Seeing stars as they explode: young core-collapse supernova observations with ZTF

White paper

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Executive summary: ZTF will have a unique capability to observe massive stars exploding as supernovae almost “as they happen”, provided the nightly cadence is high enough. The science case for such observations is both strong and well-developed, based on preliminary results from PTF and iPTF, as well as a handful of cases observed serendipitously by other projects. The impact on our understanding of the late stages of stellar evolution, the explosion mechanism and physics of core-collapse SNe, and the physics of shocks, will be significant. The three specific science goals we review here include observations of the shock breakout and early shock-cooling phases, including CSM shock cooling; “flash spectroscopy” of infant SNe that reveals the composition and final evolution of the progenitor via illuminated CSM; and well-sampled studies of the rise time of core-collapse supernovae that trace the distribution of radioactive elements within their ejecta and the shock-cooling phase. Unique science results require relatively high cadence (optimally 8 times per nights) and prefer blue (g-band) filters for most visits; a combination with observations in redder filters is a good option. The estimated rate of events is modest (tens per year at most), making follow-up requirements manageable, as detailed below.

Section 1: The scientific motivation of the project

1.1 Goals and competitiveness of ZTF.

1.1.1 SN first light – searching for evidence of the shock breakout: The first photons arriving at an external observer from a stellar explosion result from the hot explosion shock breaking out of the stellar surface. Observing such energetic UV/X photons requires space facilities, and is very challenging. A very interesting prospect is to observe the low-energy "tail" of the shock-breakout flare in visible light from the ground, where powerful wide-field survey machines like ZTF have an advantage. A recent result from Kepler (Garnavich et al. 2016, ApJ, 820, 23; Fig. 1) motivates this as it may indicate a visible-light detection of such a flare (Fig. 1). The temporal shape of the flare is debated among theorists. Garnavich et al. use models from Nakar & Sari (2010) which predict a spiky flare (Fig. 1), while models from Sapir et al. (see Fig. 1 of Ganot et al. 2016, ApJ, 820, 57) and Waxman & Katz (2016, arXiv: 1607.01293) predict a much shallower, plateau-like feature. With a time sampling of 1h (for a nightly cadence of 8 visits) ZTF can both test the existence and significance of such shock breakout features, and, if they exist, map their temporal evolution and test the competing models. This would provide unique constraints on the progenitors (Waxman & Katz 2016) as well as drive an important advance in shock-breakout theory. Shock breakout from the CSM will shed additional light on mass loss (Ofek et al. 2010). Scaling from Kepler and PTF studies, ZTF will be able to observe several such flares per year.

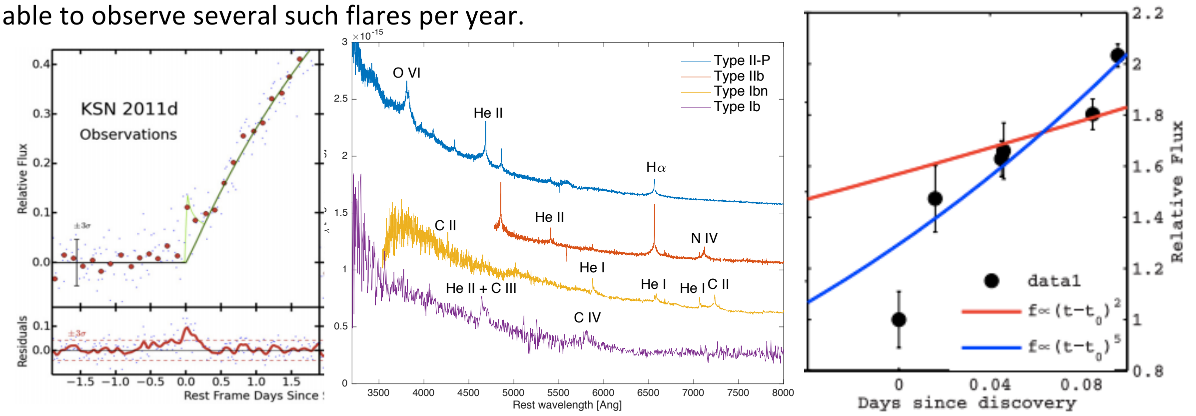

Fig. 1 (left): Kepler observations of the Type II SN KSN2011d suggest an anomaly during its early rise that may be the signature of shock breakout (green line shows a model based on Nakar & Sari 2010). With a better, 1h temporal cadence (the red, binned Kepler points have a cadence of 3.5h) ZTF will be able to validate the significance of such events and resolve the temporal profile of the shock breakout flare. **Middle**: Flash spectroscopy of iPTF events reveal diversity in line features seen as we progress from non-stripped SNe II (blue, top), partially stripped SNe IIb (red) and more highly stripped SNe Ibn and Ib (yellow and magenta, bottom). The CSM composition reflects the surface composition of the deceased progenitor shortly prior to explosion. **Right**: rare high cadence PTF observation of PTF12gzk (Ben-Ami et al. 2012) indicate a remarkably rapid rise.

1.1.2 Probing SN progenitors via rapid-response ("flash") spectroscopy of infant SNe: The study of emission lines seen in very early spectra of core-collapse SNe ("flash spectroscopy") is one of the most prominent results of iPTF (e.g., Gal-Yam et al. 2014, Nature; Yaron et al. 2017, Nature physics). The capability to systematically obtain spectra of SNe shortly (hours to a day) after explosion has been a unique feature of iPTF and will be an even more prominent advantage of ZTF, with the SEDM fully online. As a massive star explodes, the shock-breakout flash ionizes surrounding CSM, which then recombines. The resulting emission lines are used to measure the CSM elemental composition (and by proxy the progenitor surface composition), if one can obtain a spectrum of the SN before the rapidly expanding SN ejecta interact with the CSM, accelerate it to high velocities and wipe out the signal. Observations during the first hours after explosion (e.g., Yaron et al. 2017) are the most useful as they trace the hottest phase of the shock via highly ionized species like OVI, as well as because they can probe more compact progenitors, or progenitors with compact, highly confined CSM, that may have been expelled just weeks prior to explosion. This tight observing window requires a combination of early identification of the SN as well as a reliable selection of targets for follow-up with precious sensitive spectrographs (e.g., Gemini ToO triggers). A multi-night, multi-color observing strategy will allow to cleanly select very young SNe that are very blue and rapidly rising, pre-screen them with SEDM if they are bright enough, then follow-up the best candidates with ToO triggers on large telescopes. As demonstrated, e.g., by Yaron et al. (2017) the combination of multicolor early light curves (ground + Swift UV) together with the information encoded in the flash spectra provides a powerful way to map the nature of the SN progenitor and the disposition of CSM around it. The iPTF sample (Fig. 1) provided a first taste of the potential of this method – ZTF will allow to use it to systematically study the progenitor of all types of core-collapse SNe that are surrounded by confined, dense CSM shells. The apparent ejection of confined CSM shells (e.g., Yaron et al. 2017) indicates that pre-explosions instabilities in massive stars are common, which is likely to drive a burst of theoretical work in stellar evolution, physics of stellar turbulence, and perhaps change the initial conditions to SN explosion models, an important clue for the struggling search for the correct explosion mechanism.

1.1.3 Well-sampled rising light curves of core collapse SNe. The rising ZTF light curves of fully-stripped SNe with compact progenitors (presumably the majority of Type Ib and Ic events; driven by the diffusion of radioactive energy from the decay of ^{56}Ni), if measured accurately enough, can constrain the mixing of radioactive material (produced in the explosion) into the outer ejecta (e.g., Piro & Naker 2013, ApJ, 769, 67). This is a big clue into the explosion mechanism – spherical neutrino-driven collapse models predict less mixing, while jet- or binary-outflow models predict strong mixing. Indeed, Ben-Ami et al. (2012; Fig. 1) showed measured a surprisingly rapid rise (faster than t^2, often seen in SNe Ia, e.g., Nugent et al. 2011). With 1h-like cadence, ZTF can provide revolutionary results on this subject. Partially-stripped massive stars may retain tenuous large envelopes around their compact cores. These stars would appear as supergiant in radii, but do not have the massive envelopes of normal red supergiants, and are probably the progenitors of some Type IIb SNe. The density distribution in these systems produces an early shock-cooling “bump” that precedes the main peak. Such observations have been obtained for numerous Type IIb SNe (a few day timescale) but only recently did Taddia et al. (2016, A&A, 592, 89) demonstrate this also for a Type Ic SN. High-cadence observations from ZTF will be able to detect or constrain such features in stripped SNe of all types, clarifying what fraction of the progenitors of stripped SNe have extended envelopes. Finally, Type II SNe are the most numerous of massive-star explosions, and likely result mainly from supergiant stars with substantial hydrogen envelopes. The ZTF sample of SNe II with well-measured rise times will allow to test previous intriguing PTF/iPTF results (e.g., Rubin & Gal-Yam 2016) that may suggest a new way to classify SNe II, and excitingly explore possible features visible in much finer sampled rising light curves.

1.2 Figures of merit - event rate estimates:

This science project focusses on detailed studies of events with unique properties that only ZTF can provide. The main figure of merit is thus the number of such events, which we estimate here. We begin by estimating the number of young (~first day) SNe expected based on direct scaling from the GALEX/PTF experiment (Ganot et al. 2016), that detected 6 such events in 600 deg^2 observed for 2 months with 50% efficiency. Assuming ZTF can observe 3760 deg^2 per hour, 5.75 hour nights, and 30% of the 40% collaboration time is spent on a high-cadence experiment, ZTF can observe about 2500 deg^2 every night. This number has to be divided by the inverse of the chosen cadence which we assume is 8. We thus expect ~20 young CC SNe per year. Scaling from the Kepler results of Garnavich et al. (2016) corrected for the 99% of nearby galaxies in the Kepler field that were not observed, we get estimates that are higher by 2-3, indicating our estimate is conservative.

1.2.1 Shock breakout signatures: Of the number above, 25% (5 events) will occur within the average 6h Palomar night, and of those 50% might show shock breakout signatures based on the Kepler results. We thus expect a handful (~3) of shock breakout detections (temporally resolved, using 30% of the collaboration time with 8 visits per night).

1.2.2 Flash Spectroscopy: based on 2016 statistics, at least 50% of the young SN count calculated above will show flash signatures (~1 a month or more). In iPTF the rate of "golden" flash-spectroscopy events was 1-2 per year (13ast, 13dqy, 14gqr, 15ayt, 16bkn, 16br). Since only a small fraction of iPTF time was actually spent in 1-night cadence surveys, and given the x10 larger survey power of ZTF and assuming much of the time will be used in surveys with cadence of 1 night or faster, we consistently expect about x10 more events per year at least, or of order 1-2 events/month.

1.2.3 Rise times: rise times would be measured for any core-collapse SN detected by ZTF. While a larger sample is better for statistical studies, the ability to stack observations obtained each night allows to measure the rising light curve for more distant and fainter events. Since such events are numerous (tens per year based on simple scaling from PTF), we do not consider the rise time science as a driver for cadence.

1.3 Real-time discovery

Our object cut will be straightforward: events not detected the night before, that show blue colors typical of young core-collapse SNe. We will prioritize events with a detected host galaxy in deep SDSS or PS1 pre-explosion images, to reject stellar flares. We will use human scanning and the involved groups (WIS and OKC) have the most experience and manpower to do this (as well as a favorable geographic location for daytime real-time scanning and ToO triggering).

Section 2: Proposed observations

Pointings: our project requires pointing at extragalactic fields that can be observed during most of the night, the exact choice in not critical. Filters and cadence: In general, young SNe are blue, and therefore our preference is for g-band observations. However, having color information is useful, so we advocate some r-band visits. I-band is not very useful for the study described above, but we recognize it is important for other science usage of the data. Replacing some of the r-band visits with i-band (especially if this is done every other night or so) is acceptable. A proposed filter sequence for an 8-visit cadence would be g-r-g-r/i-g-r-g-g/r. Our rate analysis for shock breakout (the most challenging case) is verified by Kepler observations that are obtained through a broad, roughly g+r filter, so any mix of g/r filters would not affect these estimates significantly. Multiple observations per night will also be very useful to set tight deep limits (stacked) on the pre-explosion nights and to search for faint pre-explosion precursors. We do not require special calibrations. High cadence in each night allows to select events based on intra-night rapid rise or same-night non-detections, alleviating the impact of weather preventing strict nightly cadence. Winter (Dec.-Jan.) is the least suitable period for this project due to weather.

Section 3: Supporting observations

As explained above, the focus of this activity is on detailed, high quality studies of a relatively small number of events with excellent early light curves and tight pre-explosion limits. The total number of events will not exceed a few tens per year, with a subset of 20 or so with the most unique features (shock breakout/cooling, flash features) that we aim to observe extensively. This makes the follow-up requirements manageable.

Spectroscopy: Our standard routine would commence with an early detection by ZTF with non-detection limits for a previous night or even (most excitingly) from the same night. All events brighter than 19mag we will send to SEDM screening at highest priority (the numbers are expected to be small: perhaps a couple per week). LCO FTN+Floyds could serve as a useful backup and complement for SEDM, accessed either through a ZTF LCO proposal via NOAO, or through the LCO SN key project. Events fainter than 19 are not accessible to SEDM or FTN, and the best option to observe these is via Gemini north ToO triggers. The science case stated above would be a very strong foundation to a ZTF Gemini proposal that we are glad to support; in parallel, we will work to secure Gemini time independently. Prior to triggering Gemini or other precious follow-up resources, we will use color information from ZTF (g-r) to pre-select blue, young core-collapse SNe from SNe Ia or dusty events.

The main goal of rapid spectroscopy is to measure flash spectroscopy features. Should we detect such features our goal is to obtain a sequence of spectra with initially a few hour cadence and later a 0.5 and 1d cadence. An optimal sequence could be (times since detection given in parenthesis) SEDM/FTN (0.5h), Gemini (1h), Gemini (5h), NOT (20h), NOT (40h), SEDM/FTN (2d), SEDM/FTN (3d), SEDM/FTN (peak), NOT (post-peak), Gemini/Keck/GTC (nebular). **The total number of SEDM spectra expected to be required for this project is <100 per year**, and can be reduced (e.g., by reliance on LCO for non-time-critical spectra). We will continue to apply for NOT time, and, towards the end of ZTF, hope to have access to the new NTE spectrograph (including guaranteed time on it; expected 2020). We have proposed a collaboration with the group in Granada (Spain) to secure additional telescope time to contribute both to early time observations using modest telescopes in La Palma (e.g., 2m LT) and, e.g., nebular spectra with GTC. We will propose to continue our work with Alex Filippenko (UCB) to obtain deep nebular spectra with Keck for selected events.

Photometry: Our experience is that the LCO network currently provides the best photometry follow-up t early times, and we will access it through a ZTF proposal (if such is submitted), the SN Key project we are part of, or the LCO access of EOO via the Israeli I-Core site partnership. We also proposed a collaboration with a Greek team that can contribute significant photometry, including at late time using their 2m telescope. We will also obtain photometry from our own telescopes in Israel. We will welcome additional collaborations within ZTF and related groups.

In space, we will seek Swift time for early UV photometry and X-ray observations. We will obtain this through ToO applications, via a ZTF-wide program if such exists, and we are also working to secure additional Swift access. We will resubmit our HST proposal (accepted cy. 22-23) to obtain UV spectroscopy of the best event.

In the radio, we plan to work with Assaf Horesh from HUJI (who is expected to remain as a ZTF associate or collaborator) to obtain VLA observations to probe CSM interaction in the radio, both at early times and at late times – this is highly complementary to flash spectroscopy studies (e.g., Yaron et al. 2017). We will support applications to ALMA for early high-frequency observations of compact dense CSM shells.

Section 4: Expertise to undertake project

The WIS and OKC groups have been conducting these studies during PTF and iPTF and have all the required observational expertise in house. Analysis tools are already in hand. We continue to work closely with relevant theorists, mostly at WIS (Waxman, Katz, Kushnir) and at OKC (Fransson), as well as with relevant other experts (e.g., Jose Groh) as needed.

Section 5: Manpower, resources and time-line

This is the main ZTF science focus of Gal-Yam (WIS). Sollerman (OKC) and Ofek (WIS) are also significantly committed to these studies. Permanent staff scientist Yaron at WIS will be working on this subject (about 50% FTE) as well as a large number of students and postdocs at OKC and WIS (currently Taddia, Nyholm, Karamehmetoglu, Fremling, Roy, Barbarino, Rubin, Ganot, Soumagnac). Funding is secured via approved grants at both WIS (including an ERC extending till 2022) and at OKC. This is the Ph.D thesis project for Ganot (WIS). Both groups have excellent publication records (e.g., >14 PTF/iPTF papers published in 2016 alone). We thus already have a secure plan for sufficient observations, follow-up, analysis and publication of these events “from start to finish”.