



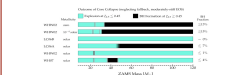
A Search for Failed Supernovae

Jill R. Gerke, C. S. Kochanek & K. Z. Stanek
(The Ohio State University)



Abstract: The SN progenies identified to date are generally less massive than expected (e.g. Smartt 2009) and models suggest that some massive stars ($> 25 M_{\odot}$) may collapse without an explosion. While the exact optical signature of a failed supernova is uncertain, ultimately a massive event or star must vanish, forming a black hole. Using the LBT to survey 25 nearby star-forming galaxies over the next 4 years, we are able to take a statistical approach to the detection of massive stars. By monitoring $\sim 10^6$ supergiants in galaxies with an expected SNR of ~ 2 per year we can place limits on the failed supernova rate. Using image subtraction we identify stars that are likely fading or whose brightness has increased. Thus we can potentially study stars that survey showing current failed supernova candidates. We also discuss the false positives and how they can be characterized. By better understanding the failed SN rate and the fates of massive stars, we can better understand the physics of stellar death, chemical enrichment by massive stars and the possible discrepancy between the cosmic SN rate and the massive star RVE.

Motivation: A search for failed supernovae is very important for our understanding of massive star evolution and end states. By looking for vanishing supergiants we can begin to place limits on the frequency of this phenomenon. This figure from CF Cassini and SN (2011) shows predicted mass ranges for successful and failed supernovae for a range of stellar models.



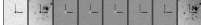
Failed supernovae can also be found by detecting gravity waves or neutrinos from core-collapse in the absence of explosion. While these probes are in early ways, optical existing and planned detectors generally lack the sensitivity to monitor enough galaxies to achieve a measurable rate. Through an optical survey we can achieve both the statistical sample and time baseline necessary to place limits on the rate of failed supernovae.

Selection Criteria: We are searching for vanishing supergiants by examining both sources that are bright stars and sources that are found to be variable. We define 'bright' as a band luminosity of $10^{4.5}$, thereby including all evolved $M_{\odot}$ stars (except for extreme WR stars). We define variable sources as those whose luminosity has changed by $\geq 10\%$ over the baseline of the observations. To be a candidate vanishing supergiant, we then require:

1. The star must be at least 80% as bright in the second epoch as it is in the first epoch.
2. The star faded in luminosity by 10% between the first and last epochs.

While we do look at the linearity of the luminosity decline, this is not a selection criteria. The first criteria is largely to eliminate noise. We are also identifying sources that brighten by 10% over the first and last epoch as a way to estimate our false-positive rate. It would be helpful to have theoretical studies of the observational properties of failed SN.

Preliminary Results: Using these selection criteria, we found 10 candidate vanishing supergiants for M31 as a first test case. Some are promising candidates.



Here we show 8-band postage stamps of a typical candidate. The central panels show the subtracted images, labeled with the date of observation. The first and last images are also displayed. This particular source had an initial luminosity of $10^{4.5}$, and in the last observation had a flux of $10^{3.5}$. The RMS range is empty; the RMS of the subtracted images and is used to identify variable sources, even the absence of crowding. While this source is still clearly visible in our first observation, to date it is still steadily fading and will continue to be monitored as we proceed. Stars showing the type of fading are quite rare.

Statistics: As an example of the limits we will place, assume that in our present survey over $T = 4$ years we find no vanishing supergiants and that the normal SN rate is $R_{SN} = 1$ per year. If the failed SN rate is some fraction C_{SN} of the SN rate, R_{SN} , then the expected number of failed SN is $N_{SN} = C_{SN} \times R_{SN} \times T$. If we find no viable candidates, this implies a 90% confidence limit $P(N_{SN} = 0 | C_{SN} = T) = 0.1 \approx 1/C_{SN}$. As the survey continues, the limit will usually improve such that at ~ 2015 ($T = 8$ years) we will be able to reduce the limit on the failed SN fraction to $C_{SN} = 0.1$ at 90% confidence. Note however, that if the actual rate is $C_{SN} = 0.01$, 0.1 or 0.2 and $R_{SN} = 1$, a 10 year survey has a 40%, 63%, or 80% probability of success, or actually finding a failed SN in a real probability.

References: Smartt, 2009; Adams, 1998; Kochanek et al., 2011; Stanek et al., 2007; Stanek et al., 2008; Stanek et al., 2009; Stanek et al., 2010; Stanek et al., 2011; Stanek et al., 2012; Stanek et al., 2013; Stanek et al., 2014; Stanek et al., 2015; Stanek et al., 2016; Stanek et al., 2017; Stanek et al., 2018; Stanek et al., 2019; Stanek et al., 2020; Stanek et al., 2021; Stanek et al., 2022; Stanek et al., 2023; Stanek et al., 2024; Stanek et al., 2025; Stanek et al., 2026; Stanek et al., 2027; Stanek et al., 2028; Stanek et al., 2029; Stanek et al., 2030; Stanek et al., 2031; Stanek et al., 2032; Stanek et al., 2033; Stanek et al., 2034; Stanek et al., 2035; Stanek et al., 2036; Stanek et al., 2037; Stanek et al., 2038; Stanek et al., 2039; Stanek et al., 2040; Stanek et al., 2041; Stanek et al., 2042; Stanek et al., 2043; Stanek et al., 2044; Stanek et al., 2045; Stanek et al., 2046; Stanek et al., 2047; Stanek et al., 2048; Stanek et al., 2049; Stanek et al., 2050; Stanek et al., 2051; 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