New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry
Proceedings IAU Symposium No. 307, 2014
G. Meynet, C. Georgy, J. H. Groh & Ph. Stee, eds.

doi:10.1017/S1743921314006231

A binary progenitor for the Type Ib Supernova iPTF13bvn

Melina C. Bersten

Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan

Abstract. The recent detection in archival HST images of an object at the the location of supernova (SN) iPTF13bvn may represent the first direct evidence of the progenitor of a Type Ib SN. The object's photometry was found to be compatible with a Wolf-Rayet pre-SN star mass of $\approx 11\,M_{\odot}$. However, based on hydrodynamical models we show that the progenitor had a pre-SN mass of $\approx 3.5\,M_{\odot}$ and that it could not be larger than $\approx 8\,M_{\odot}$. We propose an interacting binary system as the SN progenitor and perform evolutionary calculations that are able to self-consistently explain the light-curve shape, the absence of hydrogen, and the pre-SN photometry. Our models also predict that the remaining companion is a luminous O-type star of significantly lower flux in the optical than the pre-SN object. A future detection of such star may be possible and would provide the first robust progenitor identification for a Type-Ib SN.

Keywords. stars: evolution, hydrodynamics, supernovae: general, supernovae: individual (iPTF13bvn)

1. Introduction

Determining the nature of the progenitor of core-collapse supernovae (SNe) is a crucial problem in astrophysics. For hydrogen-deficient SN (Types Ib and Ic) this is particularly controversial, and single massive stars and close binary systems are the most appealing alternatives. The search for progenitor stars in deep pre-explosion images is a powerful, direct approach, although it so far yielded no firm detection for Type Ib or Ic SN (Yoon *et al.* 2012; Groh *et al.* 2013b). The recent identification of the Type Ib SN iPTF13bvn with a luminous, blue object may represent the first such case (Cao *et al.* 2013) and it led to the suggestion that the progenitor, assuming it to be single, was a Wolf-Rayet star with an initial mass of $31 - 35\,M_{\odot}$ (Groh *et al.* 2013a).

Hydrodynamical modeling of SN observations is an alternative method to infer progenitor properties. This methodology is particularly powerful when combined with stellar evolution calculations. A recent example of the predictability of this technique can be seen in our analysis of the Type IIb SN 2011dh (Bersten *et al.* 2012; Benvenuto *et al.* 2013), which allowed us to provide a self-consistent explanation of the progenitor nature that was later confirmed (Van Dyk *et al.* 2013; Ergon *et al.* 2014). Here we use the same approach to address the problem of the progenitor of iPTF13bvn.

2. Hydrodynamical modeling

A set of explosion models was calculated using our one-dimensional, local thermodynamical equilibrium, radiation hydrodynamics code (Bersten *et al.* 2011). Helium stars of different masses were adopted as initial structures. Specifically, we tested models with $3.3\,M_{\odot}$ (HE3.3), $4\,M_{\odot}$ (HE4), $5\,M_{\odot}$ (HE5), and $8\,M_{\odot}$ (HE8), which correspond to main-sequence masses of 12, 15, 18, and $25\,M_{\odot}$, respectively (Nomoto & Hashimoto 1988).

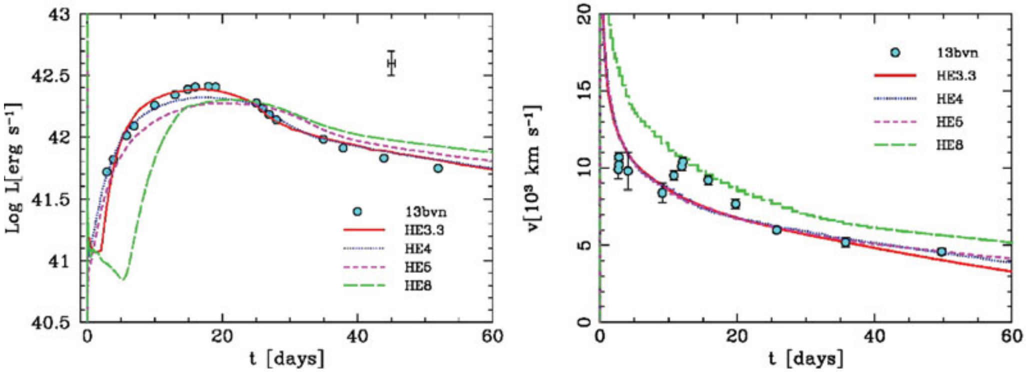

Figure 1. Hydrodynamical modeling of iPTF13bvn. Bolometric light curve (*left panel*) and photospheric velocity evolution (*right panel*) are compared with observations (dots). Models with different masses are shown with different line types and colors. HE3.3 and HE4 give a good representation of the observations but a slightly more massive object, HE5, provides a worse comparison. A model with $8\,M_{\odot}$ (HE8) is clearly not acceptable. The error bars at the top of the figure indicate the nearly constant uncertainty in luminosity and the adopted uncertainty in the explosion time.

Figure 1 shows the results for these models. While HE3.3 and HE4 can reproduce reasonably well the observations (light curve and velocities), a slightly more massive model, HE5, already shows a worse agreement. We adopted as preferred model the one with intermediate parameters between HE3.3 and HE4, i.e. a low-mass He star of $\approx 3.5\,M_{\odot}$, with an ejected mass of $M_{\rm ej} \approx 2.3\,M_{\odot}$, an explosion energy of $E = 7 \times 10^{50}$ erg, and a ^{56}Ni yield of $M_{\rm Ni} \approx 0.1\,M_{\odot}$.

The low progenitor mass suggested by our modeling is in clear contradiction with the range of masses allowed for Wolf-Rayet stars (Langer 2012). Specifically, in Figure 1 we also show the case of a He star with $8\,M_{\odot}$. From the figure it is clear that this model is not able to reproduce the SN observations even considering all the uncertainties related with the model hypotheses and with the observations. Therefore, based on the hydrodynamical modeling we can firmly rule out models with He core mass $\gtrsim 8\,M_{\odot}$ as progenitors of iPTF13bvn.

3. Binary progenitor

The mass we derived from hydrodynamical modeling is difficult to reconcile with the idea of a single progenitor for the Type Ib SN iPTF13bvn. The question is if there are binary configurations capable of simultaneously reproducing the SN properties and the pre-explosion photometry. To address this question we performed binary evolution calculations with mass transfer using a code developed by Benvenuto & De Vito (2003). Figure 2 shows the evolutionary tracks in the Hertzsprung-Russell (H-R) diagram for a system composed by a donor (primary) star of $20\,M_{\odot}$ and an accretor (secondary) star of $19\,M_{\odot}$ on a circular orbit with initial period of 4.1 days, assuming conservative mass transfer (parametrized by the accretion efficiency, $\beta = 1$).

At the time of explosion the primary is a H-free star with a mass of $3.74\,M_{\odot}$ and a radius of $32.3\,R_{\odot}$, in concordance with our hydrodynamical estimations. The companion star reaches a mass of $33.7\,M_{\odot}$, with luminosity and effective temperature $[\log(L_2^{\rm f}/L_{\odot}) = 5.36$ and $\log(T_{\rm eff}/{\rm K}) = 4.64]$ comparable to a zero-age main sequence (ZAMS) star of

https://doi.org/10.1017/S1743921314006231 Published online by Cambridge University Press

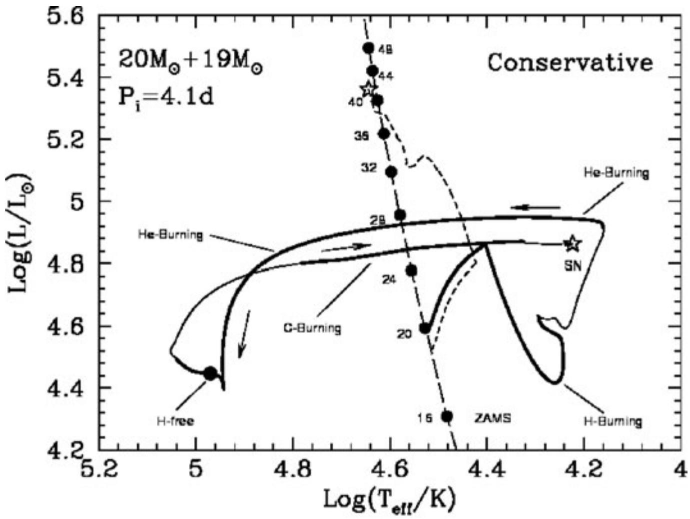

Figure 2. Evolutionary tracks of the binary components of the progenitor of iPTF13bvn for a proposed system with initial masses of 20 $M_\odot$ and 19 $M_\odot$ and an initial orbital period of 4.1 days. The solid line indicates the track of the primary (donor) star (arrows show the evolutionary progress). The short-dashed line shows the evolution of the secondary (accretor) star. Fully conservative accretion ($\beta = 1$) is assumed. The star symbols show the location of both components at the moment of explosion of the primary star. Thick portions of the primary's track indicate the phases of nuclear burning at the stellar core. The long-dashed line shows the locus of the ZAMS, with dots showing different stellar masses (labels in units of $M_\odot$).

$\approx 42\,M_\odot$. Figure 3 shows the composed spectral energy distribution (SED) of the system at the moment of the explosion, compared with the pre-explosion *Hubble Space Telescope* (*HST*) observations of the SN site. A black body spectrum was assumed for the primary star, and an atmosphere model from Kurucz (1993) for the secondary. The synthetic photometry of the progenitor system in the three existing bands is in agreement with the observations within the uncertainties, with differences of less than 0.1 mag. We note that the primary star dominates the flux in the optical regime, so as a result of the SN explosion we predict that the flux in the observed bands will decrease significantly when the SN fades.

The solution to the progenitor system presented here is not unique but it serves to demonstrate the feasibility of the binary progenitor scenario. Based on the pre-explosion photometry and the SN observations, it is possible to analyze the range of allowed binary systems with the aim of predicting the nature of the remaining companion star. We found that the remaining star should necessarily be close to the ZAMS, with a range of luminosities of $4.6 \lesssim \log(L_2^{\rm f}/L_\odot) \lesssim 5.6$ (Bersten *et al.* 2014). This means that the companion star may be detected in the future with deep *HST* imaging in the ultraviolet–blue range. The detection of the companion would produce the first robust identification of a hydrogen-deficient SN progenitor as a binary system.

Note

This work is based on an article recently accepted for publication (Bersten *et al.* 2014).

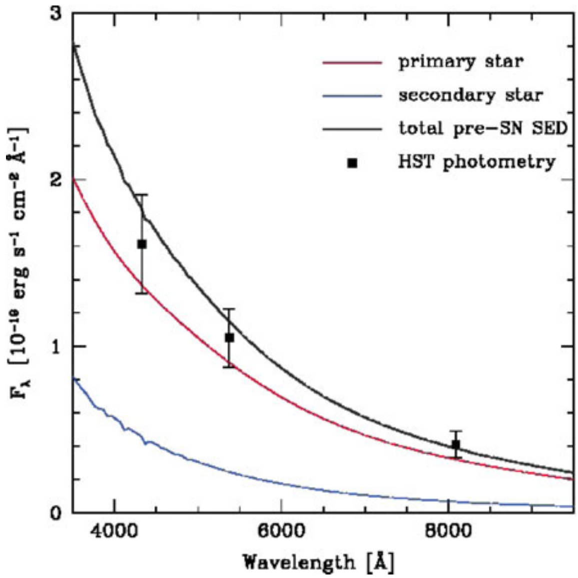

Figure 3. Predicted spectrum of the binary progenitor (solid black line) compared with (*HST*) pre-SN photometry (black squares). The binary spectrum is the sum of a primary star approximated by a black body (red line) and a secondary star represented by an atmosphere model of Kurucz (1993) (blue line). The HST photometry was adopted from Cao *et al.* (2013) and converted to specific fluxes at the approximate effective wavelength of the F435W, F555W, and F814W bands.

References

Benvenuto, O. G., Bersten, M. C., & Nomoto, K. 2013, *ApJ* 762, 74
Benvenuto, O. G. & De Vito, M. A. 2003, *MNRAS* 342, 50
Bersten, M. C., Benvenuto, O., & Hamuy, M. 2011, *ApJ* 729, 61
Bersten, M. C., Benvenuto, O. G., Folatelli, G., *et al.* 2014, *AJ* in press (ArXiv:1403.7288)
Bersten, M. C., Benvenuto, O. G., Nomoto, K., *et al.* 2012, *ApJ* 757, 31
Cao, Y., Kasliwal, M. M., Arcavi, I., *et al.* 2013, *ApJ (Letters)* 775, L7
Ergon, M., Sollerman, J., Fraser, M., *et al.* 2014, *A&A* 562, A17
Groh, J. H., Georgy, C., & Ekström, S. 2013a, *A&A* 558, L1
Groh, J. H., Meynet, G., Georgy, C., & Ekström, S. 2013b, *A&A* 558, A131
Kurucz, R. L. 1993, *Physica Scripta Volume T* 47, 110
Langer, N. 2012, *ARA&A* 50, 107
Nomoto, K. & Hashimoto, M. 1988, *Phys. Rep.* 163, 13
Van Dyk, S. D., Zheng, W., Clubb, K. I., *et al.* 2013, *ApJ (Letters)* 772, L32
Yoon, S.-C., Gräfener, G., Vink, J. S., Kozyreva, A., & Izzard, R. G. 2012, *A&A* 544, L11

Discussion

Groh: You showed very convincingly that the SN lightcurve modeling of iPTF13bvn requires a low mass progenitor, likely from a binary system. Would you be able to user other observables (such as the oxygen mass and radio lightcurve) to further constrain the binary properties such as the mass ratio and initial orbital period?

Bersten: The oxygen mass only provides information about the progenitor mass. I think that the only observable that can provide more information about the binary parameters is the detection of the binary companion. We plan to observe the field with HST in the future to do this.

https://doi.org/10.1017/S1743921314006231 Published online by Cambridge University Press