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A supergiant progenitor for SN 2011dh

Melina C. Bersten[1], **Omar Benvenuto**[2] **and Ken Nomoto**[1]

[1]Kavli Institute for the Physics and Mathematics of the Universe, Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Japan 277-8583 (Kavli IPMU, WPI)
email: `melina.bersten@ipmu.jp`

[2]Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque S/N, B1900FWA La Plata, Argentina
email: `obenvenu@fcaglp.unlp.edu.ar`

Abstract. A set of hydrodynamical models based on stellar evolutionary progenitors is used to study the nature of SN 2011dh. Our modeling suggests that a large progenitor star —with $R \sim 200\ R_\odot$— is needed to reproduce the early light curve (LC) of SN 2011dh. This is consistent with the suggestion that the progenitor is a yellow super-giant star detected at the location of the SN in deep pre-explosion images. From the main peak of the bolometric light curve (LC) and expansion velocities we constrain the mass of the ejecta to be $\approx 2\ M_\odot$, the explosion energy to be $E = 8 \times 10^{50}$ erg, and the ^{56}Ni mass to be 0.063 $M_\odot$. The progenitor star is composed of a helium core of $\approx 4\ M_\odot$ and a thin hydrogen envelope, and it had a main-sequence mass of $\approx 13\ M_\odot$. Our models rule out progenitors with helium-core masses larger than 8 $M_\odot$, which correspond to $M_{\rm ZAMS} \gtrsim 25\ M_\odot$. This suggests that a single evolutionary scenario for SN 2011dh is highly unlikely.

Keywords. hydrodynamics, stellar evolution, supernovae, SN 2011dh

1. Introduction

SN 2011dh was discovered in the nearby spiral galaxy M51 and classified as a type IIb supernova (SN IIb) because of the early presence of H lines in the spectra that were later dominated by He lines. Soon after discovery, a source was identified as the possible progenitor of SN 2011dh in archival, multi-band HST images (Maund *et al.* 2011; Van Dyk *et al.* 2011). Photometry of the source was compatible with a yellow super-giant (YSG) star with $R \sim 270 R_\odot$. However, some authors have suggested a more compact progenitor ($R \sim R_\odot$), claiming that the YSG star detected in the pre-SN images may be its binary companion or even an unrelated object (Arcavi *et al.* 2011; Van Dyk *et al.* 2011; Soderberg *et al.* 2011). Here we use hydrodynamical models applied to stellar evolutionary progenitors that aim to elucidate the compact or extended nature of the progenitor of SN 2011dh, as well as the main physical parameters of the explosion.

2. Hydrodynamical Models

Our supernova models were computed using a one-dimensional Lagrangian hydrodynamic code with flux-limited radiation diffusion including $\gamma-$ray transfer in gray approximation for any distribution of ^{56}Ni (Bersten *et al.* 2011). As initial model we adopted progenitors with different He core mass from stellar evolution calculations by Nomoto & Hashimoto (1988). The external envelope of the models was removed by hand without specifying the responsible mechanism of such mass loss, thus leaving a compact structure, similar to a Wolf-Rayet star. To take into account the thin hydrogen envelope, we

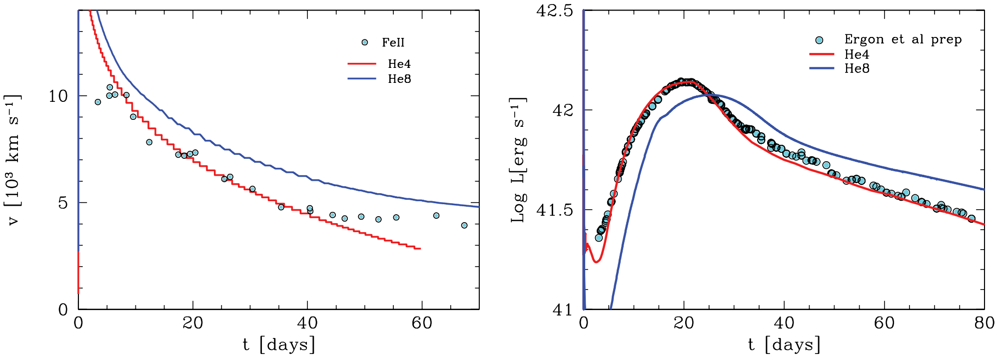

Figure 1. Evolution of the photospheric velocity (**left panel**) and bolometric LC (**right panel**) for our optimal model, He4, with a He core mass of $\approx 4M_\odot$ (red line) and for a model with He core mass of $8M_\odot$ (He8; blue line) as compared with the observed bolometric LC and Fe II line velocities of SN 2011dh (cyan dots). Note that the model with large helium core mass is not compatible with the observations.

smoothly attached a low-mass H-rich envelope in hydrostatic and thermal equilibrium to the He core. The presence of the external envelope significantly modified the progenitor radius but not the mass of the progenitor.

LCs of SNe IIb show two distinct phases (1) the early cooling phase with strong dependence on progenitor radius (see §2.1) and (2) the second peak mainly powered by radioactive decay but also dependent on explosion energy and ejecta mass. Comparing our models with the observed bolometric LC during the second peak and with line expansion velocities we found that a progenitor with He core mass of $\approx 4M_\odot$, an explosion energy of 8×10^{50} erg, and a ^{56}Ni mass of 0.063 $M_\odot$ reproduce very well the observations. This optimal model (He4) is presented in Figure 1 and it is consistent with a main-sequence mass of $\approx$13 $M_\odot$.

2.1. *Compact versus extended progenitor*

In order to test the effect of the progenitor radius on the LC we attached a H/He envelope to the optimal model He4, in hydrostatic and thermal equilibrium. The envelope mass and composition was fit so that the luminosity and effective temperature matched those of a YSG star. Figure 2 (left panel) shows a comparison of our models with the g'-band observations of Arcavi *et al.* (2011) for a compact ($R \approx 2\ R_\odot$; blue line) and an extended ($R \approx 270\ R_\odot$; red line) progenitor. The latter model (He4R270) produces a pronounced spike, in agreement with the observations, while the compact progenitor shows a much weaker bump. From the figure it is clear that obtaining data during the early adiabatic cooling phase is critical to elucidate the progenitor radius.

The right panel of Figure 2 shows the evolution of the effective temperature for the compact and extended models along with a measurement obtained from a spectrum by Arcavi *et al.* (2011). Although the models show large differences at $t \lesssim 2$ days, the evolution is remarkably similar thereafter. That is why the observation obtained at 2.4 days is not a good discriminant of the progenitor radius. Also shown for comparison are the analytic expressions of Rabinak & Waxman (2011) for compact and extended progenitors which do show large temperature differences.

From this analysis we conclude that an extended progenitor, similar to the YSG star detected in pre-SN images, is favored by the early-time observations.

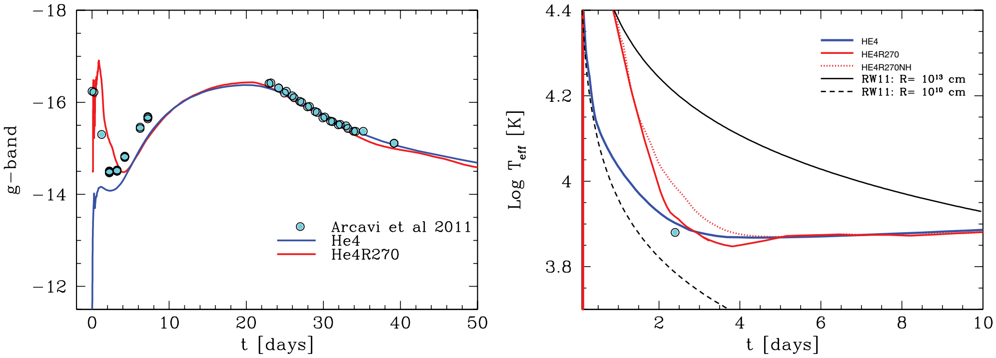

Figure 2. Observed and modeled g'-band LCs **(left panel)** and effective temperature evolution **(right panel)** for the compact model He4 and the extended He4R270 model. The effective temperature calculated using the analytic expression of Rabinak & Waxman(2011) with $R \sim 10^{13}$ cm (solid black line) and $R \sim 10^{10}$ cm (dashed black line) are also shown. The black-body temperature (cyan dot) estimated from a spectrum of SN 2011dh obtained at 2.4 days is included for comparison.

2.2. *Single versus binary progenitor*

Fig1 shows that progenitors with He core masses larger than 8 $M_\odot$ (model He8) which correspond to $M_{\rm ZAMS} \gtrsim 25 M_\odot$ are ruled out. Considering the limitations of single stars of such stellar masses to almost entirely expel the H-rich envelope via stellar winds, as required for SNe IIb, this result is indicative of a binary origin for SN 2011dh.

To test the plausibility of a binary system compatible with the pre-SN observations of SN 2011dh we performed binary evolution calculations with mass transfer using a code developed by Benvenuto & De Vito (2003). Figure 3 shows the evolutionary tracks in the H-R diagram for a system with 16 $M_\odot$ + 10 $M_\odot$ and an initial period of 150

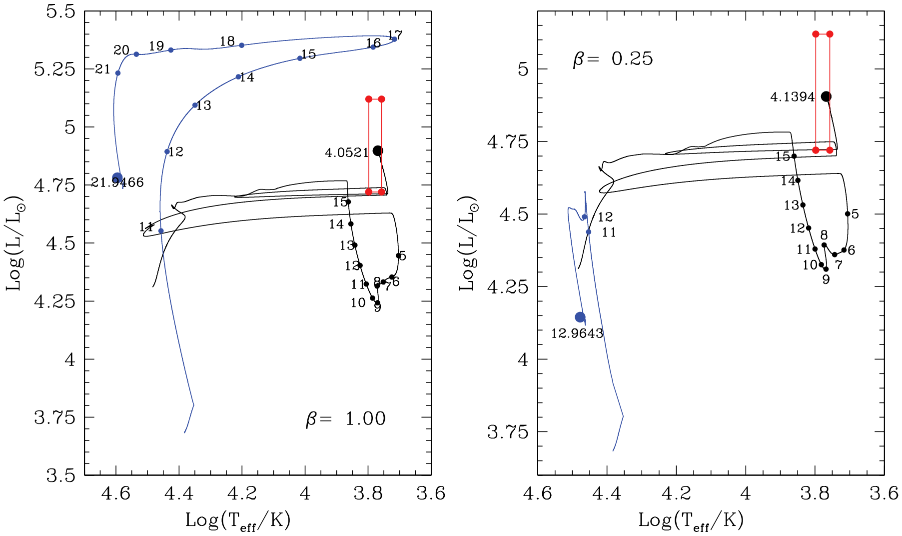

Figure 3. Evolutionary tracks in the Hertzsprung-Russell diagram for both components of a binary system with solar composition. The stars have $M_{\rm ZAMS}$ of 16 $M_\odot$ and 10 $M_\odot$ and an initial period of 150 days. **Left panel:** assuming conservative mass transfer (β = 1). **Right panel:** non-conservative mass transfer (β = 0.25). Labeled dots along the tracks indicate the masses of the stars (in solar units) while mass-transfer by Roche-Lobe overflow occurs.

days. In this configuration the primary star ends its evolution at the right position as compared with the YSG star detected in the pre-SN images. Furthermore, the final mass of the primary is $\approx 4M_{\odot}$, which is consistent with our hydrodynamical modeling. The calculations further predict that a hydrogen envelope with a mass of $\approx 4 \times 10^{-3} M_{\odot}$ is retained by the primary star, which is required to produce a SN IIb.

The binary scenario was further tested by estimating the effect of the putative companion star on the pre-explosion photometry and comparing this with the observations. Because the secondary star is predicted to be much hotter than the primary star, we found that the largest effect appears in the blue and UV ranges. The contribution of the secondary to the flux in the F336W band, however, is marginal, at the 1.5-σ level for a conservative mass-transfer case, and at the 0.6-σ level for a non-conservative case. The existence of the binary companion can be tested in a few years time by a search for a blue object at the location of the SN.

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Discussion

N. Kawai: What is the exact radiation process during the early spike of the LC?

Bersten: The early spike is produced by the shock breakout (the arrival of the shock wave to the object surface). This is also observed for compact progenitors but it is less noticeable because a larger fraction of the shock energy is lost to expand adiabatically a more compact object.

A. Gal-Yam: Would this model fit SN 1993J?

Bersten: I did not calculate a model for SN 1993J in detail but I did some tests and the model seems consistent. In any case the progenitor of SN 1993J was a RSG with a radius $\sim$2 times larger than the radius of the YSG star detected in pre-explosion images of SN 2011dh.

I. Rabinak: What is the mass you have outside of the He-core?

Bersten: The mass of the envelope is a free parameter which is fit when attaching the envelope to the He core for values of L and T_{eff} consistent with a YSG star. The envelope mass in this case is $\approx 0.1M_{\odot}$.