VLT DETECTION OF A RED SUPERGIANT PROGENITOR OF THE TYPE II-P SUPERNOVA 2008bk

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ABSTRACT

We report the identification of a source coincident with the position of the nearby Type II-P supernova (SN) 2008bk in high-quality optical and near-infrared preexplosion images from the ESO Very Large Telescope (VLT). The SN position in the optical and near-infrared preexplosion images is identified to within about ±70 and ±40 mas, respectively, using postexplosion Ks-band images obtained with the NAOS CONICA adaptive optics system on the VLT. The preexplosion source detected in four different bands is precisely coincident with SN 2008bk and is consistent with being dominated by a single point source. We determine the nature of the point source using the STARS stellar evolutionary models and find that its colors and luminosity are consistent with the source being a red supergiant progenitor of SN 2008bk with an initial mass of 8.5 ± 1.0 M☉.

Subject headings: stars: evolution — supernovae: general — supernovae: individual (SN 2008bk)

Online material: color figure

1. INTRODUCTION

The red supergiant progenitors of several Type II-P supernovae (SNe) have now been directly identified in preexplosion observations. All these are moderate mass red supergiants in the range ∼7–16 M☉ (Smartt et al. 2004; Van Dyk et al. 2003; Maund & Smartt 2005; Maund et al. 2005; Hendry et al. 2006; Li et al. 2006, 2007). Recently, Smartt et al. (2008) have presented a volume-limited systematic study of the progenitors of 20 Type II-P SNe with high-quality preexplosion images available. They find a minimum initial mass of 8.5−1.5 M☉ for the progenitors and suggest that there is a “red supergiant problem” with the red supergiant progenitors more massive than ∼17 M☉ remaining undetected.

In this Letter we report the identification of the progenitor of the Type II-P event, SN 2008bk, making use of adaptive optics (AO) assisted target of opportunity (ToO) observations of the SN using the ESO Very Large Telescope (VLT). SN 2008bk was discovered by Monard (2008) on 2008 March 25.14 UT in the nearby (3.9 Mpc; Karachentsev et al. 2003) Scd-type galaxy NGC 7793. Li et al. (2008) obtained a more precise position for the SN which is 9.2° east and 126.4° north of the host galaxy nucleus. It was spectroscopically classified by Morrell & Stritzinger (2008) as a Type II-P similar to SN 1999em at 36 days after explosion on 2008 April 12.4 UT. This classification is also supported by amateur photometry6 showing a very flat plateau, consistent with a normal Type II-P SN. NGC 7793 has a wealth of prediscovery images available and based on their astrometry, Li et al. (2008) identified a possible progenitor star in an archival J-band image from VLT/FORS. Subsequently Maoz & Mannucci (2008) estimated the J and Ks magnitudes for the progenitor from archival near-infrared (NIR) preexplosion images from VLT/ISAAC. Using accurate relative astrometry between our high-resolution postexplosion AO images and the preexplosion images from the VLT we show that the possible progenitor identified by Li et al. and Mannucci & Maoz is precisely coincident with the position of SN 2008bk and characterize its properties using stellar evolutionary models.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Observations and Data Reductions

The pre- and postexplosion observations of SN 2008bk analyzed in this study are summarized in Table 1. We obtained high quality preexplosion imaging of the SN 2008bk site from the ESO Science Archive. The optical observations were taken with FORS1 (0.20” pixel−1) on UT3 and the NIR observations with ISAAC (0.148” pixel−1) on UT1 and HAWK-I (0.1064” pixel−1) on UT4 of the VLT. The optical frames were bias-subtracted and flat-fielded in IRAF. Zero-point magnitudes were obtained using standard stars in the fields of Mark A, SA 110-362, and PG 1657+078 (Landolt 1992) observed during the same night as the site of SN 2008bk. For this we adopted average color terms and extinction coefficients from Patat (2003). The ISAAC and HAWK-I frames were sky-subtracted using sky frames created from the on-source exposures with the IRAF XDUMISUM package, de-dithered using centroid coordinates of a bright field star visible in all the frames, and median-combined. For the ISAAC J and Ks-band images zero-point magnitudes were obtained using the standards FS1, FS6, FS10, FS32, and FS114 (Leggett et al. 2006) observed before and after the SN site on the same night of observation. Average ESO extinction coefficients were adopted and no color term corrections were applied. For both FORS1 and ISAAC data the average of the zero points obtained from the different standard fields was adopted with their standard deviation as the uncertainty. The calibration was also checked against three bright 2MASS stars which gave the same results within 0.05 mag. The SN site was only covered in two jittered HAWK-I H-band frames which were combined together. For the HAWK-I image the zero-point magnitude and its uncertainty were obtained using five 2MASS stars within the image field.

SN 2008bk was observed with VLT/NACO (Rousset et al. 2003) using Target of Opportunity (ToO) observations as a part of program 081.D-0279 (PI: S. Mattila) on 2008 May 19.4...
(UT). The imaging was carried out in the $K_s$-band with the S27 camera (0.027" pixel$^{-1}$) using the fixed sky offset imaging sequence. The AO correction was performed using the visual wavefront sensor with the SN ($m_v \sim 13$) itself as a natural guide star. The NACO data were reduced using IRAF. The jittered offset frames were median-combined to form a sky frame, the sky subtracted images de-dithered making use of the centroid coordinates of the SN, and the de-dithered frames median-combined. The final reduced image is of very high quality showing near-diffraction limited resolution of $\sim 0.1''$ for the SN (see Fig. 1).

2.2. Relative Astrometry

To precisely determine the SN position on the preexplosion images we derived a geometric transformation between the pre- and postexplosion images. Centroid positions of 26 and 30 point sources were measured in the preexplosion $J$- and $K_s$-band frames, respectively, and in the postexplosion $K_s$-band frame. The IRAF GEOMAP task was used to derive a general geometric transformation between the frames. The identification of a sufficient number of stars common between the pre- and postexplosion observations in other bands was not possible. Instead, we used centroid positions of 19 stars to derive a general geometric transformation between the $I$- and $J$-band frames. The $B$- and $V$-band images were then transformed to the $I$-band image with simple “rscale” transformations (including $x$ and $y$ shifts and a common scale factor and rotation for $x$ and $y$) using centroid positions of 10 stars common between the frames. A transformation was also derived between the preexplosion $H$- and $K_s$-band images. The rms values of the transformations were adopted as the uncertainties (Table 2).

The average of the positions measured for the SN using four different methods (centroid, gauss, and ofilter within the IRAF APHOT package and PSF fitting with SNOOPY$^7$) was then transformed to each preexplosion image. A point-like source is clearly visible at the SN location in the $IJ,H,$ and $K_s$-band preexplosion images. In Figure 1, subsections of the $IJ,$ and $K_s$-band preexplosion images are shown together with the postexplosion image, all centered on the SN position. However, in the $B$ and $V$ bands no source was detected at the SN position. To confirm the coincidence of the preexplosion source with the SN, its position was measured with the four different methods also used for the SN. The average of the measurements was then adopted as the source position and the standard deviation as its uncertainty. In Table 2, the difference between the source and SN positions in $I,J,$ and $K_s$-bands are compared with the total error budget in the relative astrometry (in x/y coordinates). This confirms that the preexplosion source is coincident with the SN position within the 1 $\sigma$ uncertainties in both optical and NIR images.

2.3. Photometry in Preexplosion Images

We used the PSF fitting package SNOOPY to measure the magnitude and coordinates for the preexplosion source in $IJ,H,$ and $K_s$-bands. For this several suitable stars were selected to build the model PSF. Prior to the actual PSF fitting a polynomial surface was fitted to a background region centered on the source position (but excluding the innermost region around the source) and subtracted from the image. In the $I,$ $J,$ and $H$-band residual images (with the PSF subtracted) there was little sign of the original point source, therefore confirming that the preexplosion object is indeed consistent with a single point source in these bands. However, in $K_s$ band there was a faint source left in the residual image about 0.5" south of the de-

\begin{table}[h]
\centering
\caption{Astrometry of Post- and Preexplosion Images}
\begin{tabular}{|c|c|c|c|c|}
\hline
Parameter & $I$ & $J$ & $K_s$ \\
\hline
Error in progenitor position (mas) & 49/28 & 27/7 & 21/4 \\
Error in SN position (mas) & 1/1 & 1/1 & 1/1 \\
Geometric transformation (mas) & 50/57 & 40/40 & 23/24 \\
Total error (mas) & 70/64 & 40/41 & 23/24 \\
Difference in position (mas) & 66/30 & 13/23 & 6/12 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Pre- and Postexplosion Observations of SN 2008bk Site}
\begin{tabular}{|c|c|c|c|}
\hline
Date (UT) & Telescope/Instrument & Filter & Exp. Time (s) \\
\hline
Preexplosion: & & & FWHM (arcsec) \\
2001 Sep 16.0 & VLT/FORS1 & $B$ & 300 & 1.2 \\
2001 Sep 16.0 & VLT/FORS1 & $V$ & 300 & 1.0 \\
2001 Sep 16.0 & VLT/FORS1 & $I$ & 480 & 0.9 \\
2005 Apr 21.6 & VLT/ISAAC & $J$ & $17 \times 60$ & 0.5 \\
2005 Oct 17.1 & VLT/ISAAC & $K_s$ & $58 \times 60$ & 0.4 \\
2007 Oct 16.1 & VLT/HAWKI & $H$ & $2 \times 60$ & 0.8 \\
Postexplosion: & & & \\
2008 May 19.4 & VLT/NACO & $K_s$ & $20 \times 69$ & 0.1 \\
\hline
\end{tabular}
\end{table}

Fig. 1.—Pre- and postexplosion images (11" $\times$ 11") of SN 2008bk site. Each panel is centered on the SN position and oriented such that north is up and east is to the left. (a) Preexplosion VLT/FORS1 $I$-band image, (b) preexplosion VLT/ISAAC $J$-band image, (c) preexplosion VLT/ISAAC $K_s$-band image, (d) postexplosion VLT/NACO $K_s$-band image observed with AO. A pointlike source coincident with the SN position (marked with ticks) is clearly visible in all the three preexplosion frames. The $K_s$-band source is likely a blend between the progenitor and a fainter source $\sim 0.5$" south making the preexplosion source appear slightly elongated compared to stellar PSF in this band (see § 2.3).
and I bands. This yielded the following magnitudes for the preexplosion source: \(m(B) > 22.9 \ (3 \sigma)\), \(m(V) > 23.0 \ (3 \sigma)\), \(m(I) = 21.20 \pm 0.19\), \(m(J) = 19.50 \pm 0.06\), \(m(H) = 18.78 \pm 0.11\), and \(m(K) = 18.34 \pm 0.07\).

### 3. The Progenitor of SN 2008bk

The SN 2008bk host galaxy NGC 7793 has two similar distance estimates of 3.91 ± 0.41 Mpc (Karachentsev et al. 2003) determined from the tip of the red giant branch and 4.1 Mpc from the Tully-Fisher relation reported in HyperLEDA. Here, we adopt the former as the more reliable estimate to be used in this study. The metallicity at the SN 2008bk position was determined using the relationship of Pilyugin et al. (2004) for NGC 7793. The offset of SN 2008bk from the host galaxy nucleus of 9.2° E and 126.4° N (Li et al. 2008) was deprojected for the PA (83.6°) and inclination (53°) of the host galaxy as given by HyperLEDA. The offset corresponds to a radial distance of 3.47′ from the nucleus, at which the oxygen abundance was determined to be about 12 + log (O/H) = 8.2 ± 0.1. Following Smartt et al. (2008) we therefore adopt an LMC metallicity (Z = 0.008) when estimating an initial mass for the progenitor.

Knowledge of the extinction toward the progenitor is important for the accurate determination of the intrinsic color, temperature, and luminosity. The foreground Galactic reddening given by Schlegel et al. (1998) is \(E(B - V) = 0.019\) and there appears to be no clear evidence that the SN suffers from high extinction. Morrell & Stritzinger (2008) suggest the spectrum of SN 2008bk taken on 2008 April 12.4 is similar to SN 1999em (with \(A_V = 0.31 \pm 0.14\); Baron et al. 2000; Smartt et al. 2003) at +36 days after explosion. An additional handle on the total (Galactic+internal) extinction can be provided by determining the Balmer decrement for nearby H II regions. The closest H II region for which a previous spectroscopic study is available is for W13 (McCall et al. 1985), located 1.5′ from the site of SN 2008bk. McCall et al. (1985) provide raw flux measurements of the Balmer lines for W13 which, assuming an intrinsic flux ratio \(H_\alpha/H_B\) of 2.85 (Hummer & Storey 1987), implies \(c(H_\alpha) = 0.67\). For a Cardelli et al. (1989) \(R_V = 3.1\) Galactic extinction law this implies a total extinction of \(A_V = 1.4\). While this estimate is clearly not directly applicable to the line of sight to SN 2008bk, it indicates that typical star-forming regions in the vicinity of SN 2008bk’s environment show significant extinction.

We have used the intrinsic colors of LMC and Galactic red supergiants of Elias et al. (1985) to fit the observed \(BVJHK\) spectral energy distribution of the progenitor. We find that a late-type M4 I supergiantSED can be fit (within the uncertainties) to the observed data with \(A_V = 1\) and Cardelli et al. (1989) extinction law (Fig. 2). The brighter \(K\)-band magnitude of the progenitor could be a suggestion that one (or more) unresolved sources make up the stellar PSF. This is also indicated by the slight elongation of the \(K\)-band preexplosion source (see Fig. 1) and the fact that a faint residual source was left after subtracting the PSF (see § 2.3). However, we note that this slight discrepancy could also be due to color differences between the standard colors and our 2MASS-like estimate. In Figure 2 we also show that we cannot definitely rule out an earlier spectral type with higher \(A_V\), as we can equally well fit the observed SED with an M0 I spectrum and \(A_V = 3\). Indeed one can fit even earlier types (~G-type yellow su-

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**Fig. 2.—** Top panel: The observed SED (open diamonds) of the progenitor matching the reddened colors \((A_V = 1)\) of an M4 I star (LMC colors) from Elias et al. (1985). The thick gray area has a width of ±0.1 mag, to illustrate the range in observed colors of M4 I stars in each band. This band fits the observed SED, with a small discrepancy seen in the range in observed colors of M4 I stars in each band. The bottom panel: Hertzsprung-Russel (H-R) diagrams showing the STARS models for initial stellar masses between 6 and 13 \(M_\odot\). The 6 and 7 \(M_\odot\) model tracks during the second dredge-up phase are indicated by dashed lines. The observed progenitor luminosity and temperature are indicated by a star and their uncertainties as a shaded square. [See the electronic edition of the Journal for a color version of this figure.]
Hence our conclusion that this progenitor is another, moderate- to high-mass red supergiant is unlikely to be affected. Although the cool surface temperature of the source is also consistent with models of super-AGB stars (e.g., Eldridge et al. 2007), its luminosity is lower than would be expected for such a star.

The two best-constrained progenitors for Type II-P SNe before SN 2008bk were for SNe 2003gd and 2005cs. The progenitor for SN 2003gd was found to be a red supergiant with a spectral type in the range of K5 to M3 Ib and an initial mass of $8.5 \pm 1.0 M_\odot$ (Smartt et al. 2004; Van Dyk et al. 2003). The progenitor for SN 2005cs was found to be a red supergiant no hotter than a K5 Ia type (Li et al. 2006; Maund et al. 2005) and have an initial mass between 6 and $8 M_\odot$ (Eldridge et al. 2007).

4. CONCLUSIONS

We have identified a source coincident with SN 2008bk in preexplosion VLT images in four different optical and near-IR bands making use of adaptive optics $K_s$-band images of the SN from VLT. The colors and luminosity of the preexplosion source are consistent with it being a red supergiant having an initial mass of $8.5 \pm 1.0 M_\odot$. The coincidence of the preexplosion source with SN 2008bk makes it the fourth intermediate-mass ($\sim 8 M_\odot$) red supergiant progenitor for a Type II-P SN directly detected in preexplosion images. Our observations also demonstrate the potential of 8 m class telescopes equipped with adaptive optics (see also Gal-Yam et al. 2005; Crockett et al. 2008) in precisely identifying SN progenitors in preexplosion images.

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