A complete survey of nearby galaxies for supernova progenitors with Roman

Roman Core Community Survey: High Latitude Time Domain Survey

Scientific Categories: stellar physics and stellar types

Additional scientific keywords: stellar physics and stellar types

Submitting Author:
Name: Morgan Fraser
Affiliation: University College Dublin, Ireland
Email: morgan.fraser@ucd.ie

List of contributing authors:
Nancy Elias-Rosa (INAF - Osservatorio Astronomico di Padova; nancy.elias@inaf.it)
Emma Beasor (Steward Observatory, University of Arizona; embeasor@gmail.com)
Robert Byrne (University College Dublin; robert.byrne.6@ucdconnect.ie)

The massive stars that explode as hydrogen-rich supernovae are luminous (log L$\gtrsim 4.3$ dex) and in most cases relatively cool ($T_{eff} < 6,000$ K). Over the past two decades, these characteristics have enabled the progenitors of a handful of core-collapse supernovae to be identified on archival pre-explosion Hubble images of nearby galaxies (e.g. Elias-Rosa et al. 2011, Fraser et al. 2012). This work has revealed a number of surprising results. While red supergiants have been confirmed to end their lives as hydrogen-rich supernovae, we have seen other cases of massive stars exploding unexpectedly as yellow hypergiants (Maund et al. 2011, Van Dyk et al. 2011) or luminous blue variables (Gal-Yam et al. 2007). Furthermore, there is a puzzling absence of high mass ($\gtrsim 17$ $M_\odot$) red supergiants which explode as core-collapse supernovae; whether this is due to obscuration by dust, incorrect interpretation of observations (Davies & Beasor 2018), missing physics in stellar models (Sukhbold & Adams 2020), or whether these stars simply collapse to form black holes remains a matter of some debate (Smartt et al. 2009). We also see evidence for enhanced mass loss on timescales of years to days before a star undergoes core-collapse (Yaron et al. 2017), as well as stars exploding within shells of circumstellar dust (Kilpatrick et al. 2023). To explain these will require both modifications to our current understanding of single star evolution (e.g. Fuller 2017), as well as a better understanding of binary stellar evolution (Eldridge, Izzard & Tout, 2008).

To advance the field observationally, we must first increase the number of nearby supernovae where there are deep, high-resolution pre-explosion images available in multiple filters - at present, if data is available most supernova progenitors are detected in only one or two bands, leading to significant uncertainties on their mass (Beasor et al. in prep). Secondly, we must extend the number of supernovae where there are pre-explosion images in the infrared[1] - this is critical to break the degeneracy between circumstellar dust and progenitor effective temperature (and hence luminosity). Thirdly, we would like to obtain time-series observations of the progenitor to gain insight into stellar activity (including outbursts and eruptions) in the years and months before core-collapse. The Roman Space Telescope can address all three of these challenges.

Identifying supernova progenitors becomes increasingly difficult at greater distances, both as the progenitors appear fainter, and due to source blending and confusion in crowded fields. Experience with the Hubble Space Telescope (which has the same primary mirror diameter as Roman) has shown that in the majority of cases, it is impossible to identify progenitors beyond 30 Mpc. To guide us as to what depth we require, we turn to SNe 2008bk (3.5 Mpc; Maund et al. 2014) and 2012aw (10 Mpc; Fraser et al. 2012). These two supernovae have some of the most comprehensive pre-explosion data covering near-infrared wavelengths. Using the Roman WFI exposure time calculator, we estimate that we would detect the progenitors of these two supernovae at 30 Mpc with a S/N of 10 per filter in a reasonable exposure time.

Assuming an average distance of 10 deg between galaxies, slew and settle and WFI readout will take another 300s. **We can hence observe one galaxy to the depth required to detect a supernova progenitor in six filters with Roman in only one hour.** The exposure times to detect the progenitors of SN 2008bk and 2012aw at a S/N of ~10 at 30 Mpc are listed in the Table below.

[1] At present, images of nearby galaxies in the near-infrared that are sufficiently deep and high resolution are scarce despite Spitzer's legacy.

F062	F087	F106	F129	F184	F213
1200s	300s	100s	100s	600s	1200s

We note that this is an inherently conservative calculation - SN 2008bk was a low mass ($\sim$8 $M_{\odot}$) progenitor, and consequently low luminosity, so detecting such a progenitor at 30 Mpc will be the most challenging case.

The full complement of WFI filters (excluding the wide F146 filter) is necessary in order to cover the full spectral energy distribution of the progenitor - modeling of the progenitor SED allows us to determine the progenitor temperature, luminosity, dust optical depth, and dust temperature. This has only been done in a handful of cases so far (e.g. SN2008bk). Multiple filters allow us to determine accurate stellar progenitors (potentially T_{eff} to $\lesssim$250K, log(L) to $\lesssim$0.1 dex); complete SEDs for a subset of progenitors will also allow us to learn how to best interpret the extant single filter detections. In most cases, a galaxy will subtend only a few arcmin on the sky, and will hence fall on a single WFI detector. For very nearby galaxies, we may mosaic the target - as we can also reduce the exposure time for each pointing, this will still only take $\sim$1 hr.

The final question to consider is how many galaxies we should observe. The core-collapse supernova rate in massive galaxies is around one per 50 years, and so to be confident that a reasonable number of supernovae will subsequently explode in our galaxy sample, we should observe a multiple of this number (the more the better). There is also an upper limit to the number of possible targets, namely the number of massive, bright galaxies within 30 Mpc. From the HyperLeda database, there are around 500 massive, star-forming galaxies within 30 Mpc that are brighter than $B = -19.5$. **We suggest that a comprehensive survey with Roman of all 500 massive galaxies within 30 Mpc would deliver a unique and lasting science legacy**.

As part of building up an archive of deep images of nearby galaxies suitable for identifying supernova progenitors, it would also be of great interest to make repeat observations of a subset of targets. Recent work (e.g. Brennan et al. 2022) has shown that some massive stars undergo hitherto unexpected eruptions and outburts prior to exploding. While some of the brighter examples of these have been serendipitously captured by ground-based surveys, repeated Roman observations over timescales of weeks, months and years allows for variability at the 10% level to be detected. **We suggest that where possible, High Latitude Time Domain Survey fields be chosen so that they also cover a subset of nearby (<30 Mpc) galaxies.**

Around 15 core-collapse supernovae explode within 30 Mpc each year; 10 of these will be hydrogen rich events. With our proposed Roman sample of 500 nearby galaxies, in just two years we could settle the question of whether red supergiants above 16 $M_{\odot}$ collapse to form black holes at the 3σ confidence level[2]. We can also make the first test of supernova explosion models (e.g. Sukhbold et al. 2016) which predict discrete mass ranges of stars to explode.

[2] In two years, we should detect the progenitors of 20 Type IIP SNe. Given a Salpeter Initial Mass Function around 5 of these progenitors should be above 16 $M_{\odot}$. Assuming Poisson statistics, the probability that we detect zero is 0.7%.

The suggested observations are ambitious, and require a substantial investment of Roman time. However, they would also benefit many other fields - resolved stellar populations, massive stars, distances to nearby galaxies, globular clusters and more. It is also important that these observations are taken as early as possible in the mission - as we must subsequently wait for supernovae to explode in our target galaxies.

References

Brennan, S.J. et al., 2022, MNRAS, 513, 5666
Eldridge, JJ., Izzard, R., Tout, C.A. 2008, MNRAS, 384, 1109
Elias-Rosa, N. et al. 2011 ApJ, 742, 6
Davies, B., Beasor, E.R., 2018, MNRAS, 474, 2116
Fraser, M. et al. 2012, ApJL, 759, L13
Fuller, J. 2017, MNRAS, 470, 1642
Gal-Yam, A. et al. 2007, ApJ, 656, 372
Kilpatrick, C.D. et al. arXiv:2306.04722
Maund, J.R. et al. 2011, ApJL, 739, 37
Maund, J.R. et al. 2014, MNRAS, 438, 1577
Smartt, S.J et al. 2009, MNRAS, 395, 1409
Sukhbold, T. et al. 2016, ApJ, 821, 38
Sukhbold, T., Adams, S. 2020, MNRAS, 492, 2578
Van Dyk, S.D. et al. 2011, ApJL, 741, L28
Yaron, O. et al. 2017, Nat.Phys., 13, 510