ZTF White Paper for Young Stripped Envelope Core-Collapse Supernovae

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Introduction:

This white paper for young stripped envelope (SE, Type IIb, Ib Ic) core collapse supernovae (SE) complements the white papers submitted for Early light curves of Type Ia supernovae and the one for helium rich (Type II) core collapse supernovae, by adding a number of Scientific projects specific for SE CC SNe, in particular for which high cadence is needed to catch the very early light curves of these objects. SE CC SNe will be the focus for the Department of Astronomy at OKC within ZTF. We briefly mention 6 different science goals, with references to the abovementioned white papers that we have been inspired by.

1. The scientific motivation of the project

SE CC SNe probe the fate of the most massive stars. The overall aim is to connect progenitors to explosions to constrain the nucleosynthesis yields to the cosmic enrichment.

1. Extended envelopes of SE CC SNe:

Stripped-envelope (SE) supernovae (SNe) come from stars stripped of most or all of the hydrogen and/or helium. Compact WR stars have long been the suggested progenitors. The actual structure of the exploded stars can, however, be different than a compact configuration and the observational consequences for more extended envelopes have been worked out (e.g., Bersten et al. 2012, ApJ, 757, 31) and even observationally constrained (for example for Type IIb SN 2011dh=PTF11eon, see eg., Arcavi et al. 2011 from the PTF group and Ergon et al. 2014, 2016 from the Stockholm group). Recently, Taddia et al. (2016, A&A, 592, 89) showed that also Type Ic supernovae (iPTF15dtg) can come from massive stars with an extended envelope. This can be shown by comparing early time photometry with models such as those by Piro & Nakar (2013, ApJ, 769, 67). A larger sample of SE CC SNe, with a good light curve coverage of the rising phase and excellent constraints on the explosion epochs are needed to further this research.

2. Early spectroscopy of SE CC SNe:

Early spectroscopy of SE CC SNe is rare, simply because these are both rare supernovae per se and since most are found long after explosion. A systematic high-cadence effort to find them early, as explained in this white paper, will also allow early time spectroscopy. One of the main drivers for this is to probe the amount of H or He in the outermost atmosphere.
Currently , Christoffer Fremling is working on the full spectral PTF sample of SE SNe. The first paper will focus on simple observational differences between the classes (IIb, Ib, Ic) but better data will also allow detailed comparison with spectral synthesis codes (Ergon, see below). The ultimate aim is to

distinguish the physical amount of H/He present in the different SE CC SNe to differentiate between different progenitor scenarios (e.g., binaries vs. line driven WR winds).

Another important aspect of early spectroscopy is that this is the most sensitive measure of the explosion energy. This kinetic energy is an important parameter required to constrain the fundamental supernova properties (Ejecta mass, Nickel mass) and are thus needed to firmly assess every single SE CC SN in terms of progenitor/explosion characteristics. We note that early spectroscopy is only warranted for the more nearby cases, and will be pre-selected on known redshifts. For the bulk of the SE CC SN sample it is enough to obtain a spectrum close to peak when the SN is brighter, and there is less urgency.

3. Nickel mixing: how it affects the early SN light curves (early dark phase and steep rise to peak), and how its measurement helps to constrain other explosion and progenitor properties of these SNe

Nickel mixing was mentioned also in the white paper for Type Ia supernovae, and in the white paper for CC SNe. It is a key observable that requires high cadence, at least every night given perfect weather. We mention a few aspects important for SE CC SNe below.
SE SN models, both hydrodynamical (Dessart et al. 2011, MNRAS, 414, 2985) and semianalytic (Piro & Nakar 2013, ApJ,769, 67), show that in case of weak 56Ni mixing the light curves of SE SNe experience a dark plateau phase (lasting up to 10 days and ~3 mag below peak) before a steep rise to the main peak. Dessart also suggests that there could be SN progenitor rich in He which appear He poor i.e. they become SNe Ic when they explode because the ^{56}Ni mixing is weak and the He does not get excited by the ^{56}Ni decay products.

We investigated the existence of this dark phase in a sample of 20 SE SN from the SDSS SN survey (Taddia et al. 2015 A&A, 574, A60), and found only one possible detection of this phase in SN Ibc 2006lc. No SN Ic was found showing this dark early phase, suggesting that the difference between SNe Ib and Ic is due to a genuine lack of He in SN Ic progenitors. Note, however, that SDSS only had an average 4 day cadence.

Learning about the early phase of SE SNe and thus about 56Ni mixing is also crucial to estimate the other explosion and progenitor properties via the modelling of the light around the main peak and at later phases. The degree of 56Ni mixing changes the shape of the light curve also at peak, with strong mixing producing flatter and earlier peaks for example (see e.g., Taddia et al., 2016, A&A, 592, 89). If we can constrain the mixing before fitting for ejecta mass (M), explosion energy (E) and Ni mass M(Ni), we would be able to better constrain all these other properties. A precise estimate of the explosion epoch that would come from high cadence observations is also fundamental to properly model the SN light curve and derive E, M and M(Ni).

With ZTF we will have the opportunity to monitor the early light curves of a large sample of SE SNe, to characterize the possible presence of the proposed early dark phase and at the same time monitoring the steepness of the rising phase and hence infer the degree of 56Ni. This will allow us to then model the later epochs and derive the explosion and progenitor parameters, to infer which kind of star produced them.

4. Statistics: Compare to current samples

We are currently studying the sample of SE CC SNe from iPTF, which includes more than 200 events of which ~120 (30 per subtype, including SN IIb, Ib, Ic and Ic-BL) have pre-max observations. Three sample papers are currently in preparation, about

i) long rising SE SNe possibly coming from single massive progenitors (Karamehmetoglu et al.),
ii) the entire sample of normal SNe Ic (Barbarino et al.),
iii) the entire sample of SNe Ic-BL (Taddia et al. 2017.).

The main point here is that with ZTF, we will outnumber the currently existing samples of each subtype by a factor of 10. Unlike for the Type Ia case, this has great statistical impact on anything we can do regarding the distributions of their progenitors' properties.

5. Color to constrain radius of SE CC SN progenitors

A multi-night, multi-band observing strategy will allow to select very young SE CC SNe that are rapidly rising. For Type Ib iPTF13bvn, Cao et al. 2013 and later Fremling et al. 2016 elaborated on constraining the radius of the progenitor from early time data. The Figure below (from Fremling et al. 2016) shows that in order to truly constrain the radius, high cadence is required. This is likely the strongest cadence constraints from these science cases, as outlined in the Figure caption.

6. Pre-explosion constraints of WR outbreaks

Cadence is important not only or the only detections, but often enough for non-detections. The early "dark phase" for SN with little Nickel mixing (mentioned above) can only be well determined with good time coverage on pre-explosion data. As we have seen in the PTF data, pre-explosion constraints and pre-explosion outbursts (most conspicuous for IIn supernovae, Ofek et al. 2013, Nature 494, 65; Ofek et al. 2014, ApJ, 789, 104; Nyholm et al. 2017, submitted to A&A) . A larger ZTF sample with higher cadence for the SE SNe would allow meaningful constraints on any outbursts from the progenitor systems of SE SNe.

2: Proposed observations

We suggest a non-pointed survey with cadence 2-6 observations per night in the g-band and with supporting intra-night r-band observations. Intersecting r band with I band is acceptable but not necessary. Colors could also come from P60. Photometric accuracy of 0.05 mag is acceptable and much of the calibrations could be done against SDSS or PS1 catalogs. Real time assessments of the candidates and scanning is required, as is fast time access to P60.

3. Supporting observations

This was outlined in the CC white paper. We will continue triggering the NOT telescope, and have also contributed to NTE which will provide guaranteed time. The similar observational strategies required also for the other two WP projects assures that we will profit from collaborating deeply on follow-up observations and initial target selection. LCOGT and/or LT would be good partners for the photometric follow-up.

We will need SEDM spectra only for the more nearby SE CC SNe, so in this sense the burden on P60 will not increase heavily for the enlarged sample. We note that much of the early color information could in fact come from P60 if a fast photometric response is provided, and that for many cases this will provide better constraints on the relevant physics (often just BB temperature) than a lower signal spectrum.

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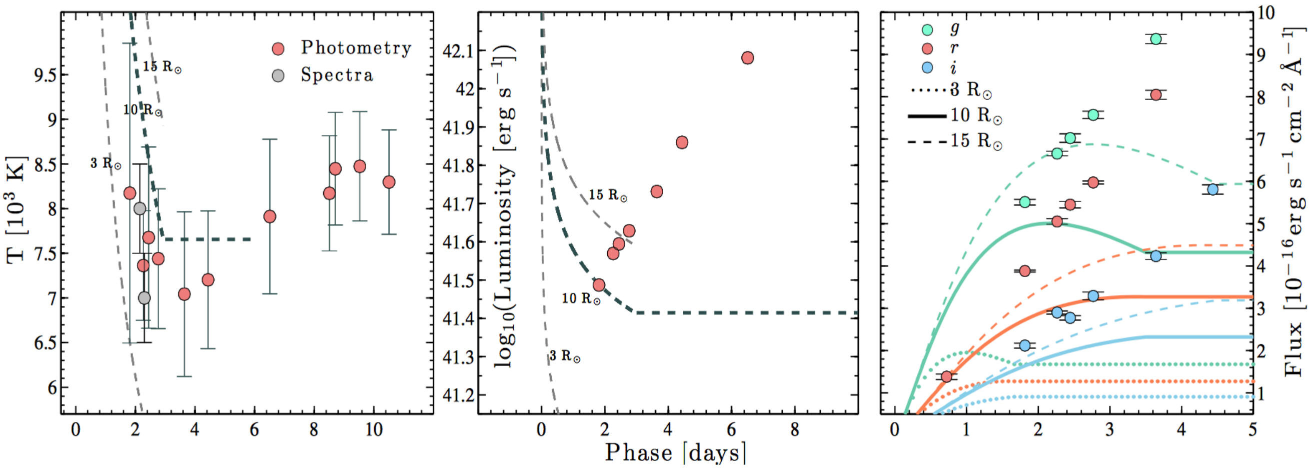
4+5) Expertise to undertake project & Manpower and time-line

As outlined in the Science cases, much of what we here propose is extensions of conducted and ongoing research at the OKC Dept. of Astronomy. In Stockholm, 2 PhD students are currently working on the SE SN science (**Fremling** and **Karamehmetolgu**). We have two post-docs (**Taddia** and **Barbarino**) fully devoted to SE SN science, and both of them have contracts running including 2019, so a large part of the (initial) ZTF era. Mattias **Ergon**, who wrote his thesis on Type IIb SN2011dh with **Sollerman** has now been hirded by **Fransson** to complete a spectral synthesis code that will be most useful for the spectral project presented above. Mattias already have a hydrodynamic light curve code that we have used extensively for SE CC SNe. The observers in Stockholm have now a lot of experience in scanning, which this project will need.



Caption: Figure from Fremling et al. 2016 on Type Ib iPTF13bvn:
Based on the example of iPTF13bvn, where Piro's model is applied, to detect the shock-break-out cooling tail emission in the optical from a SE SN with a progenitor of 10 Rsun we need at least g and r observations once per night of the same field.
The two bands are crucial to build a BB SED which will give us temperature and luminosity at early epochs. If we want to detect the same emission from a 3 Rsun progenitor SE SN, then we need at least 8 visits per night in both g and r, otherwise the early cooling phase is too short to be detected.