Young Type I Supernova Science With ZTF

1 Background

A major goal of supernovae (SNe) studies is to determine properties of the progenitors. Early photometry can constrain or even yield the radius of the pre-explosion star (core) whereas surface composition of the pre-explosion star can be diagnosed with early-time spectroscopy. "Flash" spectroscopy allows us to probe the composition of the pre-SN stellar winds. Next, the circumstellar medium (CSM) can be probed at larger radii (which correspond to earlier episodes of mass loss) via radio and X-ray emission generated in the forward shock of the ejecta. Surprisingly, early time light curves of type I SNe are sensitive to the radial distribution of radioactive ^{56}Ni in the exploding core. Finally, should the progenitor is a member of a binary system then the collision of the ejecta with the stellar companion will give rise to strong UV emission at early times.

The key to realizing these rewards is early detection of SNe – a strength of ZTF. This white paper (WP) focuses in large part on a systematic study of young Ia supernovae.[1] This WP also includes searches for new sub-classes of type I supernovae, which may be found during the course of investigation.

2 Type Ia SN

Despite the use of Ia supernovae for cosmography and their central role in elemental build up of the Universe the origin of Ia supernovae is not settled. Two channels have been proposed: single degenerate (SD; white dwarf accretes matter from a hydrogen companion and explodes) and double degenerate (DD; white dwarfs coalesce and the merger product explodes). PTF11kly (SN2011fe) is widely considered to be a poster child for the DD channel while iPTF14atg has been (reasonably) argued to be the same for the SD channel.

2.1 Signature of the SD Channel

In the SD scenario one expects strong emission arising from the reverse shock propagating into the ejecta as it collides with the companion. On timescales of an hour the resulting emission peaks in the UV and then declines gradually. As can be seen from the model light curves (Figure 1) the phenomenon is best seen at UV. In contrast, there are two contributions to the flux in the optical bands: the Rayleigh-Jeans tail of the declining UV emission resulting from the reverse shock (discussed above) and the rising standard early SN emission. Figure 1 suggests the following approach: identify, in g band, young ($\lesssim 1\,$day) SNe candidates and then trigger *Swift* UV follow-up within a day of discovery.

2.2 Early SN Curves: Structure of Pre-explosion star

In this section we focus on the exploding core, regardless of its antecedents. Much of the discussion below is general enough that it is also applicable to any SN explosion that does not involve a thick hydrogen envelope (not only Ib/Ic but also other peculiar supernovae such as Calcium transients).

The light curves of Ia SNe, around peak, are remarkably homogeneous, thanks to a less than a factor of ten variation in the mass of synthesized radioactive ^{56}Ni and the curious (but very helpful) Phillips' relation. In contrast, variations are expected in early light curve (and some have already

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[1] Most of the underlying physics is common to Ib/Ic SNe; see companion WP by Sollerman & Taddia

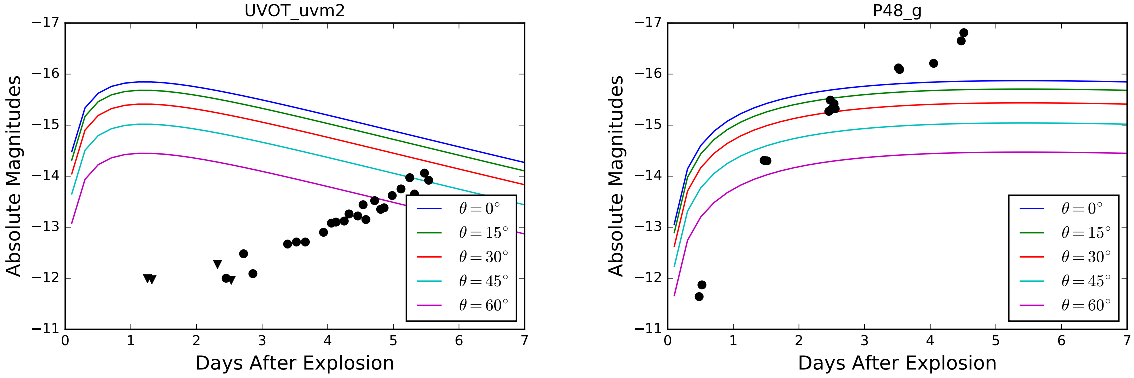

Figure 1: Theoretical light curves of SN-companion collision in a binary separated by 10^{13} cm in the UVOT *uvm2* (left panel) and PTF g (right panel) bands. The ejecta mass is assumed to be $1.4M_{\odot}$, and the opacity of the ejecta is $0.2\,\mathrm{cm}^2\,\mathrm{g}^{-1}$. Colors are used to represent different viewing angles. In comparison, the observed light curve of PTF11kly is shown in black circles. Theory from K10 and angular dependence from B12.

been seen; cf. Cao's thesis). Simple explosion models (e.g. Arnett's relation) assume that the radioactive ^{56}Ni lies in the deep interior. However, in the DD scenario one can expect considerable turbulence in the merger product. This may then result in strong mixing of ^{56}Ni and in particular place some ^{56}Ni close to the surface. Even in the SD scenario, off-center ignitions followed in 3D show signs of ^{56}Ni mixing to the surface [K09]. The outer layers are cooled by expansion but also *heated* by radioactivity. Thus the surface temperature is no longer set by the the diffusion timescale from the interior but is instead set by the timescale for the photons to diffuse from the shallowest ^{56}Ni layer to the photosphere.

The early light curves for strong and weak ^{56}Ni mixing are shown in Figure 2. Two observations can be made. First, a supernova with deeply deposited ^{56}Ni has a dark period of up to $\simeq$ two days before the rise of its radioactively powered light curve, while a SN with strong ^{56}Ni mixing has a negligible dark period. Second, the initial rise rate of a supernova with weak mixing is less than that of a SN with strong mixing. Hence, the early time rise rates allow us to probe the layering of ^{56}Ni in the core prior to explosion, which in turn give insight into the physics of explosion.

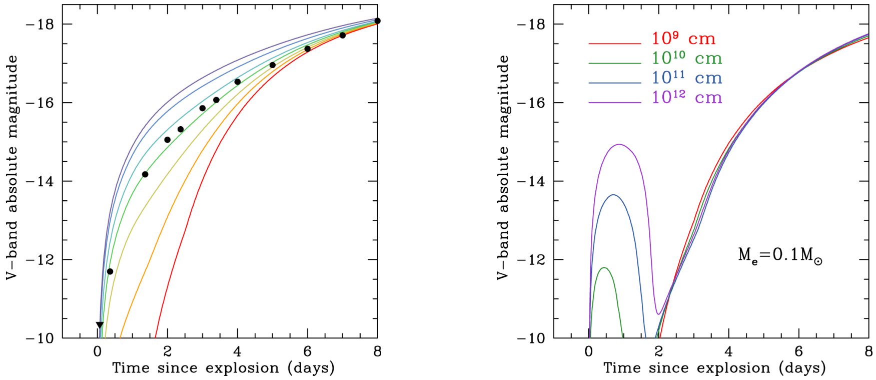

Figure 2: *Left panel:* The radioactively powered light curves of SNe with weak (red) and strong (blue) mixing. The circles and triangle are the observed light curve of SN2011fe/PTF11kly. Figure 7 of P16. *Right panel:* The early light curve peak produced by an extended material of $0.1M_{\odot}$ at different distances from the explosion center. The SN ejecta is assumed to have weak mixing of ^{56}Ni . Figure 10 of [P16].

2.3 SN-CSM Interaction

Most progenitor scenarios of SNe Ia, Ib and Ic involve some sort of mass transfer process, which in principle, should leave excess material around the progenitor system. The SN ejecta will interact with the CSM and the resulting forward shock generate emission and thus modify the light curves (right panel of Figure 2). This extra peak in the early-phase SN Ia light curve is accessible to a survey with a 1-day cadence.

3 Proposed experiment

From the above discussion it is clear that we need a survey with a 1-day cadence. As can be seen from both the Figures the experiment must reach at least -15 mag to be meaningful. Next, the search volume should be large enough to yield a meaningful number of sources. Finally, the proposed experiment should be competitive in a landscape that includes ATLAS and PS-1. We remark that ATLAS and PS-1 use filters optimized for NEO detection. Thus, a natural differentiator for ZTF is the g band.

All these considerations lead us to a survey with one day cadence and three three epochs per night in g band. In detail, the coadded limit is 21 mag (after taking into account of the background contribution from the host). The corresponding distance limit for a -15 mag event is 150 Mpc. For the usual values (5.75 hour/night, 3760 deg^2/hr, 3 exposures) the active area is 2882 deg^2. The total annual volumetric SN rate is $[3, 7] \times 10^{-5}\ \mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$. The annual yield, assuming a distance limit of 150 Mpc, is then [30, 70]. Narrowly speaking the first value is "signal" for this experiment and the second the "false positive". Catalogs of nearby galaxies will be used to cull the candidates. The completion of these catalogs is about 75% (SRK, report in prep.). Thus the net yield is [23, 54] per year.

The size of the Ia sample is set by the expectation[2] that only 10% of supernovae exploding via the SD channel are expected to exhibit the UV pulse. In three years we will have a sample of 70 young SN Ia. Thus if the fraction of the SD SN rate is greater than a fifth of the total Ia rate then we have an opportunity to detect an SN exploding via the SD channel.

To meet the scientific goals listed above, we request the following experiment:

- Pointings: We prefer fields that are away from the moon during a given month. Equally low Galactic latitude fields should be avoided.
- Cadence: One-day cadence with three epochs per night.
- Filter: The early SN emission is hot and blue. The sky is darker in the g band. So we advocate g band.
- Scanning Query: We need the ability to execute a realtime query for events with (a) multiple detections (at low thresholds as a proxy for coadd), (b) non-detection in the coadd of previous night and (3) spatially associated with galaxies within 150 Mpc.

4 Supporting Observations

We start by noting that other SN experiments (II, Ibc) also face the same issues of early classification, possibly early spectroscopy, possibly multi-epoch light curve (early to late times) and quality

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[2] arising from the geometry of the binary system and not due to variations in the physical processes.

spectrum at peak. Our “signal” is “noise” to these experiments and vice-versa. We are prepared to contribute our fair share of the follow up load using Palomar and Keck.

4.1 Photometric Follow-Up

The key to detecting SN-companion collision signatures is rapid UV observations. This is ideally undertaken with *Swift*. We have a dozen *Swift* triggers allocated for the coming year (PI: Kasliwal). We note that following: at the *Swift* annual meeting Cenko & Kulkarni argued for *Swift*, in view of the explosive growth in synoptic optical facilities, to give priority to the study of young SNe. The *Swift* PI and team has accepted this recommendation. Thus we can safely assume that larger requests can be made in the next *Swift* cycle. In addition we envisage ground-based u band observations. This could be done via APO, LCOGT (via proposal process) or Liverpool Telescope (via collaboration).

Optical colors at early times provide important diagnostics: the $B - V$ color evolution is a sensitive measure of the degree of ^{56}Ni mixing (Figure 8, [P16])and separately of the radius of the extended circumstellar medium (Figure 12, [P16]). One approach is to add R band observation. This is problematic on two counts: a decrease in sky coverage (leading to a smaller sample) and signal mismatch between R and g bands (the large $g - R$ necessitates deeper integration in R band). Our preferred approach is to trigger another facility to get colors (and as before APO, LCOGT or LT).

4.2 Spectroscopic Follow-Up

The minimal spectroscopic need is a single classification spectrum and that too at peak. The SEDM is sufficient for this purpose. However, in order to probe the surface composition (intermediate mass elements) we aim to get sensitive early-time spectra (cf. iPTF16abc) with Palomar or Keck either via “soft” TOO or scheduled observations.

5 Gap Transients

An added benefit of this experiment is the possibility of detecting fast “gap” transients (which peak at -16 mag or fainter) on timescale of a day. Fast, gap transients could arise from Helium-shell detonations on the surfaces of white dwarfs, shock breakouts of failed supernovae, white dwarf - neutron star mergers etc. Those which peak on longer scales (e.g. low luminosity core-collapse SNe) are better probed with MSIP’s Celestial Cinematography. We note that this sub-experiment would yield more sources with a shallower (e.g. two epochs per night) but wider survey.

6 The Team: Expertise, Manpower & Timeline

The interested parties are: Cao (UW), Kulkarni (CIT), Kasliwal (CIT), Nugent (LBL) and Cenko (UMd). We are in communication with the OKC group. While nothing concrete can be stated at this point we hope to entice a graduate student for the Ia project. Kasliwal is personally interested in the “gap” transients. The senior and junior members of the team have proven track record and proven commitment for this area of research.

[B12] Brown, P. J. e al., ApJ 749, 18 (2012)
[K09] Kasen, D. et al., Nature 460, 869 (2009) [K10] Kasen, D., ApJ 708, 1025 (2010)
[P16] Piro, A. & Morozova, V. S., ApJ 826, 96 (2016)