Discovering Failed Supernovae with ZTF

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February 1, 2017

1 Motivation

The Zwicky Transient Facility provides a fantastic opportunity to complete our understanding of the Zwicky Diagram (Fig. 1). In particular, the study of "gap" transients in the luminosity gap between novae and supernovae (SNe) could grow by leaps and bounds. We define the absolute magnitude range for the gap as transients fainter than -16 mag and brighter than -10 mag. Here, we focus on fast gap transients that evolve on a few day timescales as the slower gap transients are better studied by the all-sky MSIP survey. Fast, gap transients could physically arise from Helium-shell detonations on the surfaces of white dwarfs, white dwarf - neutron star mergers, and shock breakouts of failed SNe. The rates of these transients are uncertain, but small compared to the SN rate. In this white paper we present the optimal survey strategy to discover the shock breakouts of failed SNe.

There is growing evidence that the most massive ($\gtrsim 17\ M_\odot$) red supergiants may end their lives with a "failed" SN, collapsing directly into a black hole without a luminous explosion. An ongoing survey begun in 2009 monitoring a million red supergiants in 25 nearby galaxies discovered the first failed SN candidate with the disappearance of a $10^{5.3}\ L_\odot$ red supergiant (Gerke et al., 2015). Subsequent follow-up with *HST* and *SST* affirms that a failed SN is the best explanation (Adams et al., 2016b). Based on this first systematic search for failed SNe the fraction of core collapses that result in failed SNe is constrained to be 0.14^{+33}_{-10} (Adams et al., 2016a).

Searching for disappearing core collapse progenitors is observationally expensive and cannot feasibly be scaled up enough to tightly constrain the rates and progenitor properties (Kochanek et al., 2008). Moreover, with this approach candidates are only identified months (or years) after core collapse, precluding detailed observations of the event and its immediate aftermath.

However, the disappearance of the progenitor is not the only possible signature of these events. Models predict that even if the energy released by the core collapse of a red supergiant fails to result in a SN, the loss of gravitational binding energy from the neutrino emission may result in a low-velocity ($\sim$ 100 km s^{-1}) ejection of the weakly-bound hydrogen envelope (Nadezhin, 1980; Lovegrove & Woosley, 2013). This ejection would result in a $\sim 10^7\ L_\odot$, few days-long shock breakout thermalized to $\sim 10^4$ K (Piro, 2013; Lovegrove, 2016), followed by a fainter, but much longer-lived recombination powered transient (Lovegrove & Woosley, 2013). Though the temporal sampling is coarse, the observations of the failed SN candidate reveal a several month long $\sim 10^6\ L_\odot$ transient consistent with the prediction of the longer-lived transient powered by the recombination of the ejected hydrogen envelope (Adams et al., 2016b). Given the likely low rate of failed SNe, the recombination powered transient is too faint to be discovered with ZTF, but the shock breakout is a more promising signature.

1.1 Goals

The goal is to discover the shock breakouts of failed SNe, which would enable, for the first time, spectroscopic follow-up and characterization of the envelope ejection and early-time fallback, and significantly improve the constraint on the rate of failed SNe. Even failure to discover any shock breakouts could significantly tighten the constraint on the fraction of core collapses resulting in failed SNe. Only ZTF and ATLAS have the necessary $M_g \sim -14$ spectroscopically-accessible volumetric survey rates to achieve this goal during a 1-2 year survey (Bellm, 2016).

1.2 Real-time Discovery

Due to the short (few-day) expected duration of the shock breakouts of failed SNe, real-time discovery is critical to the success of this project, though follow-up will only be triggered by detections on consecutive nights (see §3). The query for selecting events will include the host galaxy distance and the luminosity evolution of the transient. The extent of human scanning will be dependent on the robustness of the machine learning real-bogus classification and the flagging of AGN.

2 Proposed Observations

We propose a 6000 square degrees survey in *g*-band with once per night, nightly cadence. This comes out to $\sim 70\%$ of the total collaboration time assuming a survey rate of 3760 square degrees/hour and that nights are 5.75 hours long on average. Due to the low peak luminosities and fast timescales predicted for failed SN shock breakouts the optimal strategy is to maximize the areal coverage of nightly g-band observations (outside of the Galactic plane).

Assuming for the fiducial case a failed SN rate of 14% of the core collapse SN rate, a failed SN shock breakout peak *g*-band magnitude of -14 (see Fig. 2 and Lovegrove 2016), and a SN rate of 10^{-4} Mpc^{-3} yr^{-1} a 6000 square degree survey with nightly *g*-band cadence should be sensitive to the failed SN shock breakout signature for 15 core collapses, which corresponds a 90% chance of discovering a failed SN shock breakout, with an expectation value of 2 failed SN shock breakout discoveries.

The exact choice of fields is flexible. The most important consideration is for each targeted field to be monitored (weather permitting) with nightly cadence to efficiently identify young ($<$ 2 day-old) transients for spectroscopic classification. Modest increases in efficiency might be possible by prioritizing the fields encompassing the highest total star formation of galaxies within 60 Mpc. Since the shock breakouts are expected to be $\sim 10^4$ K *g*-band is the best filter choice for this survey and, given the faint expected peak luminosities, the only filter choice for which this project has a reasonably high chance of success (see Fig. 2).

3 Supporting Observations

Our selection criterion would be two-fold: (a) spatial coincidence with a galaxy within 60 Mpc, (b) a photometric sequence that is an upper limit on night zero, detection on night one, and a relatively fainter magnitude on night two. We will not undertake any follow-up until night two. Requiring fading between nights one and two would reject all rising events such as young supernovae and other slowly evolving transients. The number of remaining targets will be small enough (one/-month to one/quarter) that we will promptly trigger target of opportunity follow-up with P200/Gemini/Keck, Swift, and VLA. In the event that a failed SN shock breakout is discovered, deep (∼26 mag) optical (*I*-band) imaging would be undertaken with monthly cadence in an effort to detect any subsequent transient powered by recombination of the ejected hydrogen envelope.

4 Expertise and Manpower

The scope of this focused project is not large. Both Adams and Kasliwal have published multiple papers on the topics of failed supernovae and gap transients and are well-prepared to execute such a project. This is not a thesis project.

In summary, the study of gap transients with a rate of 10% the supernova rate, absolute magnitude fainter than -14 and timescale of few days is only marginally possible if the majority of the collaboration time is spent on 1 epoch/night every night cadence. We completely understand such a large investment for a high risk survey is not feasible given the many other science aspirations of the collaboration. However, we are presenting the results of this thought experiment to the collaboration as it just might be of interest for future planning!

References

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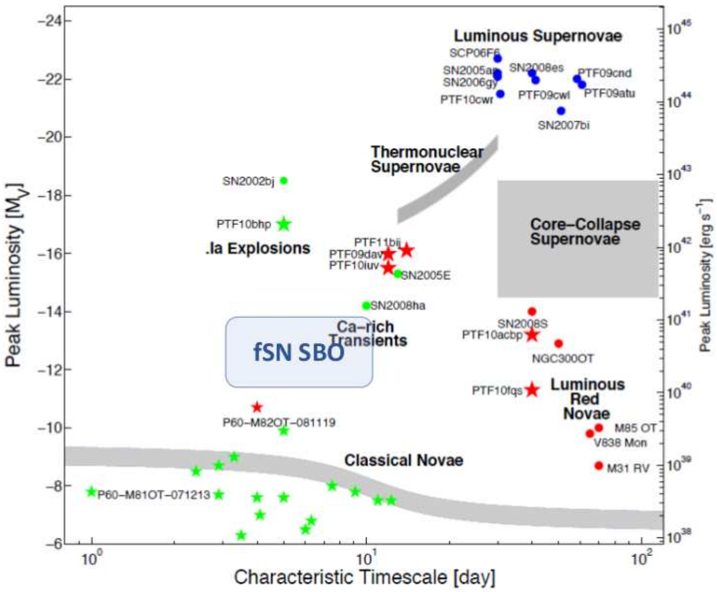

Figure 1: Zwicky Diagram showing the luminosity/timescale parameter space of known transients. This proposal is focused on exploring the short timescale parameter space in the luminosity gap between SNe and novae, where the shock breakouts of failed SNe (fSN SBO) are predicted to reside.

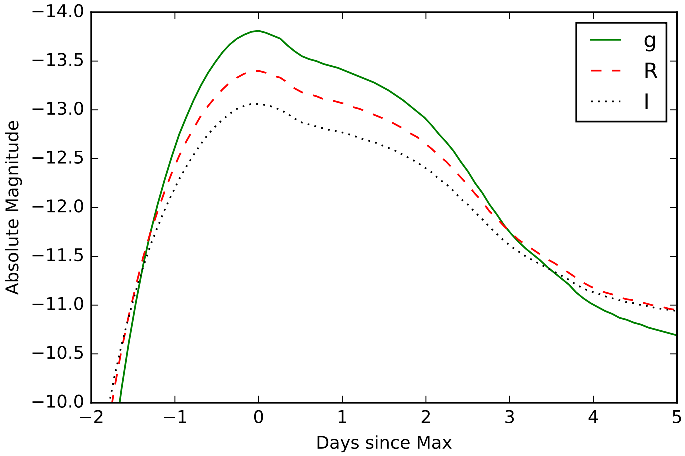

Figure 2: Predicted optical light curves based on the failed supernova shock breakout model in Lovegrove (2016) for a 15 $M_\odot$ red supergiant progenitor that has a kinetic energy of 1.5×10^{48} erg.