Rapidly Fading Supernovae from Massive Star Explosions

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SN 2010X Discovery

- Extremely rapidly declining light curves
- Similar shape to peculiar SN 2002bj

Kasliwal et al. 2010
Spectroscopic similarity to other SNe Ic suggests a similar origin, but the light curves decline much more rapidly than normal Ibc SNe.
A Small but Growing Class

- Diffusion time (Arnett 1979):
  \[ t_{\text{sn}} \propto M_{\text{ej}}^{1/2} \kappa^{1/2} \nu^{-1/2} \]

- Suggests a small ejected mass (\( \sim 0.1 \, M_\odot \)) as in "Ia" and similar models

SN 2002bj (Poznanski et al. 2010)
SN 2010X (Kasliwal et al. 2010)
SN 2005ek (Drout et al. 2013)
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- Parameterized 1D simulations in homologous expansion
- Broken power law density structure
- Uniform composition (two layers: O/Ne-rich and He+solar)
Problems with the “.Ia” Model

- No radioactive tail seen (could be below limits; could be little γ-ray trapping)
- Deep oxygen features require a large O mass (≈ 0.3 M☉), larger than the total “.Ia” ejected mass of ≈ 0.1 M☉
Different Approach: Core-Collapse Model with Recombination

- If little or no nickel is present, the luminosity could be due to the diffusion of thermal energy deposited in the explosion shock.
- O recombination allows radiation to be released more rapidly.
- This is analogous to a Type II "plateau" (see Ensman & Woosley 1988, Dessart et al. 2011)
Model Light Curves

SN 2010X data; representative model fit; Type Ic SN 1994I for comparison

Model parameters:

\[ M = 3.5 \, M_\odot \]
\[ E = 1 \, B \]
\[ R = 2 \times 10^{12} \, \text{cm} \]

Dominantly O, Ne, Mg in composition
Model Spectrum

O/Ne/Mg-rich ejecta + thin He/solar outer layer
Spectral Time Series

- Color evolution is faster in model spectra than in data, but most major features are reproduced.
- Discrepancies may be due to simplicity of the 1D uniform-composition model and potentially could be reduced with finer tuning.
Hiding Radioactive Nickel
Large Presupernova Radii

| Stage    | Duration (t_{nuc}) | L_{fusion} (L_{\odot}) | Mach (M_{conv}) | \( \tau_c \) (s) |
|----------|--------------------|-------------------------|----------------|------------------|
| Carbon   | \( \sim 10^3 \) yr | \( \sim 10^6 \)         | \( \sim 0.003 \) | \( \sim 10^{4.5} \) |
| Neon     | \( \sim 1 \) yr    | \( \sim 10^9 \)         | \( \sim 0.01 \)  | \( \sim 10^3 \)   |
| Oxygen   | \( \sim 1 \) yr    | \( \sim 10^{10} \)      | \( \sim 0.02 \)  | \( \sim 10^3 \)   |
| Silicon  | \( \sim 1 \) day   | \( \sim 10^{12} \)      | \( \sim 0.05 \)  | \( \sim 10^2 \)   |

See e.g. Quataert & Shiode 2012
Summary

- SN 2010X and similar SNe (SN 2002bj, SN 2005ek, others upcoming) are generally thought to be small-mass explosions, perhaps related to the “.Ia” model.
- Lack of a visible radioactive tail is difficult but not impossible to accommodate in these models.
- Particularly, prominent oxygen features suggest that a large ejected mass is needed.
- We explore core-collapse models in which little or no radioactive material is present in the ejecta—recombination allows for higher masses (O plateau).
- Parameterized radiative transfer calculations agree with the data, but more detailed modeling is required to understand the progenitors.
- How can we avoid ejecting radioactive nickel?
- How can we expand progenitor radii enough to achieve observed luminosities?
Host Galaxies

Hosts of SN 2010X (left) and SN 2002bj (right) are both star-forming galaxies and do not constrain the progenitors

Kasliwal et al. 2010
The presence of helium (He\textsuperscript{ii}) in SN 2010X has three relevant lines: \(\lambda 5876\), \(\lambda 6678\), and \(\lambda 7065\). The absorption feature around 5700 Å can be explained by both He\textsuperscript{ii} and Ca\textsuperscript{ii}. Ti\textsuperscript{ii} has three relevant lines: \(\lambda 5270\), \(\lambda 5314\), and \(\lambda 5354\). The most prominent line is the He\textsuperscript{ii} line at 5876 Å. Therefore, we cannot conclusively say whether or not helium is present in SN 2010X.

The simplest model is an explosion in which all the explosive material is completely ejected. While the expansion speed varies from \(12,000\) km s\(^{-1}\) to \(20,000\) km s\(^{-1}\), the absence of hydrogen at any phase in type II supernovae makes sense if the progenitor had an envelope. Following peak luminosity, the decay is rapid: \(\tau\approx\tau_0\approx\tau_1^{1/2}\). For SN 2002bj as SN 2010X, the decay with the desired value for the slope.

The primary difference is the presence of Ca\textsuperscript{ii} in SN 2010X. We re-fit the spectrum of SN 2002bj with the same elements as in SN 2010X. We find that the presence of Al\textsuperscript{ii} is just as ambiguous as the presence of Ca\textsuperscript{ii}.

Type Ic light curve showing strong features of C, O, Ca.
Degeneracy in the Model

- These three parameters can be adjusted to fit a wide range of Ni-free light curves.
- SN 2010X can also be fit with other combinations of values (lower right panel).

![Graph showing absolute magnitude over time for different values of Mej, E51, and R0.](image)