THE PROGENITOR OF SUPERNOVA 2011dh/PTF11eon IN MESSIER 51

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ABSTRACT

We have identified a luminous star at the position of supernova (SN) 2011dh/PTF11eon, in pre-SN archival,
multi-band images of the nearby, nearly face-on galaxy Messier 51 (M51) obtained by the *Hubble Space Telescope*
with the Advanced Camera for Surveys. This identification has been confirmed, to the highest available astrometric
precision, using a Keck-II adaptive-optics image. The available early-time spectra and photometry indicate that the
SN is a stripped-envelope, core-collapse Type IIb, with a more compact progenitor (radius $\sim 10^{11}$ cm) than was the
case for the well-studied SN IIb 1993J. We infer that the extinction to SN 2011dh and its progenitor arises from
a low Galactic foreground contribution, and that the SN environment is of roughly solar metallicity. The detected
object has absolute magnitude $M_V^0 \approx -7.7$ and effective temperature $\sim$6000 K. The star's radius, $\sim 10^{13}$ cm, is
more extended than what has been inferred for the SN progenitor. We speculate that the detected star is either
an unrelated star very near the position of the actual progenitor, or, more likely, the progenitor's companion in a
mass-transfer binary system. The position of the detected star in a Hertzsprung–Russell diagram is consistent with
an initial mass of 17–19 $M_\odot$. The light of this star could easily conceal, even in the ultraviolet, the presence of a
stripped, compact, very hot ($\sim 10^5$ K), nitrogen-rich Wolf–Rayet star progenitor.

Key words: galaxies: individual (NGC 5194) – stars: evolution – supernovae: general – supernovae: individual
(SN 2011dh)

1. INTRODUCTION

Determining the stellar origins of supernovae (SNe) is one
of the most compelling areas of modern astrophysics. Progress
has been made over the last two decades in the identification of
the progenitor stars of core-collapse SNe. In this Letter, we con-
sider initial results on the progenitor of SN 2011dh/PTF11eon
in M51. SN 2011dh was discovered independently by sev-
eral amateur astronomers and by the Palomar Transient
Factory (PTF) collaboration between May 31 and June 1
(UT dates are used throughout), within $\sim$1 day of explo-
sion; see Arcavi et al. (2011) and references therein. The
confirmation spectrum by Silverman et al. (2011) showed a
relatively blue continuum and well-developed P-Cygni pro-
files in the Balmer series, with the Hα absorption mini-
mum blueshifted by $\sim$17,600 km s^{-1}, indicating that the
SN was of Type II. The SN has been further classified
as Type IIb (Arcavi et al. 2011). SN 2011dh is being in-
tensely studied at a number of wavelengths. For instance,
the SN was detected early by Margutti & Soderberg (2011)
with the X-ray telescope (XRT) and by Kasliwal & Ofek
(2011) with the ultraviolet-optical telescope (UVOT) on board
Swift; by Horesh et al. (2011b) with the Combined Array for
Research in Millimeter-wave Astronomy (CARMA); and by
Horesh et al. (2011a) with the Expanded Very Large Array
(EVLA). Soderberg et al. (2011) also present early panchromatic
SN observations. The SN position at centimeter wavelengths is
α(J2000) $= 13^h30^m05^s.104$, δ(J2000) $= +47°10'10''.92$ ($\pm 0''.01$

in each coordinate). It is offset $126''.35$ E and $91''.70$ S
from the nucleus of M51a (NGC 5194; $\alpha = 13^h29^m52^s.711$,
$\delta = +47°11'42''.62$; Turner & Ho 1994), along a prominent
spiral arm.

Chevalier & Soderberg (2010) have argued that SNe IIb
can arise from progenitor stars with two very different radii,
extended and compact. Aldering et al. (1994) concluded that
the SN IIb 1993J progenitor was a massive K0-type supergiant,
with bolometric magnitude $M_{\rm bol} \approx -7.8$. The radius of the
star was extended, $\sim 4 \times 10^{13}$ cm (Woosley et al. 1994). The
SN 1993J properties could be explained well by an interacting
binary system model (e.g., Podsiadlowski et al. 1993; Nomoto
et al. 1993; Woosley et al. 1994); furthermore, the progenitor
companion appears to have been recovered spectroscopically a
decade later (Maund et al. 2004). Arcavi et al. (2011) report on
the detection of the shock-breakout cooling tail for SN 2011dh,
which was also seen for SN 1993J (Richmond et al. 1994).
However, the more rapid decline in the early light curve and the
much lower temperature inferred from the SN 2011dh spectra
than was observed for SN 1993J (e.g., Filippenko et al. 1993;
Swartz et al. 1993; Woosley et al. 1994), indicate that the SN
2011dh progenitor was likely more compact, with radius $<$
10^{13} cm. In fact, spectroscopically SN 2011dh more closely
resembles the SN IIb 2008ax (Pastorello et al. 2008; Chornock
et al. 2011; Taubenberger et al. 2011), the progenitor of which
Chevalier & Soderberg (2010) estimated to have had a radius
$\sim 10^{11}$ cm. Soderberg et al. (2011) suggest a radius $\sim 10^{11}$ cm
for the SN 2011dh progenitor as well. We find this evidence
for a compact SN 2011dh progenitor to be plausible and have
assumed it to be the case in this Letter.

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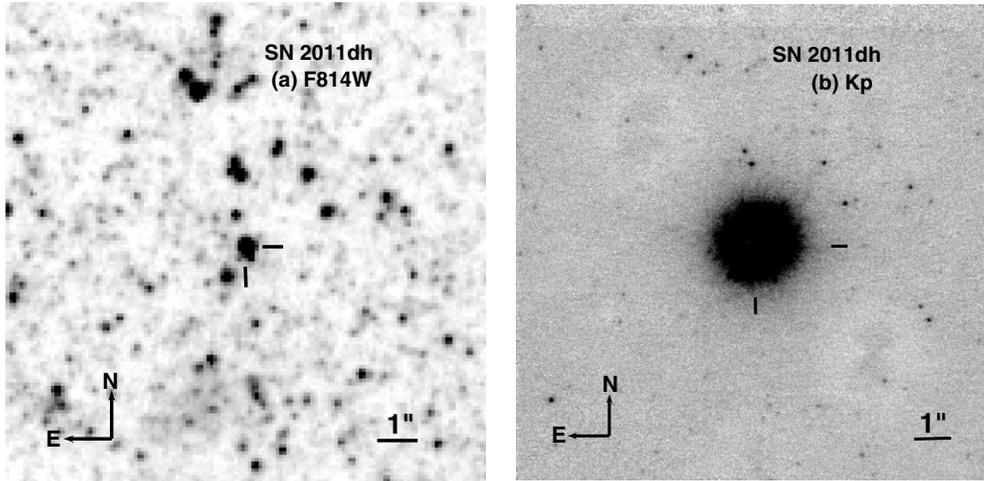
Figure 1. (a) A portion of the archival *HST* F814W image of M51 from 2005; the star detected at the precise location of SN 2011dh/PTF11eon is indicated by tick marks. (b) A portion of the K_p-band AO image obtained using NIRC2 on the Keck-II telescope on 2011 June 6; the SN is indicated by tick marks.

Li & Filippenko ([2011]) first identified a progenitor candidate for SN 2011dh in archival *Hubble Space Telescope* (*HST*) Advanced Camera for Surveys (ACS) images. Li et al. ([2011]) performed further preliminary studies, measuring initial properties of the candidate. Here we undertake a more extensive analysis and attempt to constrain the properties of the SN progenitor system.

The nearly face-on M51, the "Whirlpool Galaxy," also hosted the Type I SN 1945A, Type Ic SN 1994I, and Type II-Plateau (II-P) SN 2005cs. We adopt a distance modulus to M51 of $\mu = 29.42 \pm 0.27$ mag (distance = 7.66 Mpc), from surface brightness fluctuation measurements (Tonry et al. [2001]).[8]

2. OBSERVATIONS AND ANALYSIS

M51 was observed on 2005 January 20–21 by the Hubble Heritage Team (GO/DD 10452; PI: Beckwith) with the ACS Wide Field Channel (WFC). A four-band (F435W, F555W, F658N, and F814W) image mosaic of M51a and NGC 5195 (M51b) was obtained in six ACS pointings, with four dithered exposures at each pointing. These data had been previously analyzed by Li et al. ([2006]) to determine the properties of the SN 2005cs progenitor. The "drizzled" mosaics in each band were taken from the Hubble Legacy Archive (HLA). Individual "flt" exposures were also acquired from the *HST* Archive. The approximate location of the SN site was first established by comparing the HLA mosaics to early-time SN images, obtained with the Katzman Automatic Imaging Telescope (KAIT; Filippenko et al. [2001]) at Lick Observatory.

We subsequently (2011 June 6) took high-resolution, adaptive optics (AO; Wizinowich et al. [2006]) K_p-band (central wavelength 2.124 μm; bandwidth 0.351 μm) images of the SN, using the Near Infrared Camera 2 (NIRC2) instrument on the Keck-II 10 m telescope, to precisely pinpoint the SN location in the archival *HST* data. The geometric distortion corrections from Yelda et al. ([2010]) were first applied to each of the individual NIRC2 frames before combination of all frames into a single image mosaic. Measuring the positions using *imexamine* in IRAF[9]

of 18 stars seen in common between the Keck AO and ACS images, we were able to obtain an astrometric transformation with formal uncertainty $(\Delta X, \Delta Y) = (0.102, 0.109)$ pixel, for a total rms uncertainty of 0.149 ACS pixel, or 7.45 milliarcsecond (mas), in the relative astrometry. The SN position, seen in Figure [1](b), coincides with the point source visible in Figure [1](a). Comparison of the expected ACS pixel position for the SN site, derived from the transformation, to the actual measured position of the source results in an uncertainty of 0.049 ACS pixel = 2.5 mas or $\sim$19,000 AU = 0.09 pc (at the distance of M51). Accordingly, we have very high confidence in the probability that this object, the same as the one identified by Li & Filippenko ([2011]), is spatially coincident with SN 2011dh.

We analyzed the ACS "flt" images in all bands using DOLPHOT[10] (Dolphin [2000]), which is especially designed for ACS. We measured the relative offsets between the dithered exposures in each band, with respect to one fiducial image, before running the package. The output from DOLPHOT automatically includes the transformation from flight-system F435W, F555W, and F814W to the corresponding Johnson–Cousins (Bessell [1990]) magnitudes in *BVI*, following Sirianni et al. ([2005]). Since color corrections are required in the Sirianni et al. ([2005]) relations to transform the flight-system broadband colors into the standard magnitude system, and no such color corrections exist for F658N, the flight-system magnitude in this narrow bandpass could not be transformed to a standard system. DOLPHOT indicates with a flag, as well as with measurements of χ^2 and the parameter "sharpness," whether a detected source is most likely a bona fide star. All of these indicators point to the detected object being stellar.

The SN site was also imaged in a pair of 1300 s exposures with WFPC2 in F336W on 2005 November 13 (GO 10501; PI: Chandar). We performed photometry of these images with HSTPHOT. A source is detected at 4.1σ at the SN position in one of the two exposures, but not in the other one. The results of all of the photometry for the detected star are in Table [1].

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[8] This distance modulus is consistent with 29.41 ± 0.22 mag, determined by Poznanski et al. ([2009]) using the SN II-P standard-candle method applied to SN 2005cs, assuming a Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1}.

[9] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[10] The ACS module of DOLPHOT is an adaptation of the photometry package HSTPHOT (a package specifically designed for use with *HST* Wide-Field Planetary Camera 2 [WFPC2] images; Dolphin [2000]). We used v1.1, updated 2010 January 6, from http://purcell.as.arizona.edu/dolphot/, with, e.g., updated ACS zero points.

Table 1
Photometry of the Star Detected at the SN 2011dh Position[a]

F336W (mag)	F435W (mag)	B (mag)	F555W (mag)	V (mag)	F658N (mag)	F814W (mag)	I (mag)
23.434(339)	22.451(005)	22.460	21.864(006)	21.808	21.392(021)	21.216(005)	21.208

Note. [a] Uncertainties (1σ) are given in parentheses as millimagnitudes.
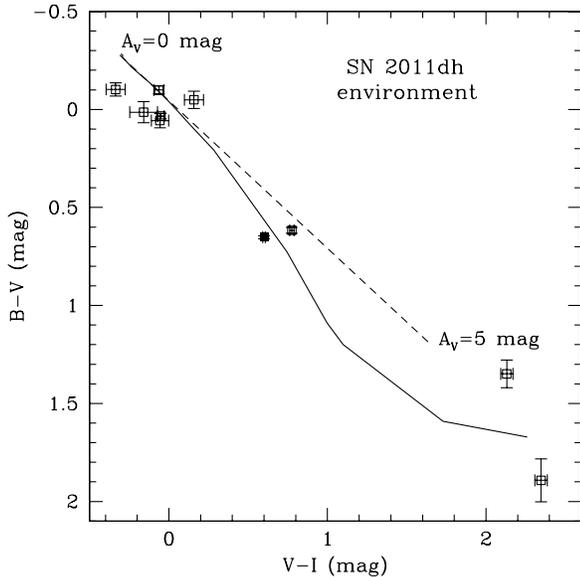
Figure 2. Color–color diagram showing the star detected at the precise location of SN 2011dh/PTF11eon (filled square), along with other stars (open squares) within an area $\sim 91 \times 91$ pc^2 around this location. Also shown for comparison are the locus of (unreddened) supergiants (solid line), derived from Castelli & Kurucz (2003) models, and the reddening vector (dashed line), assuming a Cardelli et al. (1989) reddening law.

3. THE NATURE OF THE DETECTED STAR

To estimate the properties of this star, we need the M51 distance (Section 1) and the SN extinction. To infer the latter, we plot the star's photometry in a color–color diagram in Figure 2. We also show the colors from DOLPHOT of stars in a $\sim 50 \times 50$ pixel ($\sim 91 \times 91$ pc^2) region centered around the SN site. Furthermore, we show the locus for normal supergiants (synthetic Johnson–Cousins colors extracted using the package STSDAS/SYNPHOT within IRAF from model supergiants; Castelli & Kurucz 2003), and the reddening vector from the Cardelli et al. (1989) reddening law. The detected star, as well as other stars in the immediate environment, appears to be subject to relatively low reddening. This agrees with the relative lack of dust emission at the SN site, as seen in pre-SN (2004 May 18 and 22), archival *Spitzer Space Telescope* images of M51 at 8 μm (program ID 159; PI: Kennicutt). This is also consistent with weak or undetectable Na I D absorption in an SN spectrum obtained on June 3 at the Keck-I 10 m telescope using the Low Resolution Imaging Spectrometer (however, see Poznanski et al. 2011 regarding the limited utility of this absorption feature in low-resolution spectra to determine SN extinction), and via a comparison of early SN photometry, obtained using KAIT, with the dereddened colors of SN 2008ax (e.g., Pastorello et al. 2008). The Galactic contribution to the extinction is also relatively low, $A_V = 0.12$ mag, and $E(B - V) = 0.04$ and $E(V - I) = 0.05$ mag (Schlegel et al. 1998). We adopt this foreground value as the extinction toward SN 2011dh.
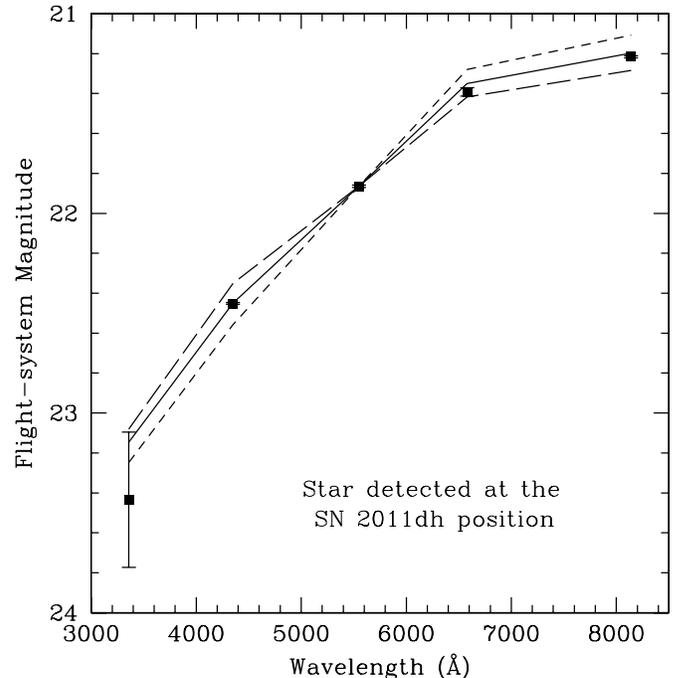

Figure 3. Spectral energy distribution (SED) of the detected star (points) in *HST* ACS/WFC and WFPC2 flight-system magnitudes. Also shown are the SEDs derived from the Castelli & Kurucz (2003) models for supergiants with effective temperatures 5750 K (short-dashed line), 6000 K (solid line), and 6250 K (long-dashed line), after application of the assumed reddening toward the SN (see the text). The models are normalized to the F555W brightness of the star.

We also require the metallicity of the SN environment, which can be inferred from spectroscopy of H II regions nearest the SN site. The regions that Bresolin et al. (2004) labeled "53" (nearest region), "54," and "55" have oxygen abundances $12 + \log(\text{O/H}) = 8.66 \pm 0.09$, 8.49 ± 0.08, and 8.60 ± 0.08, respectively. We assume that these are representative of the SN environment. Given that the solar value is $12 + \log(\text{O/H}) = 8.66 \pm 0.05$ (Asplund et al. 2004) and the average abundance for H II regions in the Large Magellanic Cloud is $12 + \log(\text{O/H}) = 8.37 \pm 0.22$ (Russell & Dopita 1990), we conclude that the SN 2011dh site is most likely of roughly solar metallicity.

We can estimate the effective temperature, T_{eff}, of the detected star by modeling its spectral energy distribution (SED) across all observed bands. We produced template SEDs via synthetic photometry, extracted using SYNPHOT, from Castelli & Kurucz (2003) model stars at solar metallicity with $\log g = 1.0$ (see below), reddened by our assumed value. We made the comparison in flight-system magnitudes, since the F658N measurement from DOLPHOT and the F336W upper limit from HSTPHOT could not be transformed to a standard system. The results are shown in Figure 3. The model with $T_{\text{eff}} = 6000$ K compares well with the observations (particularly those in the ACS bands).

We therefore adopt this temperature for the observed star, with a conservative uncertainty of ±100 K.

From the adopted distance modulus, extinction, and reddening, we find that the object had an absolute intrinsic magnitude of $M_V^0 = -7.73$, and intrinsic colors $(B - V)^0 = 0.61$ and $(V - I)^0 = 0.55$ mag. We estimate that the probability is $\sim4 \times 10^{-6}$ that a star more luminous than this in M51a could be found at this exact location. From the $T_{\rm eff} = 6000$ K model, above, we estimate that the bolometric correction for the detected star is $BC_V = 0.00$ mag, and therefore $M_{\rm bol} = -7.73$ mag. The bolometric luminosity with respect to the Sun (assuming $M_{\rm bol\odot} = 4.74$ mag) is $\log(L_{\rm bol}/L_\odot) = 4.99$. The star has a radius of $\sim290\ R_\odot$, and we estimate its surface gravity to be $\log g \approx 0.77$ (assuming the star's mass is $\sim18\ M_\odot$; see below), so our choice for the model $\log g$ is warranted. We note that the star is significantly more extended than a normal supergiant at this temperature (e.g., Drilling & Landolt 2000).

It is unlikely that the detected star is the one that actually exploded. As already noted, the early SN data indicate that the progenitor was far more compact (radius $\sim 10^{11}$ cm). Either the detected star is unrelated to the progenitor and is merely a very close ($\lesssim 0.1$ pc) neighbor, or, more likely, it is the companion to the progenitor in a binary system. The fact that He I lines were seen in the SN spectra within the first few weeks of explosion (Marion et al. 2011) implies that the progenitor had been substantially stripped of its H envelope, presumably via a wind or mass exchange with its companion (similar to SN 1993J; e.g., Podsiadlowski et al. 1993).

The compact primary star would therefore be very hot, probably a star in a Wolf–Rayet (W-R) phase. From Figure 3 one can see that the presumed secondary star alone can account for much of what was marginally detected in the F336W bandpass. (Additionally, nothing is detected at the SN position in archival *Galaxy Evolution Explorer* near-UV and far-UV band data for M51.) A star with characteristics similar to a weak-lined, early-type, N-rich W-R, with $T_{\rm eff} \approx 10^5$ K, $\log(L_{\rm bol}/L_\odot) \approx 5.3$, and $M_V^0 \approx -2.1$ mag (adopting the corresponding WNE model from Hamann & Gräfener 2004), would be $\gtrsim 2.2$ mag fainter in the F336W bandpass and would also be concealed by its brighter companion in all redder bands. This W-R star, therefore, would have little effect on the total light of the system, although any W-R more luminous than this would have been detected at F336W.

In Figure 4, we show the loci of the detected secondary star and the hypothetical primary in a Hertzsprung–Russell diagram. (The main uncertainty in the luminosity of the detected star arises from the assumed distance modulus uncertainty, ±0.27 mag.) We also show model stellar evolutionary tracks for massive stars with equatorial rotation ($v_{\rm rot} = 300$ km s^{-1}; Hirschi et al. 2004). These single-star tracks are meant to be merely *suggestive* of possible masses for the binary components; in particular, these tracks do not even adequately account for the position of the hypothetical primary in the diagram. Clearly, what is required is a full modeling of the components of this possible interacting binary system and its evolution up until the primary's explosion.

4. DISCUSSION AND CONCLUSIONS

We have detected in archival *HST* images a star at the precise location of SN 2011dh/PTF11eon. The star has colors consistent with mid-F-type, although its luminosity is higher ($M_V^0 \approx -7.7$ mag) and its radius more extended ($\sim290\ R_\odot$) than is the case for a normal supergiant. The early properties of
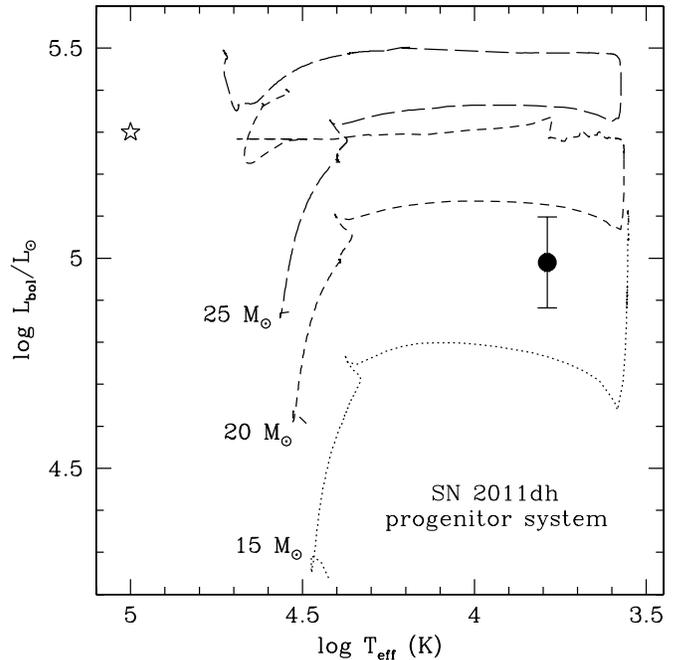

Figure 4. Hertzsprung–Russell diagram showing the locus of the star detected at the precise location of SN 2011dh/PTF11eon (filled circle). We speculate that this star is the companion to the progenitor in an interacting binary system. We also indicate the locus of a hypothetical compact, hot, Wolf–Rayet primary (five-pointed star), which we further speculate is the actual SN progenitor. Also shown are model single-star evolutionary tracks at solar metallicity with equatorial rotation ($v_{\rm rot} = 300$ km s^{-1}) for initial masses 15, 20, and 25 $M_\odot$ (Hirschi et al. 2004), which are intended merely to be suggestive of the possible mass ranges for the two stars.

SN 2011dh, however, point to its having a compact progenitor (Arcavi et al. 2011, radius $\sim 10^{11}$ cm; Soderberg et al. 2011), indicating that the detected star is likely not the star that exploded. (Maund et al. 2011 favor the interpretation that the star is the yellow supergiant progenitor of the SN.) It is possible that the detected star is just a very close neighbor of, yet generally unrelated to, the actual progenitor. We consider it more likely, though, that the star is the companion to the progenitor in a binary system. The extended radius for the detected star and the compact radius for the progenitor implies that the two stars may have been interacting. We note, however, that no direct observational indication yet exists that the SN 2011dh progenitor was a member of a binary system.

The compact SN 2011dh progenitor and the extended SN 1993J progenitor are within similar ranges of initial mass (13–22 $M_\odot$ for the latter; Van Dyk et al. 2002). (Note that Crockett et al. 2008 concluded that, if the compact progenitor of SN 2008ax were also in a binary system, its initial mass range would have been significantly lower, 10–14 $M_\odot$.) We note that many of the model SN Ib progenitors experiencing Case A/Case B mass transfer, which Yoon et al. (2010) have recently considered, are also in a mass range similar to that suggested for the SN 2011dh progenitor. As both Chevalier & Soderberg (2010) and Dessart et al. (2011) point out, the difference between SN IIb and Ib progenitors could be razor thin, depending on the H mass remaining in the progenitor star's envelope.

We will, of course, also develop a clearer picture once the SN has significantly faded, most likely several years in the future. At that time, imaging of the SN site can be undertaken, presumably with *HST*, and we can determine if the possible secondary star is

still there. For example, Ryder et al. (2006) detected what they concluded to be the late-B- to late-F-type supergiant companion to the compact SN IIb 2001ig in ground-based Gemini images obtained ∼1000 days after explosion. If the star has vanished or significantly faded, we can investigate if any fainter stars were present, contributing to the observed point-spread function of the star detected in the pre-SN *HST* images. Further work is clearly required to understand more fully the nature of this interesting, and potentially important, SN.

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