# Predictions of supernovae shock emergence for wide-field x-ray surveys

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## Abstract

There are currently many large-field surveys operational and planned including the powerful Vera C. Rubin Observatory Legacy Survey of Space and Time. These surveys will increase the number and diversity of transients dramatically. However, for some transients, like supernovae (SNe), we can gain more understanding by directed observations (e.g. shock breakout, γ-ray detections) than by simply increasing the sample size. For example, the initial emission from these transients can be a powerful probe of these explosions. These observations require a large field-of-view X-ray mission with a UV follow up within the first hour of shock breakout. The emission in the first one hour to even one day provides strong constraints on the stellar radius and asymmetries in the outer layers of stars, the properties of the circumstellar medium (e.g. inhomogeneities in the wind for core-collapse SNe, accreting companion in thermonuclear SNe), and the transition region between these two. We generate expected numbers of observations based on instrument parameters in order to determine the performance of future observatories

## Introduction

By studying the shock emergence of supernovae, we can probe the characteristics of the progenitor. The characteristics we will constrain are

- Basic Characteristics (Radius, Asymmetries in Outer Layers)
- Circumstellar Medium
- Characteristics of Stellar Wind

The need to observe shock emergence places significant limitations on the effectiveness of observations using ground based wide field observatories as they are not suited for

- UV Observations
- X-Ray Observations

## Methodology

We use both analytical and simulation based models to generate light curve data for simulated supernovae based on population data. For these methods

- The analytical models focus on
  - The effect of the forward shock in a spherically symmetrical regime
  - Calibrated using SN 2008D & SN 2006aj.
- The simulated models include
  - Spherically symmetrical
  - Constrained by UV during later stages
  - Prescription for shock heating
  - Electron scattering based opacity
  - Solar Metallicity & LTE Assumption

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**Table 2.** Light-Curve Models

| Model | $L^p_{>0.1keV}$ (Log ergs$^{-1}$) | $t^{dur}_{>0.1keV}$ (s) | $L^p_{>0.3keV}$ (Log ergs$^{-1}$) | $t^{dur}_{>0.1keV}$ (s) | $L^p_{UV}$ (Log ergs$^{-1}$) | $t^{dur}_{UV}$ (s) |
|---|---|---|---|---|---|---|
| Analytic | | | | | | |
| $RSG_{Analytic}$ | 43 | | 43 | | | |
| $BSG_{Analytic}$ | 44 | | 44 | | | |
| $WR_{Analytic}$ | 45 | | 45 | | | |
| Simulations | | | | | | |
| RSG1 | 45.2 | 600 | 42.1 | 5000 | 43.9 | 400 |
| RSG2 | 45.5 | 1000 | 43.0 | 600 | 43.7 | 3000 |
| RSG3 | 43.0 | 500 | 36.0 | 3000 | 42.2 | 10,000 |
| RSG4 | 43.2 | 450 | 35.4 | 3000 | 42.1 | 20,000 |
| RSG5 | 43.2 | 450 | 35.4 | 3000 | 42.1 | 20,000 |
| RSG6 | 45.3 | 1600 | 42.7 | 600 | 43.9 | 2000 |
| RSG7 | 45.2 | 800 | 42.4 | 600 | 43.8 | 400 |
| RSG8 | 45.2 | 600 | 42.1 | 6000 | 43.9 | 400 |
| RSG9 | 45.5 | 1000 | 43.2 | 600 | 43.3 | 3000 |

In order to correctly characterize the progenitors and better understand the underlying physics we will need an instrument with X-Ray requirements based on

- need for wide enough field of view to capture sufficient supernovae
- Sensitivity needed to capture breakout peak.
- Far UV is based on need for follow-up during post shock emergence

**Table 1.** Key Instrument Performance Characteristics

| Characteristic | X-ray Instrument | Far-UV Instrument |
|---|---|---|
| Spectral Range | 0.1-10 keV | 136-300 nm |
| Sensitivity ($5\sigma$) | $1.2 \times 10^{-10}$ erg/s/cm$^2$ (24-s exposure) | $8.0 \times 10^{-14}$ erg/s/cm$^2$ (24-s exposure) |
| Field-of-view | 0.20 sr | 900 sq-arcmin |
| Temporal Cadence | 8 s | 0.3 s |
| Localization Accuracy | 3.1′ | 1.0″ |

## Results

We determined an estimate for the number of CCSN observed by a mission characterized by the instrument requirements over a 2 year period.

We included both a 1-sigma and a 3-sigma Gaussian spread in order to bound an optimistic and conservative spread of predicted observations. The information is summarized in the following table.

**Table 4.** Number of CCSNe Visible All-Sky Assuming a Limiting X-Ray Sensitivity of $1.2\times10^{-10}$ erg/s/cm$^2$. This shows a comparison between a higher peak luminosity average with a narrower (1-sigma) distribution versus a lower luminosity peak with a wider (3-sigma) distribution. The values here represent an average from five simulations with the standard deviation from simulation to simulation noted.

| | Gaussian 1-sigma X-ray | Gaussian 1-sigma UV | Gaussian 3-sigma X-ray | Gaussian 3-sigma UV | LANL 1-sigma X-ray | LANL 1-sigma UV | LANL 3-sigma X-ray | LANL 3-sigma UV |
|---|---|---|---|---|---|---|---|---|
| Total SNe at 500 Mpc: | 8232±37 | 5404±56 | 12567±134 | 8831±77 | 9683±61 | 6587±46 | 13028±107 | 10767±111 |
| Total SNe at 200 Mpc: | 1137±18 | 760±18 | 1125±37 | 818±20 | 1276±23 | 942±21 | 1178±17 | 998±12 |
| By Type: | | | | | | | | |
| RSG (500 Mpc): | 668±33 | 324±20 | 5827±23 | 3881±41 | 655±22 | 563±21 | 5832±62 | 5128±68 |
| RSG (200 Mpc): | 209±15 | 111±13 | 540±21 | 368±21 | 197±3 | 168±9 | 556±13 | 496±17 |
| BSG (500 Mpc): | 71±12 | 36±7 | 224±14 | 163±9 | 72±7 | 58±8 | 246±10 | 210±15 |
| BSG (200 Mpc): | 13±4 | 6±2 | 18±2 | 15±3 | 11±3 | 10±3 | 19±3 | 19±3 |
| WR (500 Mpc): | 6905±22 | 4742±49 | 4592±123 | 3408±75 | 8366±37 | 5450±46 | 5041±70 | 3727±59 |
| WR (200 Mpc): | 816±16 | 590±15 | 402±11 | 309±15 | 960±15 | 666±13 | 445±19 | 336±14 |
| Other (500 Mpc): | 588±12 | 303±10 | 1925±22 | 1379±29 | 591±17 | 515±17 | 1909±46 | 1702±43 |
| Other (200 Mpc): | 100±8 | 53±11 | 165±7 | 125±10 | 109±9 | 98±8 | 159±11 | 147±9 |

In addition to these calculations, we will be extending the simulations to examine the parameters of several existing and potential UV/X-Ray missions. This will involve

- Transition to Python Based Tools
- Predict potential observations based on different mission and instrument parameters (vary wavelength, sensitivity, etc.)
- Help determine value of doing archival searches for previous transient observations (Alp 2020)

## Conclusion

Shock breakout has the potential to provide one of the most direct probes of supernova explosions and their progenitors. But to use these as probes, we need to move from observing 1 or 2 serendipitous
shock breakout events to observing a large sample of shock breakout signatures. In this work we used both analytical and simulated models of supernovae shock emergence to predict observed events based on the required.numbers of observed events. This will help constrain the necessary mission parameters to complete a systematic study which would allow us to dramatically increase our understanding of shock breakout and its constraints on supernova explosions and their progenitors.
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