THE YELLOW SUPERGIANT PROGENITOR OF THE TYPE II SUPERNOVA 2011dh IN M51

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ABSTRACT

We present the detection of the putative progenitor of the Type IIb SN 2011dh in archival pre-explosion *Hubble Space Telescope* images. Using post-explosion Adaptive Optics imaging with Gemini NIRI+ALTAIR, the position of the supernova (SN) in the pre-explosion images was determined to within 23 mas. The progenitor candidate is consistent with an F8 supergiant star ($\log L/L_\odot = 4.92 \pm 0.20$ and $T_{\mathrm{eff}} = 6000 \pm 280$ K). Through comparison with stellar evolution tracks, this corresponds to a single star at the end of core C-burning with an initial mass of $M_{\mathrm{ZAMS}} = 13 \pm 3\, M_\odot$. The possibility of the progenitor source being a cluster is rejected, on the basis of: (1) the source not being spatially extended, (2) the absence of excess Hα emission, and (3) the poor fit to synthetic cluster spectral energy distributions (SEDs). It is unclear if a binary companion is contributing to the observed SED, although given the excellent correspondence of the observed photometry to a single star SED we suggest that the companion does not contribute significantly. Early photometric and spectroscopic observations show fast evolution similar to the transitional Type IIb SN 2008ax and suggest that a large amount of the progenitor's hydrogen envelope was removed before explosion. Late-time observations will reveal if the yellow supergiant or the putative companion star were responsible for this SN explosion.

1. INTRODUCTION

The search for the progenitors of core-collapse supernovae (CCSNe) is an integral part of the study and understanding of nearby supernovae (SNe). The last decade has shown that archives of high-resolution images of nearby galaxies can provide definitive detections of progenitor stars on images of galaxies gathered before explosion (for a review, see Smartt 2009). The luminosity and inferred mass of progenitors give an insight into the origin of the SN types, the last stages of stellar evolution, and the initial conditions of the explosion.

The most common types by volume, the Type II Plateau (IIP) SNe (Li et al. 2011), have been shown to originate from red supergiants (Van Dyk et al. 2003; Smartt et al. 2004; Maund et al. 2005; Li et al. 2006). The absence of these stars in images taken several years after explosion provides confirmation that they were the stellar progenitors (Maund & Smartt 2009). However, the low- and high-mass ends of the distribution of progenitor masses are providing some unexpected results. The lack of high-mass stellar progenitors is becoming statistically significant (Smartt et al. 2009), and the question of what SNe these high-mass stars ($M_{\mathrm{ZAMS}} > 20\, M_\odot$) produce is critical to understanding stellar evolution, black hole and neutron star formation, and galactic chemical evolution. While a number of high-mass progenitors have been associated with Type IIn SNe (Smith et al. 2011), the frequency of high-mass progenitor

detection is not high enough to comfortably match the expected numbers from initial mass function considerations (Smartt et al. 2009). At the low-luminosity end, faint progenitors have been frequently detected (Maund et al. 2005; Li et al. 2006; Mattila et al. 2008; Fraser et al. 2011). They are often associated with the sub-luminous, low kinetic energy, and ^{56}Ni-poor SNe that resemble SNe 2005cs and 1997D (Pastorello et al. 2009). The obvious interpretation is that these are low-mass stars (7–9 $M_\odot$) producing explosions of low energy $\sim 10^{50}$ erg.

Several observers independently reported discoveries of SN 2011dh in M51 (Reiland et al. 2011), with the earliest recorded epoch being May 31.954, at a position $\alpha_{\mathrm{J2000}} = 13^{\mathrm{h}}30^{\mathrm{m}}05.12$, $\delta_{\mathrm{J2000}} = +47°10'11''$. Silverman et al. (2011) and Yamanaka et al. (2011) classified it as a young Type II SN. The Whirlpool galaxy has hosted three modern SNe (1994I, 2005cs, and 2011dh), and the Hubble Heritage images (Mutchler et al. 2005) provide deep multi-color images for a progenitor star search, as already done for SN 2005cs (Maund et al. 2005; Li et al. 2006). This Letter reports the discovery of a progenitor candidate for SN 2011dh using Gemini North Near InfraRed Imager (NIRI) and ALTitude conjugate Adaptive optics for the InfraRed (ALTAIR) Adaptive Optics (AO) images of the SN and archival pre-discovery optical images. We adopt a distance of 7.1±1.2 Mpc (Takáts & Vinkó 2006) and a recessional velocity of 600 km s^{-1} from NED.[12] The foreground reddening toward M51 as quoted by NED, after Schlegel et al.

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[12] http://ned.ipac.caltech.edu/
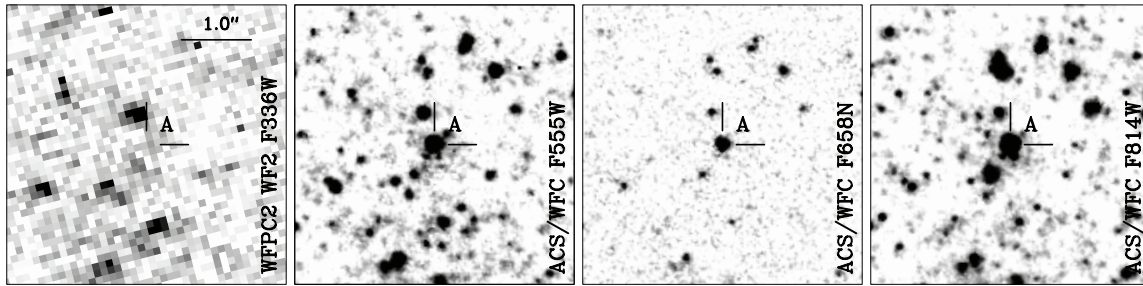
Figure 1. Pre-explosion observations of the site of SN 2011dh. Each panel has dimensions $4'' \times 4''$, and is oriented such that north is up and east is left. The progenitor candidate is denoted Source A. From left to right, the panels are pre-explosion WFPC2 WF2 $F336W$ image and pre-explosion ACS WFC $F555W$, $F658N$, and $F814W$ images.

(1998), is $E(B - V) = 0.035$. Using the metallicity gradient derived by Bresolin et al. (2004) for H II regions in M51, we adopt a metallicity at the SN position of $\sim 0.9 \pm 0.1\ Z_\odot$.

2. THE PROGENITOR STAR

The site of SN 2011dh was observed, prior to explosion, with the *Hubble Space Telescope* (*HST*) Wide-Field Planetary Camera 2 (WFPC2) and the Advanced Camera for Surveys (ACS) Wide Field Channel (WFC) instruments, on 2005 November 13 and 2005 January 20–21. ACS observations were conducted with the $F435W$, $F555W$, $F658N$, and $F814W$ filters of total duration 2720, 1360, 2720, and 1360 s, respectively. A WFPC2 observation from 2005 November 13 used the $F336W$ filter, composed of two equal exposures (1300 s). Additional WFPC2 observations of the site, acquired on 2001 June 9, used the $F450W$, $F555W$, and $F814W$ filters with total exposure times of 2000 s per filter. For both sets of WFPC2 observations, the site of the SN fell on the WF2 chip with pixel scale $0''.1$.

The *HST* data were retrieved from the *HST* archive.[13] The ACS images were combined using the `multidrizzle` task running under PyRAF to correct for the geometric distortion of the ACS WFC chip and improve sampling of the point-spread function (PSF), resulting in a final pixel scale of $0''.025$. Photometry of these images was conducted using DAOPHOT, with PSFs and aperture corrections derived from the data themselves. No correction was applied for charge transfer inefficiency in the drizzled images. In parallel, the four distorted images for each filter were processed separately using the DOLPHOT package,[14] which utilizes pre-computed PSFs and does include corrections for charge transfer inefficiency. The photometry from these two techniques was found to agree to within the photometric errors. The WFPC2 images were processed and analyzed using the HSTPHOT package (Dolphin 2000).

We observed SN 2011dh in the K-filter with NIRI and the ALTAIR AO system on the Gemini North Telescope on 2011 June 6. The bright SN was used as the guide star for ALTAIR. The data were reduced using the IRAF GEMINI NIRI package. The final image has a co-added exposure time of 3000 s, and a full-width at half-maximum of $0''.2$ (after binning by two pixels in both the x- and y-directions).

Geometric transformations between the post-explosion NIRI image and the pre-explosion *HST* ACS and WFPC2 images were calculated with the IRAF task GEOMAP using 18 common stars. Transforming the coordinates of the SN as measured in the NIRI image to the ACS $F814W$ image, we find the SN position to be coincident with a bright, compact source as shown in Figure 1 which we denote as Source A. This progenitor candidate is located 3 mas from the transformed position of the SN (within the 23 mas rms error of the transformation).

In the WFPC2 pre-explosion $F336W$ image, Source A was detected at 4.4σ with $m_{F336W} = 23.39 \pm 0.25$ (in flight system Vega magnitudes). In the drizzled ACS WFC images, Source A was measured to have $m_{F435W} = 22.36 \pm 0.02$, $m_{F555W} = 21.83 \pm 0.04$, $m_{F658N} = 21.28 \pm 0.04$, and $m_{F814W} = 21.20 \pm 0.03$. The 2001 WFPC2 $F450W$, $F555W$, and $F814W$ images give similar magnitudes, approximately 0.1–0.2 mag brighter than the ACS images (due to a number of nearby sources completely blended with Source A in the WFPC2 WF2 images). There is no evidence for variability in the brightness of Source A before explosion. At the adopted distance to M51, after correction for foreground reddening, this implies $M_{F555W} = -7.54 \pm 0.37$. In this region of M51 (for which we use an area of ≈ 8600 arcsec^2), the density of stars as bright or brighter than Source A implies the probability of randomly finding such a source, within the rms error circle of the transformed SN position, as 9.6×10^{-6}.

To determine if Source A was a cluster or a stellar object, we employed the ISHAPE package (Larsen 1999) to probe its spatial extent in the pre-explosion ACS WFC images. After subtracting nearby, well-resolved stars from within a radius of $0''.75$ (or 1.5 times the radius of the calculated PSF), ISHAPE was run on the images with both delta and Moffat (order 1.5) functions convolved with the PSF. ISHAPE was permitted to recalculate the coordinates of the source and the source was permitted to be elliptical. In all cases, the shape of Source A was found to be consistent with an unresolved, point source.

The observed photometry was compared with synthetic photometry for model spectral energy distributions (SEDs) for single stars. We used CHORIZOS (Maíz-Apellániz 2004), an SED fitting package, with ATLAS synthetic spectra (Kurucz 1993)[15] assuming a solar metallicity and a Cardelli et al. (1989) $R_V = 3.1$ reddening law. The observed SED is shown in Figure 2. The parameters derived for Source A are $T_{\rm eff} = 6000 \pm 280$ K, $\log(g) < 4$ and $E(B - V) = -0.01 \pm 0.1$ with $\chi^2 = 2.05$ (dof = 1). The CHORIZOS analysis was tested using a reddening-free index $Q = (F555W - F658N) - 0.947 \times (F658N - F814W)$, which was selected due to its monotonic nature from 4000 to 8000 K and being single-valued for $T > 10{,}000$ K, which yielded identical results using the same ATLAS spectra.
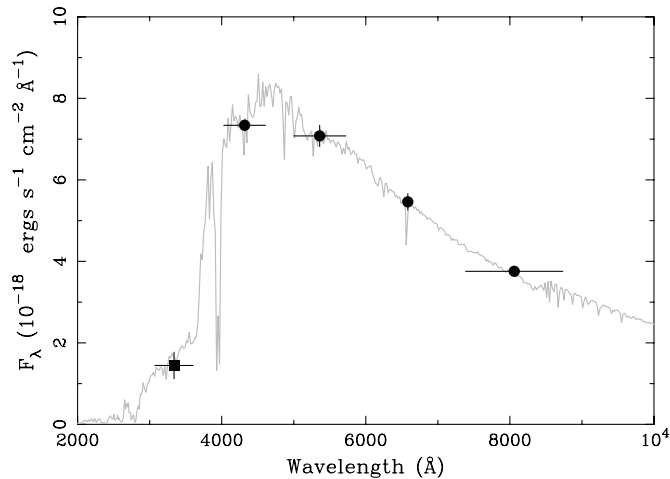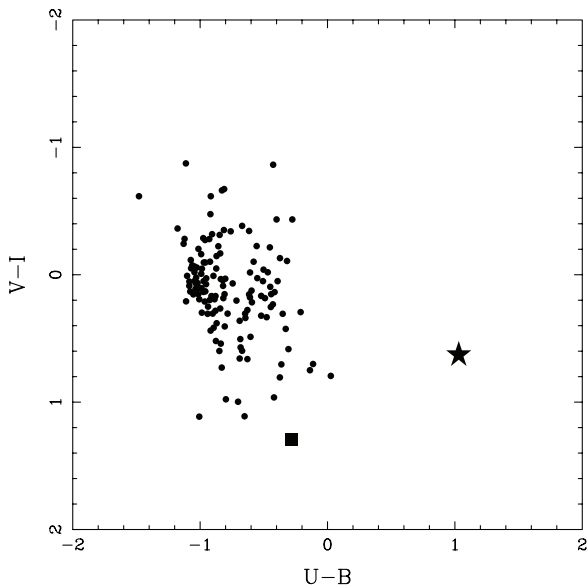

Figure 2. Observed SED of Source A, as measured from pre-explosion *HST* WFPC2 (■) and ACS/WFC (●) images. An ATLAS synthetic spectrum for a star with $T_{eff} = 6000$ K and $\log(g) = 1.0$ is shown in gray.

Figure 3. Observed $U-B$ and $V-I$ colors of Source A (the progenitor candidate for SN 2011dh; ★) and the progenitor of SN 1993J (■), compared with the colors of W-R stars (●) in M33 (Massey et al. 2006). All colors have been corrected for foreground reddening.

The photometry was also compared with the synthetic SEDs of clusters generated using Starburst99 (Leitherer et al. 1999) yielding $\log(\text{age/years}) = 9.9 \pm 0.1$ with $\chi^2 = 11.7$ (dof = 2). This age is significantly higher than the age of clusters observed around the SN location ($\log(\text{age/yr}) < 7.5$; Scheepmaker et al. 2009). This age is also inconsistent with the lifetimes of massive stars $M_{ZAMS} > 8\,M_\odot$ that are expected to end their lives as SNe. A further deficiency in interpreting the observed SED as that of a cluster is the absence of Hα excess, with the observed brightness in $F658N$ being consistent with stellar continuum (see Figure 2).

We compared the $U-B$ and $V-I$ colors of the progenitor candidate to those of the observed population of Wolf-Rayet (W-R) stars in M31 (Massey et al. 2006). All the W-R data have been corrected for foreground Milky Way extinction. As can be seen in Figure 3, the colors of Source A are not consistent with a W-R star. Note that the colors of Source A are in the *HST* flight system, which for the $F435W$, $F555W$, and $F814W$ ACS filters
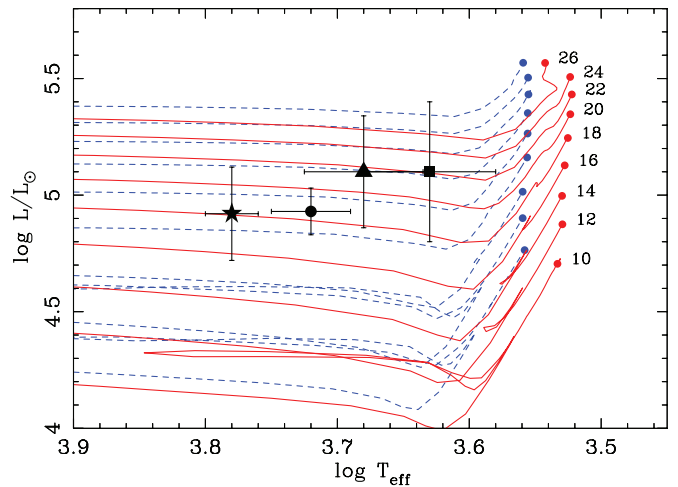
Figure 4. Hertzsprung–Russell diagram showing the luminosities and temperatures of the progenitors of SNe 2011dh (Source A; ★), 1993J (■; Maund et al. 2004; Aldering et al. 1994), 2008cn (●; Elias-Rosa et al. 2009), and 2009kr (▲; Fraser et al. 2010; Elias-Rosa et al. 2010). Overlaid are STARS stellar evolution tracks for solar (red solid) and LMC (blue dashed) metallicities. The initial mass for the progenitor candidate is estimated through comparison with the luminosities of the *end points* of these tracks.

(A color version of this figure is available in the online journal.)

are consistent (to within our photometric uncertainties) with the Johnson–Cousins filters. In the case of the *U*-band, however, the difference between the $F336W$ filter and the Johnson *U* is non-negligible. Using synthetic photometry of Potsdam W-R model SEDs (Gräfener et al. 2002), we find a $U-F336W$ color difference of 0.55 ± 0.2 mag. Applying this to the progenitor, the $U-B$ color increases to 1.5 mag, which makes the discrepancy between the W-R population even more marked.

Given the point-like nature and colors of Source A, we conclude that Source A is consistent with an F8 supergiant star. Utilizing a bolometric correction of (-0.013 ± 0.074) and a color correction Johnson $V - F555W = -0.01 \pm 0.01$, derived from ATLAS spectra, we infer a luminosity for Source A of $\log(L/L_\odot) = 4.92 \pm 0.20$. The location of this object on the Hertzsprung–Russell (H-R) diagram is shown in Figure 4 and compared with STARS stellar evolution tracks (Eldridge & Tout 2004). In deriving the mass estimate we use the *final end point* luminosities for stars at the end of core C-burning (for a discussion see Smartt et al. 2009 and their Figure 1) which yields an initial mass of $13 \pm 3\,M_\odot$. The temperature of the progenitor star is not representative of the star's initial mass, as it may be influenced by external factors such as interaction with a binary companion (which affects the radius). The final luminosity is dependent on the evolution of the core, whose size is dependent on the initial mass of the star (hence, it is inappropriate to compare the position of a progenitor star with the closest stellar evolution track, which in this case would correspond to a star that has just finished core H-burning). This mass estimate using the STARS code is similar to the mass estimates derived using other models that include rotation (see Smartt et al. 2009 and their Figure 2). The object we have called Source A is the same source identified by Van Dyk et al. (2011), however they derive an initial mass of 18–21 $M_\odot$.

3. THE EARLY CHARACTERISTICS OF SN 2011dh

Soon after the announcement of the SN discovery, a wide European collaboration started a monitoring campaign
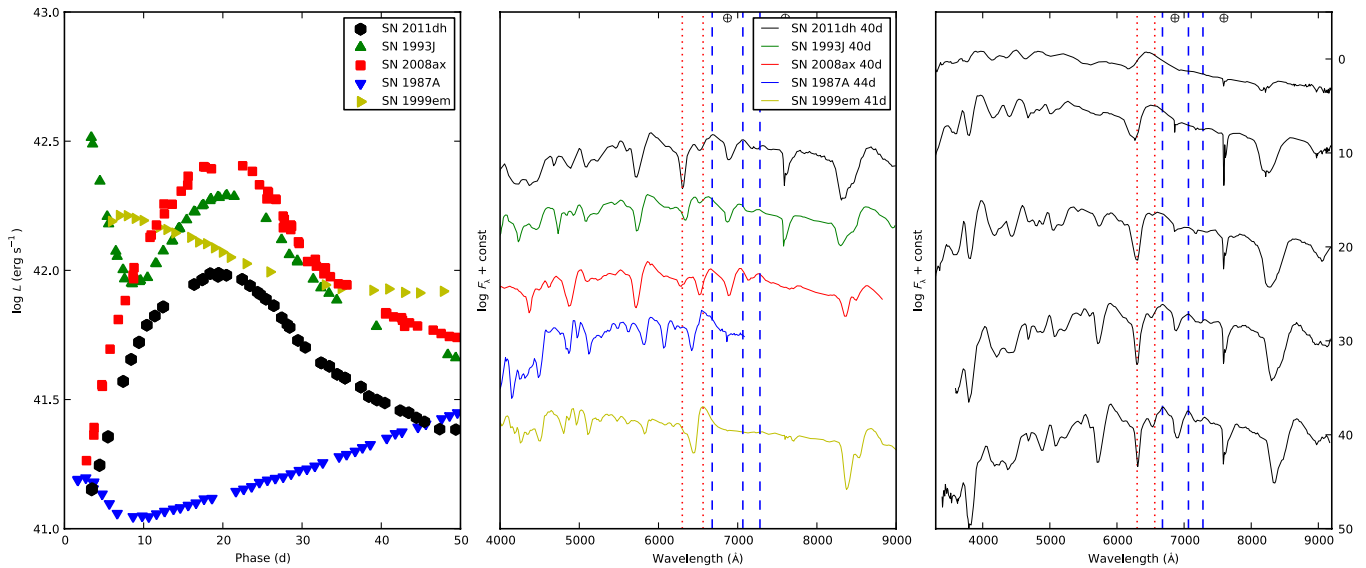
Figure 5. Left panel: pseudo-bolometric UBVRI light curves for SN 2011dh and comparison SNe calculated as described in Fraser et al. (2011). Middle panel: optical spectra for SN 2011dh and comparison SNe at ∼40 d. Telluric lines are indicated with a ⊕ symbol. All spectra have been corrected for redshift as given by NED. Right panel: the spectroscopic evolution of SN 2011dh. Blue (dashed) lines mark the He I λλ6678, 7065, 7281 lines. Red (dotted) lines mark Hα at the rest wavelength and at $-12,500$ km s^{-1}. All spectra and photometry have been corrected for reddening using the extinction law of Cardelli et al. (1989) and $R_V = 3.1$. The phase is given in days relative to an assumed explosion date of 2011 May 31.5, estimated from reported detections and non-detections (Reiland et al. 2011).

(A color version of this figure is available in the online journal.)

using, primarily, the Nordic Optical Telescope, the Liverpool Telescope, the Telescopio Nazionale Galileo, as well as a number of other telescopes available to the collaboration. The results of the complete follow-up campaign will be published in a forthcoming paper (M. Ergon et al. 2011, in preparation). Here we present data obtained during the first ∼50 days after the explosion. All processing of the photometric and spectroscopic data have been performed with the QUBA pipeline (Valenti et al. 2011). The photometry were calibrated using a subset of the reference stars presented in Pastorello et al. (2009).

Our data are presented in Figure 5, where we compare SN 2011dh to the Type IIb SNe 2008ax (Pastorello et al. 2008; Taubenberger et al. 2011; Tsvetkov et al. 2009) and 1993J (Lewis et al. 1994), the peculiar Type IIP SN 1987A (Menzies et al. 1987; Phillips et al. 1988), and the normal Type IIP SN 1999em (Leonard et al. 2002; Baron et al. 2000). The distance and extinction of SN 1987A are from Suntzeff & Bouchet (1990); the explosion epoch and extinction of SN 1999em is from Elmhamdi et al. (2003), while its distance is taken from Leonard et al. (2003).

The spectral evolution (Figure 5) shows the transition from H-dominated spectra at early phases, to spectra showing prominent He I lines typical of Type IIb SNe. At ∼40 days this transition is almost complete. The light curve is similar to those of SNe 2008ax and 1993J, except for the first ∼10 days and the lower luminosity of SN 2011dh. Based on the light curve, the spectral evolution and the overall similarity with SNe 2008ax and 1993J we conclude that SN 2011dh is a Type IIb SN. Arcavi et al. (2011) suggest that the decay of the light curve immediately after shock breakout is consistent with a progenitor of radius ∼10^{11} cm, rather than 10^{13} cm determined for Source A (Soderberg et al. 2011). This may indicate that a companion, rather than Source A, is the progenitor.

Our inference of low reddening from our study of the SED of Source A is supported by the non-detection of Na I D, at the rest wavelength of M51, in high-resolution spectra acquired

as part of our monitoring campaign (M. Ergon et al. 2011, in preparation). We do observe a Na I D component arising in the Galaxy, but this is consistent with the low value of the foreground reddening.

4. DISCUSSION AND CONCLUSIONS

Despite the canonical prediction that Type II SNe arise from red supergiants, there is mounting evidence that some stars explode as yellow supergiants (YSGs). A handful of Type II SNe have been observed to arise from YSGs: SNe 1993J (Aldering et al. 1994; Maund et al. 2004), 2008cn (Elias-Rosa et al. 2009; M. Fraser et al. 2011, in preparation), and 2009kr (Fraser et al. 2010; Elias-Rosa et al. 2010). The locations of the progenitors on the H-R diagram (Figure 4) shows clearly that these stars are not located on the predicted end points for single star stellar evolution tracks. In addition, despite arising from supposedly similar YSG progenitors, these SNe display a wide range of properties. While SN 1993J was a Type IIb SN (with most of its H envelope stripped by mass transfer onto a binary companion), SN 2008cn was a bright Type IIP SN. Elias-Rosa et al. (2010) present evidence that SN 2009kr is a Type IIL SN.

The classification scheme for Type II SNe (IIP → IIL → IIb) may be interpreted as being due to increasing mass loss (i.e., stripping of the H envelope) from the progenitor. The effective temperatures derived for the YSG progenitors and the classification of the resulting SNe shows this scheme is not correlated with the observed $T_{\rm eff}$ of the progenitors (Figure 4).

It is clear from our observations that the SED of Source A is consistent with a late-F supergiant. While possible combinations of two stars in a binary might also be employed to fit the SED, any improvement in the quality of the fit is mitigated by two key factors: (1) a binary companion requires three additional parameters (the temperature and gravity of the secondary and the ratio of the brightness of the two stars) in the fit; and (2) a companion star may not be contributing any measurable

flux to observed SED, yielding a single star SED despite an underlying binary system. Unlike the case of SN 1993J, we do not observe a UV excess associated with a possible companion onto which mass from the progenitor of SN 2011dh may have been transferred (see R. R. Strickler et al. 2011, in preparation for a discussion). We propose that any binary companion is below the detection limit of the pre-explosion observations.

The necessary binary parameters to produce such a YSG progenitor are also unclear. For example, the binary models of Claeys et al. (2011) only produce progenitor stars with $T_{eff} < 3860$ K and in that extreme case the companion is of similar luminosity to the progenitor (with $T_{eff} = 32,200$ K) that would produce significant UV excess not observed in these pre-explosion images.

Despite the photometric and spectroscopic similarity to SN 2008ax, there are significant differences between the proposed progenitor scenarios for that SN (Crockett et al. 2008) and SN 2011dh. While Crockett et al. concluded the photometry of the progenitor of SN 2008ax required either a single W-R star or two stellar components, our observations of the progenitor of SN 2011dh are consistent with a single normal stellar component. If Source A is a companion to the progenitor, rather than the progenitor itself, then the progenitor initial mass will be higher than that inferred for Source A.

In isolation, very massive stars >20 $M_{\odot}$ can lose significant amounts of mass through stellar winds and eruptions (e.g., as luminous blue variables (LBV) and W-R stars). We have demonstrated, however, that the broadband colors of Source A are inconsistent with those of W-R stars. While some caution is required in the application of this analysis to all YSG progenitors of Type II SNe (e.g., the locus of the progenitor of SN 1993J, which was not a W-R star (Maund & Smartt 2009), in Figure 3), that caution is not justified for Source A. As noted by Fraser et al. (2010) for SN 2009kr, there is similarly no evidence for previous LBV eruptions of the progenitor, as we do not detect the signatures of eruptive mass loss such as excess Hα emission in the progenitor photometry or the spectroscopic signature of the SN interacting with a dense circumstellar medium (Figure 5).

The nature of Source A as a single star or binary can be ultimately confirmed at late times, once the SN has disappeared. At these late times it will be possible to ascertain if Source A was indeed the star that exploded or if an unseen companion was responsible (Maund et al. 2004; Maund & Smartt 2009).

REFERENCES

Aldering, G., Humphreys, R. M., & Richmond, M. 1994, AJ, 107, 662
Arcavi, I., et al. 2011, arXiv:1106.3551
Baron, E., Branch, D., Hauschildt, P. H., et al. 2000, ApJ, 545, 444
Bresolin, F., Garnett, D. R., & Kennicutt, R. C. 2004, ApJ, 615, 228
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Claeys, J. S. W., de Mink, S. E., Pols, O. R., Eldridge, J. J., & Baes, M. 2011, A&A, 528, A131
Crockett, R. M., Eldridge, J. J., Smartt, S. J., et al. 2008, MNRAS, 391, L5
Dolphin, A. E. 2000, PASP, 112, 1383
Eldridge, J. J., & Tout, C. A. 2004, MNRAS, 353, 87
Elias-Rosa, N., Van Dyk, S. D., Li, W., et al. 2009, ApJ, 706, 1174
Elias-Rosa, N., Van Dyk, S. D., Li, W., et al. 2010, ApJ, 714, L254
Elmhamdi, A., Danziger, I. J., Chugai, N., et al. 2003, MNRAS, 338, 939
Fraser, M., et al. 2011, MNRAS, in press (arXiv:1101.6558)
Fraser, M., Takáts, K., Pastorello, A., et al. 2010, ApJ, 714, L280
Gräfener, G., Koesterke, L., & Hamann, W.-R. 2002, A&A, 387, 244
Kurucz, R. 1993, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid, Kurucz CD-ROM No. 13 (Cambridge, MA: Smithsonian Astrophysical Observatory), 13
Larsen, S. S. 1999, A&AS, 139, 393
Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJS, 123, 3
Leonard, D. C., Filippenko, A. V., Gates, E. L., et al. 2002, PASP, 114, 35
Leonard, D. C., Kanbur, S. M., Ngeow, C. C., & Tanvir, N. R. 2003, ApJ, 594, 247
Lewis, J. R., Walton, N. A., Meikle, W. P. S., et al. 1994, MNRAS, 266, L27
Li, W., Chornock, R., Leaman, J., et al. 2011, MNRAS, 412, 1473
Li, W., Van Dyk, S. D., Filippenko, A. V., et al. 2006, ApJ, 641, 1060
Maíz-Apellániz, J. 2004, PASP, 116, 859
Massey, P., Olsen, K. A. G., Hodge, P. W., et al. 2006, AJ, 131, 2478
Mattila, S., Smartt, S. J., Eldridge, J. J., et al. 2008, ApJ, 688, L91
Maund, J. R., & Smartt, S. J. 2009, Science, 324, 486
Maund, J. R., Smartt, S. J., & Danziger, I. J. 2005, MNRAS, 364, L33
Maund, J. R., Smartt, S. J., Kudritzki, R. P., Podsiadlowski, P., & Gilmore, G. F. 2004, Nature, 427, 129
Menzies, J. W., Catchpole, R. M., van Vuuren, G., et al. 1987, MNRAS, 227, 39P
Mutchler, M., et al. 2005, BAAS, 37, 452
Pastorello, A., Kasliwal, M. M., Crockett, R. M., et al. 2008, MNRAS, 389, 955
Pastorello, A., Valenti, S., Zampieri, L., et al. 2009, MNRAS, 394, 2266
Phillips, M. M., Heathcote, S. R., Hamuy, M., & Navarrete, M. 1988, AJ, 95, 1087
Reiland, T., Griga, T., Riou, A., et al. 2011, CBET, 2736, 1
Scheepmaker, R. A., Lamers, H. J. G. L. M., Anders, P., & Larsen, S. S. 2009, A&A, 494, 81
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Silverman, J. M., Cenko, S. B., & Filippenko, A. V. 2011, CBET, 2736, 4
Smartt, S. J. 2009, ARA&A, 47, 63
Smartt, S. J., Eldridge, J. J., Crockett, R. M., & Maund, J. R. 2009, MNRAS, 395, 1409
Smartt, S. J., Maund, J. R., Hendry, M. A., et al. 2004, Science, 303, 499
Smith, N., Li, W., Miller, A. A., et al. 2011, ApJ, 732, 63
Soderberg, A. M., et al. 2011, arXiv:1107.1876
Suntzeff, N. B., & Bouchet, P. 1990, AJ, 99, 650
Takáts, K., & Vinkó, J. 2006, MNRAS, 372, 1735
Taubenberger, S., Navasardyan, H., Maurer, J. I., et al. 2011, MNRAS, 413, 2140
Tsvetkov, D. Y., Volkov, I. M., Baklanov, P., Blinnikov, S., & Tuchin, O. 2009, Peremennye Zvezdy, 29, 2
Valenti, S., et al. 2011, MNRAS, in press (arXiv:1106.3030)
Van Dyk, S. D., et al. 2011, arXiv:1106.2897
Van Dyk, S. D., Li, W., & Filippenko, A. V. 2003, PASP, 115, 1289
Yamanaka, M., Itoh, R., Ui, T., et al. 2011, CBET, 2736, 6