DISCOVERY OF THE DUST-ENSHROUDED PROGENITOR OF SN 2008S WITH SPITZER

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ABSTRACT

We report the discovery of the progenitor of the recent Type IIn SN 2008S in the nearby galaxy NGC 6946. Surprisingly, it was not found in deep, preexplosion optical images of its host galaxy taken with the Large Binocular Telescope, but only through examination of archival Spitzer mid-IR data. A source coincident with the SN 2008S position is clearly detected in the 4.5, 5.8, and 8.0 μm IRAC bands, showing no evident variability in the 3 years prior to the explosion, yet is undetected at 3.6 and 24 μm. The distinct presence of ~440 K dust, along with stringent LBT limits on the optical fluxes, suggests that the progenitor of SN 2008S was engulfed in a shroud of its own dust. The inferred luminosity of \( \approx 3.5 \times 10^4 L_\odot \) implies a modest mass of \( \sim 10 M_\odot \). We conclude that objects like SN 2008S are not exclusively associated with the deaths or outbursts of very massive \( \eta \) Carinae–like objects. This conclusion holds based solely on the optical flux limits even if our identification of the progenitor with the mid-IR source is incorrect.

Subject headings: stars: evolution — supernovae: general — surveys

1. INTRODUCTION

Over the last ~20 years, several significant milestones have been reached in the preexplosion detection of core-collapse supernova progenitors. These began with the “peculiar” Type II-P supernova 1987A in the Large Magellanic Cloud (e.g., Menzies et al. 1987), where a cataloged \( \sim 20 M_\odot \) blue supergiant star was identified as the progenitor (SK –69 202; e.g., West et al. 1987). Next came the transition Type IIb 1993J in M81, with a progenitor identified as a red supergiant in a binary system (e.g., Podsiadlowski et al. 1993; Maund et al. 2004). During the last decade, analyses of preexplosion archival optical imaging of nearby galaxies obtained (mainly) with the Hubble Space Telescope have convincingly shown red supergiants with masses \( 8 M_\odot \leq M \leq 20 M_\odot \) to be the typical progenitors of Type II-P supernovae (e.g., Smartt et al. 2004; Li et al. 2007), the most common core-collapse supernovae. Curiously, the progenitors of nearby Type Ib/c supernovae, thought to result from very massive (\( \geq 20 M_\odot \)) stars with strong winds that end their lives as Wolf-Rayet stars, have evaded optical detection (e.g., Crockett et al. 2008).

The rarest and most diverse class of core-collapse supernovae are the Type II (Schlegel 1990), which represent \( \sim 2\%–5\% \) of all Type II supernovae (e.g., Cappellaro et al. 1997). Their optical spectra, dominated by Balmer lines in emission, and slowly declining light curves show clear signatures of interactions between the supernova ejecta and a dense, hydrogen-rich circumstellar medium (e.g., Filippenko 1997). Mainly due to their low frequencies, high mass-loss rates, and the massive circumstellar envelopes generally required to explain the observations, some luminous Type II supernovae have been associated with the deaths of the most massive stars (e.g., Gal-Yam et al. 2007; Smith 2008 and references therein). Recently, evidence for this association has increased with the report of a very luminous source in preexplosion images of the Type IIIn SN 2005gj (Gal-Yam et al. 2007) and the discovery of an LBV eruption 2 years before the explosion of SN 2006jc (Pastorello et al. 2007). On the other hand, some low-luminosity Type II In supernovae have been associated with the superboutbursts of LBVs like \( \eta \) Carinae (e.g., Van Dyk et al. 2000, 2006).

The appearance of the Type II In SN 2008S in the nearby galaxy NGC 6946 (\( d \approx 5.6 \) Mpc; Sahu et al. 2006) was fortuitous, since a massive stellar progenitor would be relatively easy to find. However, preexplosion images serendipitously obtained from the Large Binocular Telescope revealed nothing at the position of SN 2008S, allowing us to put stringent limits on the optical emission. In this Letter, we report the discovery of an infrared point source coincident with the site of SN 2008S using archival Spitzer Space Telescope data. The Spitzer mid-IR detection, and deep optical nondetections, of the progenitor are the tell-tale signs of a \( \sim 10 M_\odot \) star obscured by dust. We describe the available data in § 2, our analysis in § 3, and our conclusions in § 4.

2. SEARCHING FOR THE PROGENITOR

NGC 6946 is quite a remarkable galaxy, giving birth to (at least) nine SNe in the last century. The latest event discovered in NGC 6946 is SN 2008S, found on February 1.79 UT at ~17.6 mag (Arbour & Boles 2008) and located 52° west and 196° south of the nucleus of NGC 6946. It was spectroscopically classified as a likely young Type II supernova from the presence of narrow Balmer lines in emission, highly reddened by internal extinction with a measured Na D absorption equivalent width of 5 Å (Stanishev et al. 2008). Steele et al. (2008) later reported that it had a peculiar spectrum due to the presence of narrow emis-
The progenitor is clearly detected at 4.5, 5.8, and 8.0 μm, corresponding to 4 times the astrometric uncertainty of 0.5 arcsec. The LBT image is bleeding from a saturated star.

If the supernova is a Type II-P, the progenitor will have features that are similar to the features of the progenitor of SN 2002hh. The progenitor of SN 2002hh has a large number of features, including Fe II and Ca II. These features suggest that the progenitor of SN 2002hh is a yellow supergiant.

We searched the Spitzer archive for all the programs that have observed NGC 6946. Observations by the SINGS survey (PID: 159), and two programs (PIDs: 2002hh and 2004et) monitoring the Type II-P SNe 2002hh and 2004et (PID: 230, 20256, 30292, 30494) provide a 2.5 year baseline (2004 June–2007 January) of IRAC and MIPS observations prior to the discovery of SN 2008S. We used aperture photometry (a 2 pixel extraction radius with aperture corrections) in the flux-calibrated images provided by the Spitzer Science Center to derive light curves for the progenitor. Figure 2 shows the flux density as a function of time (in days before the discovery) for the progenitor of SN 2008S. The solid line in each panel shows the mean for each band and the dashed lines show the rms deviations of ±3.3, 12.2, and 13.0 μJy, respectively.

The Large Binocular Telescope (Hill et al. 2006) obtained deep optical images of NGC 6946 on 2007 May 19–21, 225 days before discovery, during Science Demonstration Time using the LBC/Blue camera (Ragazzoni et al. 2006; E. Giallongo et al. 2008, in preparation). We combined the 12 × 300 s images obtained using the U filter (seeing 1.0″), and the 4 × 300 s images obtained using the B and V filters (seeing 1.5″). After finding an astrometric solution for the combined images using the USNO-B catalog (σ = σ = 0.2 ″), we do not detect a source at the position of SN 2008S (see Fig. 1). After calibrating the images using ancillary optical data obtained by the Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003) and Swift, we obtained 3σ upper limits on the progenitor magnitudes of $U > 25.8$, $B > 25.9$, and $V > 26.0$, which correspond to absolute magnitudes $M_V > -4.8$, $M_B > -4.3$, and $M_R > -3.8$, correcting for $A_V = 1.1$ mag of Galactic extinction (Schlegel et al. 1998). The upper limits are calculated using aperture photometry from the standard deviation of the sky at the SN position using a 10 pixel (2.2″) diameter aperture.

We correct these values with aperture corrections estimated using bright stars. The ~0.2 mag uncertainties in the 3σ upper limits are due to the uncertainties in the aperture corrections and the standard deviation of the sky (which is estimated from the rms variations in the standard deviation measured in equal-sized apertures placed in the background around the SN position). Welch et al. (2008) reported 3σ upper limits from preexplosion Gemini GMOS observations of $V > 24.0$, $R > 24.5$, and $I > 22.9$. These correspond to absolute magnitudes $M_V > -6.8$, $M_B > -5.2$, and $M_R > -6.5$, correcting for Galactic extinction.

Such a deep nondetection led us to investigate IRAC (3.6–8.0 μm; Fazio et al. 2004) and MIPS (24–160 μm; Rieke et al. 2004) images obtained by the SINGS Legacy Survey in 2004. We astrometrically calibrated the images in the same way as the optical images from Swift and LBT. We detect a point source at $α = 20^h34^m45.35^s$, $δ = 60°05′58.0″$ (J2000.0), with rms uncertainties $σ = 0.5 ″$, $σ = 0.3 ″$. This is consistent with the position of SN 2008S given the estimated uncertainties, and thus likely to be the progenitor. The source is not detected at 3.6, 24, or 70 μm. We estimate a probability of random coincidence given the uncertainty in the SN position (0.5″) of 0.8% (0.02%) from the density of 4.5 μm sources (with $[3.6] - [4.5] > 1.5$ mag) detected within a 1′ radius of the SN position.

We searched the Chandra archive to determine if the progenitor was an X-ray source. All five ACIS-S observations of NGC 6946 include the location of SN 2008S. These observations include a 60 ks exposure in 2001, a 30 ks exposure in 2002, and 3 × 30 ks exposures in 2004. No source is detected at the supernova position in any of these images. We
The measured fluxes and upper limits in the mid-IR bands are shown in Figure 3. The shape of the spectral energy distribution (SED) suggests thermally radiating dust as the source of the emission. We derive a best-fit single-temperature blackbody of \( T \approx 440 \) K, with a luminosity of \( L_{\text{bb}} \approx 3.5 \times 10^5 L_\odot \) (\( d = 5.6 \) Mpc; Sahu et al. 2006), which implies a blackbody radius \( R_{\text{bb}} \approx 150 \) AU. This luminosity points to a \( \sim 10 \) \( M_\odot \) star at the end of its life (e.g., Meynet & Maeder 2003). The 3 \( \sigma \) upper limit at 70 \( \mu \)m further limits the total luminosity of the dust-enshrouded source and the geometry of obscuring dust distribution.

As shown in Figure 3, a blackbody yields a relatively poor fit to the data (\( \chi^2 \approx 4.9 \) per dof). The inability of a single-temperature blackbody to accommodate the data follows primarily from the rapid change in the SED implied by the 3.6 \( \mu \)m upper limit and the 4.5 \( \mu \)m detection. Radiation transport calculations using DUSTY (Ivezic & Elitzur 1997) were performed as a sanity check. Using a central incident blackbody with the approximate temperature (100 K) and luminosity (10^5 \( L_\odot \)) of the blue supergiant progenitor of SN 1987A, which has similar properties to the lowest luminosity LBVs observed (e.g., Smith 2007). The models were reddened with \( A_r = 2.5 \) mag, the total extinction estimated from the colors of SN 2008S.

4\( \pi R_{\text{bb}}^2 \rho c_{\gamma} \sim 10^{-3} M_\odot \) yr^{-1}, where \( c_{\gamma} \sim 2 \) km s^{-1} is the gas sound speed in the medium on the scale of \( R_{\text{bb}} \).

The lack of variability in the mid-IR fluxes (see Fig. 2) limits the expansion velocity of the photosphere. Given our estimated temperature and luminosity, keeping the mid-IR fluxes constant to within \( \sim 10\% \) over the \( \sim 10^4 \) days covered by the observations means that the dust photosphere cannot be expanding by more than \( \sim 10 \) km s^{-1}, which is below the escape velocity of 13 km s^{-1} for a 10 \( M_\odot \) star at the estimated photospheric radius of 150 AU. This is further evidence that the dust is part of a relatively steady, massive wind rather than an explosively expelled dust shell.

### 4. DISCUSSION AND CONCLUSIONS

Our preexplosion detection of the progenitor of the Type IIn SN 2008S is, to the best of our knowledge, the first in the mid-IR. The Spitzer observations suggest an enshrouded star with a mass of \( \sim 10 \) \( M_\odot \), buried in \( \sim 10^{-3} M_\odot \) of gas and dust. If SN 2008S was a real supernova explosion, this is direct evidence that relatively low-mass stars can end their lives as Type IIn SNe when they have a sufficiently dense CSM from a massive wind, as proposed by Chugai (1997). If this event was the luminous outburst of an LBV, it presents evidence for low-luminosity, low-mass LBVs that have not been observed before. These conclusions about the relatively low mass hold even if the identification of the progenitor with the Spitzer source is incorrect. In this case, we know the total extinction from the colors of the SN (see below). As shown in Figure 3, our optical limits with this ex-

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**TABLE 1**

Spectral Energy Distribution of the Progenitor of SN 2008S

| \( \lambda \) | \( \lambda \left(10^{17} \text{ W m}^{-2}\right) \) | Source |
|---|---|---|
| 0.3–8 keV | <0.3 | Chandra ACIS-S |
| 0.36 \( \mu \)m | <0.07 | LBT/LBC-Blue |
| 0.44 \( \mu \)m | <0.11 | LBT/LBC-Blue |
| 0.55 \( \mu \)m | <0.08 | LBT/LBC-Blue |
| 0.64 \( \mu \)m | <0.22 | Welch et al. (2008) |
| 0.80 \( \mu \)m | <0.63 | Welch et al. (2008) |
| 3.6 \( \mu \)m | <0.45 | Spitzer IRAC |
| 4.5 \( \mu \)m | 1.47 ± 0.22 | Spitzer IRAC |
| 5.8 \( \mu \)m | 2.54 ± 0.64 | Spitzer IRAC |
| 8.0 \( \mu \)m | 2.48 ± 0.50 | Spitzer IRAC |
| 24 \( \mu \)m | <1.20 | Spitzer MIPS |
| 70 \( \mu \)m | <40 | Spitzer MIPS |

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tinction correspond to mass limits of \( \lesssim 12 M_\odot \) for red supergiants and \( \lesssim 20 M_\odot \) for blue supergiants.\(^9\)

Interestingly, we see luminous dust-enshrouded stars in the Milky Way and the LMC whose physical properties match well the observed properties of the progenitor of SN 2008S. Van Loon et al. (2005 and references therein) studied the properties (\( T_\ast \), \( T_{\text{dust}} \), \( L_{\text{bol}} \), \( M \)) of dust-enshrouded AGB stars and red supergiants in the LMC using mid-IR observations. These are M-type stars with effective temperatures \( \sim 2500 \sim 3800 \) K, which have strong winds with high (gas + dust) mass-loss rates \( (M \sim 10^{-6} \sim 10^{-3} M_\odot \text{ yr}^{-1}) \), and warm dust emission from their dusty envelopes (200 K < \( T_{\text{dust}} < 1300 \) K). Due to these similarities, we conclude that the progenitor of SN 2008S was likely a dust-enshrouded AGB (core-collapse produced from electron capture in the O-Ne-Mg core; e.g., Eldridge et al. 2007; Poelarends et al. 2008) or red supergiant like the ones observed in the LMC.

Although the detection and physical properties of the progenitor are the main results of this study, we can also try to understand something about the progenitor and explosion mechanism from the supernova itself. The classification spectrum of SN 2008S is similar to the published spectrum of SN 1997bs (Van Dyk et al. 2000), which showed narrow Balmer lines in emission and many weaker Fe II lines (V. Stanishev 2008, private communication; Steele et al. 2008). SN 2003gm had photometric and spectroscopic characteristics similar to SN 1997bs (Maund et al. 2006). Since both of these were faint \( (M_V \sim -14 \text{ mag}) \) compared with the typical absolute magnitudes at maximum of Type II SNe \( (M_V \sim -19 \sim -18 \text{ mag}) \), it is still debated whether they were intrinsically faint explosions or superoutbursts of LBVs.

The early optical photometry obtained with Swift also indicates that SN 2008S was a low-luminosity object, with \( M_V \sim -14 \) mag after correcting for the total extinction along the line of sight. We estimate the total extinction for \( R_V = 3.1 \) to be \( A_V \approx 2.5 \text{ mag} \) from the observed color \( B - V \approx 0.8 \text{ mag} \) and assuming a typical intrinsic temperature of \( \sim 10000 \text{ K} \) at this early phase of the evolution. This value is roughly consistent with the estimated reddening obtained from the reported equivalent width of the Na D absorption feature (2.5 < \( A_V < 7.8 \); based on Turatto et al. 2002). This implies the presence of significant internal extinction with \( A_V \approx 1.4 \text{ mag} \) after correcting for \( A_V \text{(Gal)} = 1.1 \text{ mag} \). Although the light from the supernova likely destroyed the dust that obscured the progenitor to significantly beyond the blackbody scale of \( \sim 150 \) AU, the existence of internal extinction in the supernova light curve implies a more tenuous dusty obscuring medium on larger scales. In fact, the rare detection of the [Ca II] \( 730 \text{ nm} \) doublet in emission by Steele et al. (2008) may provide direct, and independent, evidence for a significant amount of dust in the CSM that was destroyed by the UV-optical flash (e.g., Shields et al. 1999). The future spectra and light curves of SN 2008S, optical as well as radio and X-ray, should further probe the environment as they show signs of interactions with the progenitors’ wind.

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REFERENCES

Arbour, R., & Boles, T. 2008, CBET, 1234, 1
Cappellaro, E., et al. 1997, A&A, 322, 431
Chugai, N. 1997, Astron. Rep., 41, 672
Crockett, R. M., et al. 2008, ApJ, 672, L99
Eldridge, J. J., Mattila, S., & Smartt, S. J. 2007, MNRAS, 376, L52
Fazio, G. G., et al. 2004, ApJS, 154, 10
Filippenko, A. V. 1997, ARA&A, 35, 309
Gal-Yam, A., et al. 2007, ApJ, 656, 372
Hill, J. M., Green, R. F., & Slagle, J. H. 2006, Proc. SPIE, 6267, 31
Ivezic, Z., & Elitzur, M. 1996, MNRAS, 279, 1019
Kochanek, C. S., et al. 2008, ApJ, in press (arXiv:0802.1744)
Kennefick, R. C., et al. 2003, PASP, 115, 928
Maund, J. R., et al. 2004, Nature, 427, 129
Maund, J. R., et al. 2007, Nature, 447, 829
Pastorello, A., et al. 2007, Nature, 447, 829
Poelarends, A. J. T., Herwig, F., Langer, N., & Heger, A. 2008, ApJ, 675, 614
Ragazzoni, R., et al. 2006, Proc. SPIE, 6267, 33
Ricke, G. H., et al. 2004, ApJS, 154, 25
Sahu, D. K., et al. 2006, MNRAS, 372, 1315
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Smartt, S. J., et al. 2004, Science, 303, 499
Snedden, D. N. 2007, AJ, 133, 1034
———. 2008, in IAU Symp. 250, Massive Stars as Cosmic Engines, ed. F. Bresolin et al. (Cambridge Univ. Press), in press (arXiv:0802.1744)
Smith, N., Vink, J. S., & de Koter, A. 2004, ApJ, 615, 475
Stanishev, V., Pastorello, A., & Piersimoni, T. 2008, CBET, 1275, 1
Stein, T. N., et al. 2008, CBET, 1275, 1
Turatto, M., Benetti, S., & Cappellaro, E. 2002, In From Twilight to Twilight, ed. W. Hillebrandt & B. Leibundgut (Garching: ESO), 200
Van Dyk, S. D., et al. 2000, PASP, 112, 1532
———. 2006, PASP submitted (astro-ph/0603025)
van Loon, J. Th., et al. 2005, A&A, 438, 273
Welch, D. L., Clayton, G. C., & Sajgurman, B. 2008, CBET, 1330, 1
West, R. M., et al. 1987, A&A, 177, L1

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\(^9\) We obtain an upper limit in the absolute optical magnitude of the progenitor of \( M_V \approx 7.1 \) if we assume an upper limit on the extinction estimate from the SN color \( (A_V \approx 3.5 \text{ mag}; \text{bluest blackbody possible}) \) and an extreme distance to NGC 6946 of 8.5 Mpc.