A Search for Failed Supernovae

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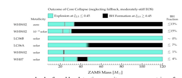
Abstract: The SN progenitors identified to date are generally less massive than expected (e.g. Smartt 2009) and models suggest that some massive stars (> 25 $M_\odot$) may collapse without an explosion. While, the exact optical signature of a failed supernova is uncertain, ultimately a massive evolved star must vanish, forming a black hole. Using the LBT to survey 25 nearby star forming galaxies over the past 4 years, we are able to take a statistical approach to the deaths of massive stars. By monitoring ~10^6 supergiants in galaxies with an expected SNR of ~1 per year we can put useful limits on the failed supernova rate. Using image subtraction we identify stars that are rapidly fading or become invisible. Here we present preliminary results from this 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 SFR.

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 phenomena. This figure from O'Connor and Ott (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 an explosion. While these probes are in many ways simpler, existing and planned detectors generally lack the sensitivity to monitor enough galaxies to achieve a reasonable rate. Through our 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 $10^4 L_\odot$, thereby including all evolved $>8M_\odot$ stars (except for extreme WR stars). We define variable sources as those whose luminosity has changed by $\nu L_\nu = 10^4 L_\odot$ 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 fade in luminosity by 50% 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 novae. We are also identifying sources that brighten by 50% 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 M51 as a first test case. None are promising candidates.

Here we show R-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 $10^{4.5} L_\odot$ and in the last observation had a flux of $10^4 L_\odot$. The RMS image is simply the RMS of the subtracted images and is used to identify variable sources, note the absence of crowding. While this source is still clearly visible in our final observation, to date it is still steadily fading and will continue to be monitored as we proceed. Stars showing this 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 vanished supergiants and that the normal SN rate is $R_{sn} = 1$ per year. If the failed SN rate is some fraction, f_{fs}, of the SN rate, R_{sn}, then the expected number of failed SN is $N_{fs} = f_{fs} \times R_{sn} \times T$. If we find no viable candidates, this implies a 90% confidence limit ($P(0) = e^{-f_{fs} R_{sn} T} = 0.1$) of $f_{fs} < 0.6$. As the survey continues, the limit will steadily improve such that in ~2015 (T = 8 years) we will be able to reduce the limit on the failed SN fraction to $f_{fs} < 0.3$ at 90% confidence. Note however, that if the actual rate is $f_{fs} = 0.05$, 0.1 or 0.2 and $R_{sn} = 1$, a 10 year survey has a 40%, 63%, or 86% probability of success, so actually finding a failed SN is a real possibility.

References: Alard, C. 2000, A&AS, 144, 363; Benvenuto O. G., et al. 2012, arXiv:1207.5807; Bono, G., et al., 2000, ApJ, 529, 293; Gerke, J. R., et al. 2011, ApJ, 743,176; Kochanek, C. S., et al. 2012, ApJ in press; O'Connor, E., & Ott, C. D. 2011, ApJ, 730, 70; Prieto, J. L., et al. 2008a, ApJL, 673, L59; Prieto, J. L., et al. 2008b, ApJL, 681, L9; Szczygiel, D. M., Gerke, J. R., et al. 2012a, ApJ, 747, 23; Szczygiel, D. M., et al. 2012b, ApJ, 750, 77

The Survey:

We are monitoring 25 nearby galaxies with the LBT to enable a statistical study of the deaths of massive stars. The sample of galaxies we are monitoring were chosen to satisfy several criteria:

1. Resolution: within 10Mpc
1. Depth: must be able to study all evolved stars with $M \geq 8M_\odot$
2. SN rate: relatively high, for a combined sample rate of 1 SN per year
3. Orientation: roughly face-on to minimize crowding

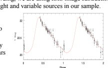
These criteria leave us with 25 nearly face-on spiral galaxies with a collective SN rate of ~1 per year and 10^6 supergiants. The base cadence is about two observations per year. We then try to cycle each galaxy through a period of intensive monitoring to identify periodic variables and control backgrounds. At present, M81, M82, NGC 4258, NGC 2403 and NGC 6946 have these better sampled data. The galaxies are being observed in UBVR, with the R filter going deeper.

State of the Survey:

The survey time baseline is now about 4 years. The galaxies have a median of 8 epochs of data. We are currently processing the data we have for each galaxy to put our first limit on the failed SN rate.

Differential Photometry:

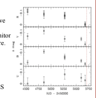
To obtain high precision light curves despite the crowding, we are using ISIS image subtraction (Alard 2000) to generate light curves for both the bright and variable sources in our sample. The example lightcurve, shown at right, is of a 30 day Cepheid in M81 (Gerke et al. 2011). We reliably identified Cepheids with periods down to ten days, which correspond to $6M_\odot$ evolved stars (Bono et al. 2000). This demonstrates that the survey depth is more than adequate to monitor the $\geq 8M_\odot$ stars expected to undergo core-collapse.



Bonus Science:

While the long-term goal of this survey is to place limits on or determine the rate of failed SN, there is a large amount of other science that can be done with this dataset.

Supernova Progenitors:
By monitoring 10^6 supergiants, we are creating an archive that can be used to identify SN progenitors in the galaxies we monitor, as well as to determine their variability. In Szczygiel et al. (2012a) we found that the candidate progenitor star of SN 2011dh in M51 was fading, as shown in the figure. With more epochs, we would easily have detected the ellipsoidal variations predicted in the binary model for this system by Benvenuto et al. (2012).



SN Impostors:
"SN impostors" such as SN 1954J, SN1997bs and SN 2008S can also be studied using the survey. Prieto et al. (2008b) and Szczygiel et al. (2012b) both use this survey to place limits at optical wavelengths for SN 2008S, before and after the explosion, respectively. There are no variable sources associated with SN 1954J or SN1997bs even though there should be given the standard models of these systems (Kochanek et al. 2012).

Cepheids:
In the galaxies we are monitoring more frequently, we can identify Cepheid variables and provide well-sampled light curves. The large field of view of LBT benefits Cepheid studies by building a sample over a large range of galactic radii, a proxy for metallicity. This approach, identifying the Cepheids from the ground and then calibrating them with HST, requires only 10% of the HST time per Cepheid compared to the Key Project. Gerke et al. (2011) presents the results for M81 and we are in the process of analyzing the maser galaxy NGC 4258.

Variable Stars:
Many types of variable stars can be studied. For example, Prieto et al. (2008a) found a yellow supergiant eclipsing binary in Holmberg IX, a dwarf galaxy near M81.