HOT AND COOL: BRIDGING GAPS IN MASSIVE-STAR EVOLUTION
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The Progenitors of Recent Core-Collapse Supernovae

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Abstract. We present the results of our analysis of *Hubble Space Telescope* (*HST*) and deep ground-based images to isolate the massive progenitor stars of the two recent core-collapse supernovae 2008bk and 2008cn. The identification of the progenitors is facilitated in one of these two cases by high-precision astrometry based on our *HST* imaging of SNe at late times.

1. Supernovae

A supernova (SN) is an explosive event disrupting a star at the end of its (single or binary) evolution, returning to the interstellar medium the major part of the gas synthesized during its evolution and explosion. Their amount and composition depends on the structure of the star and the explosion physics.

A first fundamental classification distinguished the SNe in two different classes based on the lack (SNe I) or presence (SNe II) of hydrogen lines in their early spectra. SNe can be very different one from another as to spectral features (i.e., chemical composition, physical conditions), photometry, overall spectral energy distribution (SED), time evolution, radio and X-ray properties, etc., so in the 1980s, subclasses were introduced—such as Ib, Ic, IIn, IIL, IIP, IIb—which are related to characteristics of their spectra (small letter) or light curves (capital letter).

The SNe of type I are subdivided in three subclasses, depending on the presence (SNe Ia) or lack of Si II (SNe Ib) and He I (SNe Ic) in the spectra.

The class of the SNe II is formed by four main subclasses and their spectra are dominated by H lines at all epochs. The SNe IIP and SNe IIL constitute the most numerous subclasses and are characterized by the shape of the light curve, but they do not show deep spectral differences. The light curve of SNe IIP shows, after the luminosity declines for a few days, a relatively constant luminosity, or plateau, with a duration of approximately 2–3 months. Instead, the light curve of SNe IIL shows a linear decline starting shortly past maximum. The SNe IIn (narrow emission lines) present spectra in which the Balmer emission lines are formed by several components that evolve in time in various ways. The spectrum of the SNe IIb, finally, is similar, during maximum light, to that of the SNe IIP and IIL, i.e., it has strong lines of H, but in the following week it metamorphoses to that of SNe Ib, thus pointing out a physical link between these two classes.

In many cases it has been seen that the appearance of an SN can change over time due to the characteristics of the progenitor or to those of the circumstellar material. Therefore, it is preferable to divide SNe according to the physical character of the explosion, rather than the morphology of the spectra or light curves. Nowadays we divide supernovae in two categories: thermonuclear (observationally called type Ia) and core-collapse SNe.

2. SN 2008bk

SN 2008bk is a type IIP supernova, discovered some weeks after explosion (Monard 2008) in the nearby Scd-type galaxy NGC 7793 (Fig. 1). Li et al. (2008a) first identified a likely red supergiant coincident with the SN position.

The progenitor was first identified in an archival VLT/FORS1 I-band image from 2001 September, using images of the SN obtained by L. A. G. Monard (discovery, Monard 2008) and by Pignata et al. (2008) with the "PROMPT 2" telescope. Additional SN images from the LCO DuPont telescope obtained by N. Morrell and M. Hamuy helped refine the position. The progenitor is not detected in the VLT B- and V-band images. However, it is clearly detected in Gemini/GMOS-S (pixel scale: $0.073''$/pix) images in *gri* filters obtained by T. Davidge (NRC-HIA) of the host galaxy in September 2007 (I-band image is shown in Fig. 1). These images were not obtained under photometric conditions, so we scaled them to the VRI images of the host galaxy obtained at the NOT (Larsen 1999, and private communication). The progenitor identification for SN 2008bk, based on these Gemini data, represents one of the best-resolved examples known, in the same league as the identification of the star Sk $-69^{\rm o}202$ in the LMC for SN 1987A. Such examples are quite rare.

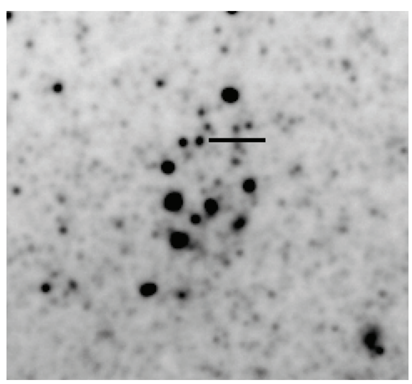
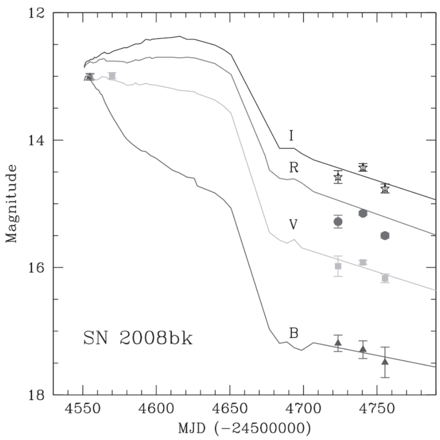


Figure 1. I-band image of the site of SN 2008bk in NGC 7793. The images were taken with Gemini GMOS-S in September 2007. The progenitor is at the left end of the black bar. North is up and east is to the left.

We have used IRAF/DAOPHOT PSF-fitting photometry of both the Gemini and NOT images. We have scaled the two images sets using stars in the environment of SN 2008bk. For the progenitor star we find $V = 23.8$, $R = 22.8$, and $I = 21.4$ mag (although somewhat brighter, the latter agrees to within 1σ, with the VLT I mag derived by Mattila et al. 2008). Other Observations were also obtained for SN 2008bk from Cafos, they are shown in Fig. 2 (*left*). These light curves, however limited, allowed us to constrain the phases of these epochs via a comparison with the light curves of the well-studied SN IIP 1999em (Hamuy et al. 2001; Leonard et al. 2002). With this information we can then compare the $V{-}I$ color for SN 2008bk to that for SN 1999em, but corrected for $E(V{-}I)_{\rm tot} = 0.11$

(Hamuy et al. 2001; Leonard et al. 2002), in order to estimate the color excess $E(V-I)$ from SN 2008bk. From this we derive $E(V-I)_{\rm tot} = 0.05 \pm 0.03$. The distance of NGC 7793 is 3.91 ± 0.41 Mpc (Karachentsev et al. 2003). As Mattila et al. (2008) indicate, the metallicity at the SN site may be subsolar (given the measured metallicity gradient at the star's distance from the host galaxy center). The extinction to SN 2008bk is low, but remains to be better defined.



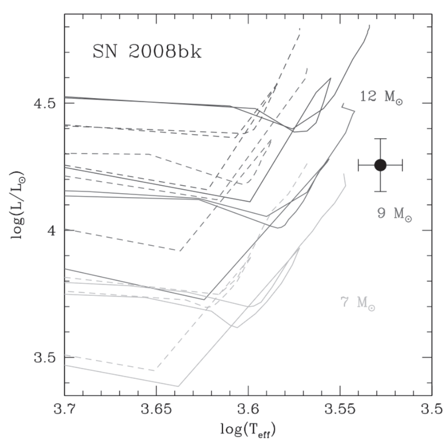


Figure 2. *Left*: *BVRI* light curves of SN 2008bk (*symbols*) compared with those of SN 1999em (Hamuy et al. 2001; Leonard et al. 2002) (*solid lines*). *Right*: Hertzsprung-Russell diagram, absolute bolometric luminosity, $L_{\rm bol}$, vs. effective temperature, $T_{\rm eff}$, for the candidate progenitor of SN 2008bk (*solid circle*), adjusted only for the assumed distance modulus of NGC 7793 (27.96 ± 0.24 mag, Karachentsev et al. 2003) and the Galactic foreground reddening. Model stellar evolutionary tracks are also shown for a range of masses (Lejeune & Schaerer 2001), assuming subsolar ($Z = 0.008$, *dashed lines*) and solar ($Z = 0.02$, *solid lines*) metallicities.

From the previous values, we confirm that the progenitor of SN 2008bk is a red supergiant located in a star cluster, with $T_{\rm eff} = 3370 \pm 100$ K, $M_{\rm bol} = -5.90 \pm 0.26$ mag and $L/L_\odot = 1.80(\pm 0.49) \times 10^4$. In Fig. 2 (*right*) we show a Hertzsprung-Russell diagram of the SN 2008bk progenitor produced using the above parameters. Our results indicate that, for subsolar metallicity, the progenitor's initial mass was $8 \pm 1\,{\rm M}_\odot$, which is in agreement with that estimated by Maoz & Mannucci (2008) and Mattila et al. (2008), and with the range of progenitor masses of other SNe IIP, as systematized by Smartt et al. (2008).

3. SN 2008cn

SN 2008cn is a type IIP supernova, discovered a few days past explosion (Martin & Monard 2008) in the spiral galaxy NGC 4603. Li et al. (2008b) identified a candidate progenitor star in ground-based images.

HST+WFPC2 data were obtained before and after the SN explosion in F555W (V) and F814W (I) filters. The pre-explosion observations were obtained between 1996 and 1997, and the SN is located on the WF2 chip (pixel scale of $0.1''$/px). The post-explosion ToO observations were obtained on 2008 August 26

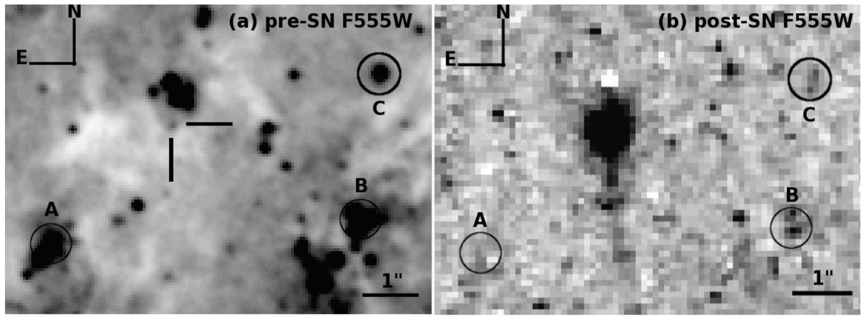


Figure 3. Subsections of the *HST* + WFPC2 images of NGC 4603 before (a) and after (b) the SN 2008cn explosion in F555W. The position of the SN candidate progenitor and SN are indicated by *bars*. The three objects "A," "B," and "C" are the same in both of the images shown. North is up, and east is to the left.

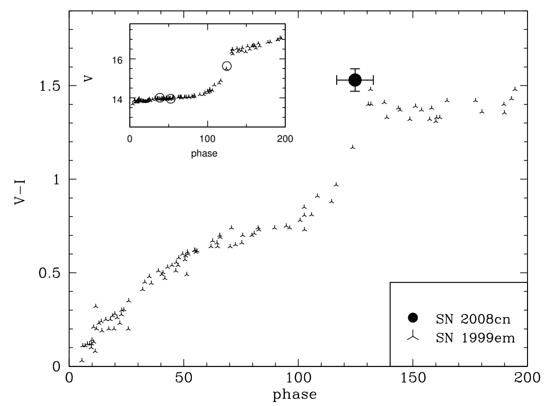


Figure 4. Observed $V - I$ of SN 2008cn (*filled circle*) compared with the color evolution of SN 1999em corrected for $E(V - I) = 0.11$ mag (Hamuy et al. 2001; Leonard et al. 2002). The inset to this figure shows the V-band light curve of SN 2008cn (*open circles*), compared with that for SN 1999em.

as part of GO-11119, and the SN was imaged on the PC chip (pixel scale of $0.049''$/px, see Elias-Rosa et al. 2009a, for more details).

We geometrically transformed the pre-explosion to post-explosion images to achieve high-precision relative astrometry between the SN and progenitor candidate positions. Due to the shallow depth of the post-explosion images, only eight stars were in common between the two sets of images. Comparing pixel-for-pixel both groups of data, we verify the proximity of a point-like candidate near the location of the SN in the pre-explosion images (Fig. 3). We measured the position of the SN and the candidate in two ways: DAOFIND and IMEXAM (both within IRAF). Averages from both methods were obtained to adopt a final position. The differences between the SN and the progenitor candidate after the geometric transformation (16/102 and 15/54 milliarcsecond [mas] in V[RA/Dec] and I [RA/Dec] respectively) are comparable with the total error estimated as a quadrature sum of the errors in the SN and candidate positions (estimated as the standard deviation of the average) and the geometric transformation errors (they are the positional differences between the common stars used in the transformation): 31/66 and 59/42 mas in V(RA/Dec) and I (RA/Dec), respectively.

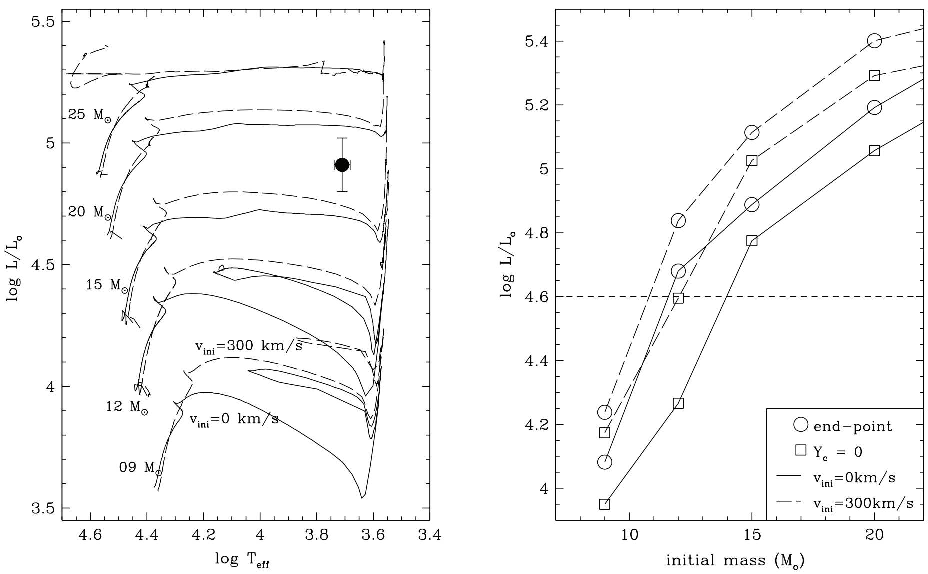


Figure 5. *Left*: A Hertzsprung-Russell diagram, showing the absolute bolometric luminosity, L_{bol}, and effective temperature, $T_{\rm eff}$, for the candidate progenitor of SN 2008cn (*filled circle*). We have assumed a reddening $E(V-I)_{\rm tot} = 0.40$ mag and distance modulus $\mu^0 = 32.61$ mag for the star. Model stellar evolutionary tracks are also shown for a range of masses (Hirschi, Meynet, & Maeder 2004), assuming solar metallicity ($Z = 0.02$) and a rotation of $v_{\rm ini}$=0 km s^{-1} (*solid lines*) and $v_{ini} = 300$ km s^{-1} (*dashed lines*). *Right*: Initial mass vs. endpoint luminosity of the stellar models (Hirschi, Meynet, & Maeder 2004) for $Z = 0.02$ at $v_{\rm ini} = 0$ km s^{-1} (*solid lines*) and $v_{\rm ini} = 300$ km s^{-1} (*dashed lines*). For each mass the luminosities corresponding to the endpoint of the model (*open circles*) and the end of the core-He-burning phase (*open squares*) are shown. The *short-dashed line* indicates the upper luminosity limit for any red supergiant (in the range $27 > V\,[mag] > 29$, $1.6 > V - I\,[mag] > 2.8$) undetected by our analysis of the site of SN 2008cn.

Photometry of the images was done using *HST*phot (Dolphin 2000). The extinction toward the SN was estimated (1) from the equivalent width of the Na I D line at the host galaxy redshift in a high-resolution SN spectrum (Carnegie Supernova Project Team, private communication) and using the relation of **?**, $E[V-I]_{\rm tot} = 0.44 \pm 0.05$; and (2) comparing our late-time *HST* photometry with the color curve of SN 1999em (Hamuy et al. 2001; Leonard et al. 2002, $E[V-I]_{\rm tot} = 0.40 \pm 0.08$, Fig. 4). The distance to NGC 4603, 33.3 ± 0.2 Mpc, has been determined using Cepheid variables (Newman et al. 1999). Given the position of the SN in the host galaxy, we consider a solar metallicity.

It can be seen that determination of the precise position of the faint progenitor is challenging, given the proximity of two brighter stars to the candidate (see Fig. 3), which may have affected the determination of the candidate and SN positions. Comparison of the SN/candidate positional difference and the astrometric uncertainties are suggestive, however, that we have indeed identified the SN progenitor. Considering all previous parameters, we estimate an initial mass for the star $M_{ini} = 18 \pm 2\,M_\odot$ (Fig. 5, *left*). This is slightly beyond the initial mass range expected for the red supergiant progenitors of normal SNe IIP, and the star's color is also somewhat more yellow than we would expect, suggesting the possibility of a blend of two (or more) stars, one being brighter and redder, the other being fainter and bluer. If we conclude that the candidate yellow supergiant is not the SN 2008cn progenitor, then the upper limit to the initial mass of any red supergiant progenitor within ∼5 pixels (∼80 pc) around the SN position is $M_{ini} < 14\,M_\odot$ (Fig. 5, *right*).

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