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# Modeling the early-time spectra of core-collapse supernovae

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Core-collapse supernovae (SNe) are the final act in the evolution of stars more massive than about 8–9 solar masses. Determining the progenitors of these explosive events and how massive stars are linked to the different SN types are topics of major significance for several fields of astrophysics. Recent progress in observational techniques now allow for rapid-response spectroscopic observations of SNe within a day of detection Gal-Yam *et al.* (2014). This allows the study of early phases when the SN shock front has not yet reached spatial scales of $10^{14}$ cm. Depending on the progenitor's wind density and SN shock front velocity, these early-time SN observations may probe epochs early enough that the dense parts of the progenitor wind and circumstellar medium (CSM) have not yet been overrun by the SN shock front.

In Groh (2014) we presented the first quantitative spectroscopic modeling of an early-time supernova (SN) that interacts with its progenitor wind. Using the radiative transfer code CMFGEN, we investigated the recently reported 15.5 h post-explosion spectrum of the type IIb SN 2013cu. We are able to directly measure the chemical abundances of a SN progenitor and find a relatively H-rich wind, with H and He abundances (by mass) of $X = 0.46 \pm 0.2$ and $Y = 0.52 \pm 0.2$, respectively. The wind is enhanced in N and depleted in C relative to solar values (mass fractions of $8.2 \times 10^{-3}$ and $1.0 \times 10^{-5}$, respectively). We obtain that a slow, dense wind or circumstellar medium surrounds the precursor at the pre-SN stage, with a wind terminal velocity $v_{\rm wind} \lesssim 100\ {\rm km\,s^{-1}}$ and mass-loss rate of $\dot{M} \simeq 3 \times 10^{-3}\ (v_{\rm wind}/100\,{\rm km\,s^{-1}})\ M_{\odot}{\rm yr}^{-1}$. These values are lower than previous analytical estimates, although $\dot{M}/v_{\rm wind}$ is consistent with previous work. We also compute a CMFGEN model to constrain the progenitor spectral type; the high $\dot{M}$ and low $v_{\rm wind}$ imply that the star had an effective temperature of $\simeq$ 8000 K immediately before the SN explosion. Our models suggest that the progenitor was either an unstable luminous blue variable or a yellow hypergiant undergoing an eruptive phase, and rule out a Wolf-Rayet star. We classify the post-explosion spectra at 15.5 h as XWN5(h) and advocate for the use of the prefix 'X' (eXplosion) to avoid confusion between post-explosion, non-stellar spectra, and those of massive stars. We show that the XWN spectrum results from the ionization of the progenitor wind after the SN, and that the progenitor spectral type is significantly different from the early post-explosion spectral type owing to the huge differences in the ionization structure before and after the SN event. We find the following temporal evolution: LBV/YHG → XWN5(h) → SN IIb. Future early-time spectroscopy in the UV will further constrain the properties of SN precursors, such as their metallicities.

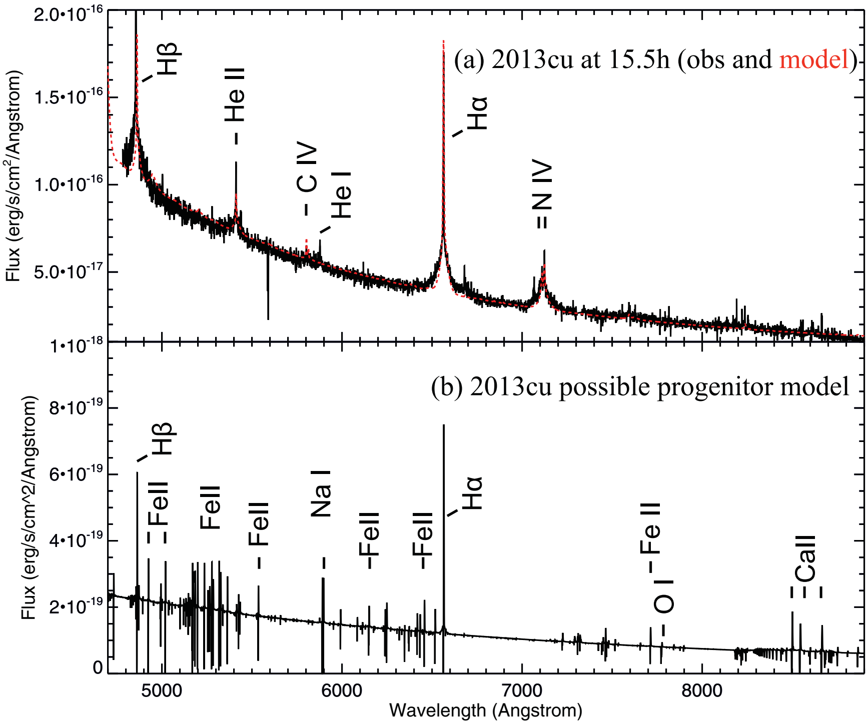

**Figure 1.** (a) Model of the spectrum of SN 2013cu at 15.5h after the explosion (red-dashed line) and the respective observations from G14 (black). The strongest features are labeled. (b) Example of a possible LBV pre-explosion spectrum of the progenitor of SN 2013cu. We note the huge difference in pre- and post-explosion morphology due to very different ionization conditions before and after the SN.

## References

Gal-Yam, A., Arcavi, I., Ofek, E. O., *et al.* 2014, *Nature*, 509, 471
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