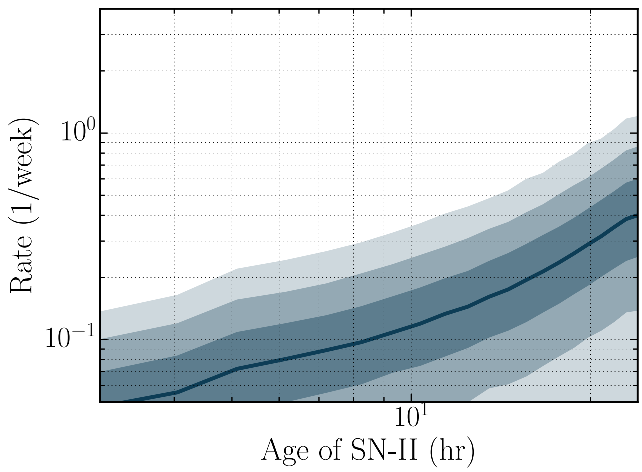

Figure 2. Rate of infant CCSNe (age < 1 day) detected in the ZTF partnership fields. The shaded regions indicate the expected 68, 95 and 99.7% confidence intervals (from dark to light).

2013; Firth et al. 2015; Miller et al. 2017). The physical reason for the variations in the slope of the light curve is unclear. This phenomenon might indicate that either the photospheric temperature, the expanding velocity, or other physical parameters, i.e., a non-standard distribution of ^{56}Ni in the ejecta throughout the population of type Ia SNe (Firth et al. 2015), of the expanding fireball exhibit significant changes during the early expansion.

A systematic study of the early behavior of type Ia SNe is essential for understanding the physics behind this scatter. Moreover, extremely early follow-up of type Ia SNe can reveal information about the nature of the thermonuclear explosions. SEDM observations at this first light phase will help us to collect more clues to the state of Ni mixing in the outer ejecta and hence to the structure and composition of the outermost layers.

2.3. *Other transients*

Any other extragalactic transient would be even more interesting!

3. EXPECTED OUTCOME &PUBLICATION PLAN

We propose to use the SEDM to obtain: **A census of the pCSM for all types of SNe** through the presence and absence of flash-ionized lines; and **Rapid multi-band photometry** to probe the temporal evolution at extremely early phases and correctly flux-calibrate the SEDM spectra from 3650–10000 Å.

For CCSNe, we will: a) Measure the strength and temporal evolution of the flash-ionized features and set constraints on the CSM; b) Trigger rapid spectroscopic follow-up with Gemini, NOT, WHT, and *Swift* for confirmed infant CCSNe; c) Trigger imaging polarimetry at the Liverpool Telescope to study correlations between spectrophotometric and polarimetric properties of CC-SNe; and d) Calculate the bolometric luminosity from early UV+*ugri* photometry and study the properties of the SNe and progenitor (e.g., radius, mass, composition, ejecta-CSM interaction) using the methodology in Rubin & Gal-Yam (2017).

For type Ia SNe, we will: a) Derive the expansion velocity and investigate the time-evolution of detached high-velocity absorption features (e.g., Ca H&K, Si II λ6355, Ca IR triplet); b) Obtain extremely well-sampled photometry and diagnose the ejecta-CSM interaction with the early light curves; and c) Investigate the correlation between the rise index and the spectral information. Studies on SNe-Ia will be led by members of the SN Physics and SN Cosmology working groups, in addition to the listed co-Is on this proposal.

We have published several papers on this subject, including two papers in Nature (Gal-Yam et al. 2014; Yaron et al. 2017). We envision to publish one sample paper on the census of infant SNe and another one on correlations between spectroscopic and polarimetric properties. Peculiar transients will be followed up with our resources at Gemini, NOT, *Swift* and WHT and published as stand-alone papers in high-impact journals.

4. MANPOWER AVAILABLE

The Weizmann Supernova team consists of three staff researchers (A. Gal-Yam, E. Ofek, O. Yaron), three postdocs (M. Soumagnac, S. Schulze and Y. Yang), and two PhD students (N. Ganot and A. Rubin). Each team member has a strong background in performing time-domain astronomy and publishing results in a timely manner.

5. TRIGGER CRITERIA

We will trigger on SN candidates with $g < 19$ that were not detected the night before and whose hosts are detected in SDSS or PanSTARRS images. We use the distance information of their hosts (estimated from broadband SEDs or previously reported distance measurements) to isolate candidates.To estimate the expected number of infant SNe, we use the type II SN 2013fs and the type Ia SN 2017cbv and the volumetric SN rates from Li et al. (2011). We predict that ZTF will detect 0.8 (3σ upper limit: 2.5) SN2013fs-like events that are not older than 24 hours per week and ~ 0.35 (3σ upper limit: 1.9) SN 2017cbv-like events and brighter than $g \sim 19$ that not older than 48 hours per week (Fig. 2). In total, we expect to observe *up to* ~ 50 SNe during the first 6 months of ZTF. Following Blagorodnova et al. (2017) we request one hour of integration time per target. We also request one epoch *ugri* after the spectroscopic observation to correctly flux-calibrate the spectrum (4×180 s) and two additional *ugri* epochs, to be completed within four hours after the SEDM trigger, to probe the temporal evolution. This totals into 101 hours of observing time, including 20% for overheads.

5.1. *False positives*

Based on the KAIT SN survey and our experience with PTF, we expect the contamination by variable stars superimposed on a background galaxy to be < 1%.