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SN 2008S: A COOL SUPER-EDDINGTON WIND IN A SUPERNOVA IMPOSTOR

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ABSTRACT

We present visual-wavelength photometry and spectroscopy of SN 2008S. Based on the relatively low peak luminosity for a supernova (SN) of $M_R = -13.9$ mag and moderate outflow speeds of $\lesssim$600 km s^{-1} indicated by the spectrum, we find that SN 2008S is not a true core-collapse SN and is probably not an electron-capture SN. Instead, we interpret SN 2008S as a "SN impostor" event much like SN 1997bs, analogous to the giant eruptions of luminous blue variables. Its total radiated energy was $\sim 10^{47.8}$ ergs, and it may have ejected 0.05–0.2 M$_\odot$ in the event. We discover an uncanny similarity between the spectrum of SN 2008S and that of the Galactic hypergiant IRC+10420, both of which are dominated by narrow Hα, [Ca II], and Ca II emission lines. We propose a scenario where the vastly super-Eddington ($\Gamma \approx 40$) wind of SN 2008S partly fails because of a reduction in the electron-scattering opacity due to recombination. We favor a stellar mass of $\gtrsim$20 M$_\odot$, and speculate that this outburst may have implications for the progenitor of SN 1987A.

Subject headings: stars: mass loss — supernovae: individual (SN 2008S)

1. INTRODUCTION

The class of Type IIn supernovae (SNe IIn) is surprisingly diverse compared to other spectral classes, and its diversity seems to be growing. SNe IIn are classified as such because of the relatively narrow H emission lines in their spectra (Schlegel 1990; Filippenko 1997), but the underlying physics of the outbursts may be quite varied. Recent examples of extremely luminous SNe IIn such as SNe 2006tf and 2006gy (Smith et al. 2008, 2007; Ofek et al. 2007; Woosley et al. 2007) and studies of SN IIn progenitors such as SN 2006gl (Gal-Yam et al. 2007) challenge our understanding of massive star evolution. The complex diversity of SNe IIn is exacerbated by SNe Ia with dense H shells that may contaminate their ranks, as in the cases of SNe 2002ic and 2005gj (Hamuy et al. 2003; Aldering et al. 2006; Prieto et al. 2007).

We also know of remarkably *faint* SNe IIn, less luminous than typical SNe II-P. It is unclear if these represent a tail of the core-collapse SN luminosity distribution or an entirely different kind of outburst. The low-luminosity SNe IIn have been referred to variously as "SN impostors" (Van Dyk et al. 2000), Type V SNe (Zwicky 1965), η Car analogs (Goodrich et al. 1989; Filippenko et al. 1995), or giant eruptions of luminous blue variables (LBVs). Such objects may be nonterminal outbursts related to historical eruptions of η Car, P Cyg, SN 1961V, and SN 1954J (see Humphreys, Davidson, & Smith 1999), where detections of the surviving progenitor stars are claimed (Van Dyk et al. 2002, 2005; Smith et al. 2001; but see also Chu et al. 2004).

The trigger mechanism of these outbursts remains unexplained, though it is thought to be caused by violating the classical Eddington luminosity limit and thereby initiating severe mass loss (Owocki et al. 2004; Smith & Owocki 2006; Smith & Conti 2008). These "impostors" exceed their pre-outburst states by several magnitudes, with typical peak absolute visual magnitudes of −11 to −14. A representative example of a SN impostor is SN 1997bs (Van Dyk et al. 2000), which was the first "SN" detected as part of the Lick Observatory SN Search (LOSS; Filippenko et al. 2001). Properties of additional examples have been discussed by Van Dyk (2005).

To this already diverse subclass of faint SNe IIn, we now add SN 2008S in NGC 6946 ($d = 5.6$ Mpc; Sahu et al. 2006), discovered on 2008 Feb. 1.8 UT (Arbour & Boles 2008). It is of particular interest because Prieto et al. (2008) discovered an associated infrared (IR) source in pre-explosion *Spitzer Space Telescope* images. These IR data and visual upper limits suggested that the progenitor was obscured by circumstellar dust and had a modest mass of only 10–20 M$_\odot$ (Prieto et al. 2008), below the range of initial masses usually attributed to LBVs (Smith et al. 2004; Smith 2007). Following the report of a similar obscured progenitor of a transient in NGC 300 (Prieto 2008), Thompson et al. (2008) proposed that these two objects constitute a new class of transients, perhaps related to electron-capture SNe in stars with initial mass $\sim$9 M$_\odot$. Here we study the outburst of SN 2008S itself. We conclude that, despite the unusual dust-enshrouded progenitors, the *outburst* properties are not extraordinary with respect to known examples of SN impostors.

2. OBSERVATIONS

We obtained photometry of SN 2008S with a 0.35 m Celestron telescope (M.P.M.), the *Swift* Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005), and the Lick Observatory 1-m Nickel telescope. The field of SN 2008S has been calibrated because its host galaxy produced several SNe over the past decade. Unfiltered M.P.M. data are treated as roughly R band. For the M.P.M. and Nickel data, we used point-spread-function (PSF) fitting to perform photometry. For the UVOT reductions, we employed the photometric calibration de-

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TABLE 1
Photometry of SN 2008S

JD[a]	B	V	R	I	Tel.[b]
1.20	–	–	16.35(07)	–	M
1.27	18.03(06)	–	–	–	U
2.55	17.94(04)	17.00(04)	–	–	U
3.20	–	–	16.35(05)	–	M
5.03	17.79(08)	16.97(08)	–	–	U
5.20	–	–	16.33(06)	–	M
6.20	–	–	16.30(05)	–	M
7.20	–	–	16.32(07)	–	M
8.20	–	–	16.33(07)	–	M
9.20	–	–	16.40(05)	–	M
10.52	17.80(05)	16.88(05)	–	–	U
12.20	–	–	16.39(07)	–	M
23.20	–	–	16.49(07)	–	M
31.03	18.18(07)	17.40(04)	16.80(03)	16.35(08)	N
33.20	–	–	16.80(11)	–	M
69.00	19.82(04)	18.57(02)	17.79(02)	17.04(02)	N
75.94	–	18.98(17)	17.85(06)	17.24(07)	N
83.00	20.51(08)	19.14(04)	18.25(02)	17.45(02)	N
89.95	20.74(10)	19.49(02)	18.52(02)	17.62(02)	N
94.97	20.98(09)	19.69(05)	18.65(02)	17.78(02)	N
95.93	21.03(17)	19.75(05)	18.72(03)	17.86(04)	N
117.96	21.73(16)	20.66(13)	19.58(08)	18.58(05)	N
127.97	–	20.51(23)	19.69(13)	18.82(07)	N
135.94	21.83(23)	21.20(23)	19.94(10)	18.85(11)	N
138.93	–	20.81(36)	19.80(15)	18.89(11)	N
142.93	22.21(18)	21.06(18)	19.96(09)	18.94(05)	N
267.20	–	–	21.17(13)	–	K

Note. — 1σ uncertainties (in units of 0.01 mag) are in parentheses. There are also U-band observations of SN 2008S with UVOT: JD = 1.27, $U = 18.55(10)$; JD = 2.55, $U = 18.39(08)$; JD = 5.03, $U = 18.19(10)$; JD = 10.52, $U = 18.41(08)$ mag.

[a] Julian Date − 2,454,000; add 3 for days since discovery.

[b] M: 0.35 m Celestron telescope owned by M.P.M., unfiltered and calibrated to the R band; U: *Swift*/UVOT; N: Lick Observatory 1-m Nickel telescope; K: Keck-I unfiltered image.

scribed by Li et al. (2006). Final photometry of SN 2008S is reported in Table 1. Figure 1 shows the R-band light curve and $B-V$ color curve.

We also obtained visual-wavelength spectra of SN 2008S using the Kast double spectrograph (Miller & Stone 1993) on the 3-m Shane reflector at Lick Observatory (days 15, 28, and 71 after discovery), and using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) at Keck Observatory (on day 270). The long slit of width $\sim 2''$ at Lick and $1''$ at Keck yielded spectral resolving powers at red wavelengths of $R \approx 670$ and 1250, respectively, and was oriented along the parallactic angle (Filippenko 1982). Standard spectral data reduction was performed for all epochs. The spectra are plotted in Figure 2 after having been corrected for Galactic reddening of $E(B-V) = 0.36$ mag (Schlegel et al. 1998). We used the unfiltered guide-camera image from the Keck observations on day 270 to derive the last photometry point in Table 1, by comparison with calibrated field stars.

Our spectra have insufficient dispersion to infer the local reddening and extinction of SN 2008S using the Na I D absorption line, and this would be problematic anyway because the line changes to emission at late times. Based on the similarity of the spectrum of SN 2008S to that of the Galactic hypergiant IRC+10420 (discussed more below; see Fig. 2), we assume that the values of $T_{\rm eff}$ for these two objects are similar. The spec-

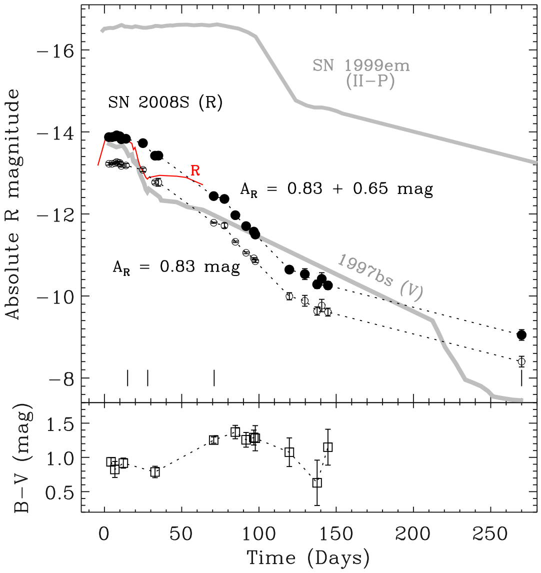

Fig. 1.— *Top:* Absolute light curve of SN 2008S (adopting $d = 5.6$ Mpc) corrected for Galactic extinction (open circles) of $A_R = 0.83$ mag (or $A_V = 1.1$ mag), and with an additional correction for local extinction (filled circles) of $A_R = 0.65$ mag (or $A_V = 0.87$ and $E(B-V) = 0.28$ mag; see Fig. 2). Light curves for a normal SN II-P (SN 1999em; Leonard et al. 2002) and the SN "impostor" SN 1997bs are also displayed for comparison. For SN 1997bs we show both the R (red line) and V (thick gray line) light curves from Van Dyk et al. (2000). Tick marks at the bottom show the epochs for which we have spectra. *Bottom:* The observed $B-V$ color curve of SN 2008S.

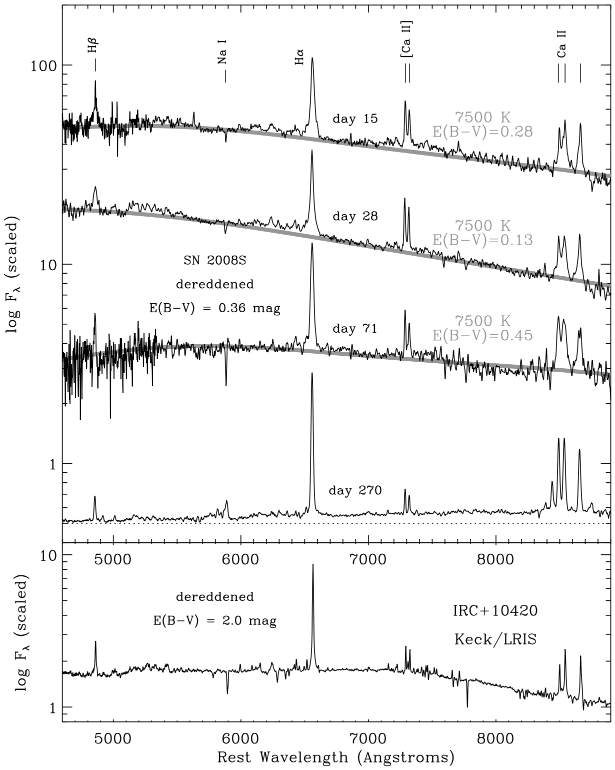

Fig. 2.— *Top:* The spectra in black are of SN 2008S corrected for Galactic extinction only, assuming $E(B-V) = 0.36$ mag. The days corresponding to each spectrum are after discovery. The gray curves show 7500 K blackbodies reddened by the indicated amounts to approximate the spectral continuum shape. *Bottom:* A Keck/LRIS spectrum of IRC+10420 obtained on 2008 Oct. 28, dereddened by an arbitrary $E(B-V) = 2$ mag for comparison.

tral type of IRC+10420 is currently mid-A (Oudmaijer 1998). Thus, with a representative $T_{\rm eff} \approx 7500$ K, the observed continuum shape of SN 2008S near peak implies a local extinction of $E(B-V) \approx 0.28$ mag in addition to the Galactic extinction already applied to the spectra in Figure 2 (this extinction or the intrinsic $T_{\rm eff}$ seems to vary as the object evolves; Fig. 2). The reddening estimated from spectra is consistent with the observed photometric $B-V$ color near maximum light: an intrinsic $B-V$ color of ∼0.2 mag for 7500 K added to the Galactic and estimated local reddening accounts for the observed $B-V$ in the bottom panel of Figure 1.

3. BASIC PARAMETERS

The extinction-corrected light curve in Figure 1 shows a peak M_R=−13.9 mag, corresponding to $L_{\rm peak} = 3\times10^7$ $L_\odot$ with zero bolometric correction. For $T_{\rm eff} = 7500$ K, the emitting radius at peak is 2.3×10^{14} cm or 15 AU. Modest expansion speeds (FWHM $\lesssim$600 km s^{-1})[4] near peak are indicated by Hα and Ca II lines, while [Ca II] lines (presumably originating at a larger radius) are even narrower, appearing unresolved in our LRIS spectra with FWHM $\simeq$ 240 km s^{-1}. Integrating the light curve in Figure 1, the total radiated energy in the first 270 days is $E_{\rm rad} = 10^{47.8}$ ergs, between those of SN 1954J ($10^{47.3}$ ergs) and the P Cygni 1600 outburst ($10^{48.4}$ ergs) (Humphreys et al. 1999).

The peak luminosity of SN 2008S occupies the very lowest end of the luminosity distribution of SNe II (Pastorello et al. 2004). The late-time decline seems to roughly match the value of 0.01 mag d^{-1} one expects for ^{56}Co decay (compare to the tail of SN 1999em in Fig. 1) from a very low ^{56}Ni mass of ∼0.002 $M_\odot$. However, Figure 1 shows only the R magnitude with no bolometric correction. Our spectra on day 270 indicate a very red continuum with a peak at ∼1 μm or longer, whereas the spectrum is much bluer at early times. Therefore, there may be a substantial bolometric correction of ∼0.5 mag at late times, making the decay rate slower than for radioactive decay. It is therefore unlikely that SN 2008S was a weak core-collapse supernova.

Thompson et al. (2008) raised the question of whether SN 2008S and the NGC 300 transient may have been electron-capture SNe from stars of initial mass ∼9 $M_\odot$. We find that this interpretation seems inconsistent with predictions of that hypothesis. For example, models by Kitaura et al. (2006) predict that electron-capture SNe will produce explosion energies $\gtrsim 10^{50}$ ergs. In order for such an explosion to produce the slow velocities of $\lesssim$600 km s^{-1} that we observe, the star's envelope mass would need to have been ∼28 $M_\odot$.

On the other hand, the low peak luminosity of SN 2008S is consistent with those observed for SN impostors. Despite apparent differences in the progenitor stars, the light curve of SN 2008S closely matches that of the SN impostor SN 1997bs (Fig. 1), for which the progenitor and possibly the surviving star were detected (Van Dyk et al. 2000; but see Li et al. 2002). Similarly, the slow expansion speeds match those observed in nearby LBVs and other SN impostors. For example, the expansion speed of ∼600 km s^{-1} observed in the ejecta of η Car (Smith 2006) matches the widths of Hα and Ca II lines in SN 2008S. These data support our earlier conjecture that SN 2008S was not a genuine core-collapse SN (Steele et al. 2008), so we interpret SN 2008S in the context of a SN impostor event.

The Eddington parameter, $\Gamma = (\kappa_e L)/(4\pi GMc)$, is the factor by which a star exceeds the classical Eddington limit, assuming that Thomson scattering ($\kappa_e \approx 0.34$) dominates the opacity. With such a high value of $L_{\rm peak} = 3\times10^7$ $L_\odot$, the Eddington parameter for SN 2008S would be $\Gamma \approx 40$ $(M/20\ M_\odot)^{-1}$. This huge Eddington parameter is a factor of ∼10 higher than that of η Car during its 1843 eruption, when the star shed ∼10 $M_\odot$ in a few years (Smith et al. 2003). In the case of SN 2008S, then, extreme mass loss from the star seems unavoidable.

4. DISCUSSION

We point out an uncanny similarity between the visual-wavelength spectra of SN 2008S near peak luminosity and the spectrum of the Galactic hypergiant IRC+10420 (see Fig. 2). Both objects exhibit a smooth continuum dominated by narrow Hα, [Ca II], and Ca II emission. Such strong, narrow Ca II emission lines have not been seen before in a SN or SN impostor, and are extremely rare among known stars. IRC+10420 is an evolved massive star in a yellow (spectral type of mid-A) hypergiant phase with strong mass loss (Humphreys, Davidson, & Smith 2002). This phase may be a counterpart to the LBVs, but at cooler $T_{\rm eff}$ (Smith et al. 2004).

This spectral similarity between SN 2008S and IRC+10420 does not necessarily mean that the objects are related. It does, however, indicate that the $T_{\rm eff}$ of SN 2008S in outburst and that of IRC+10420 in its current quiescent state must be similar. It also requires similar circumstellar medium densities, suggesting that the mass-loss rate of the progenitor of SN 2008S was comparable to that of IRC+10420, $\sim 10^{-3}$ $M_\odot$ yr^{-1}. This is qualitatively consistent with the observation that both IRC+10420 and the progenitor of SN 2008S are (or were) obscured by dust (Jones et al. 1993; Prieto et al. 2008). One potential explanation for the unusually strong Ca II lines is that radiation from SN 2008S might have vaporized grains that were previously in equilibrium around a less luminous progenitor. The grain vaporization radius for $T_d \approx 1200$ K is $\sim$ 600 AU or 9×10^{15} cm. IRC+10420 has changed its spectral type from late F to mid A-type in the past 30 years (Klochkova et al. 1997; Oudmaijer 1998), hinting that the bright Ca II and [Ca II] emission may trace rapid changes in luminosity or $T_{\rm eff}$.

Effective temperatures around 7500 K imply an interesting regime where H is recombining. As such, the classical Eddington limit may be altered in the outermost layers of the star or wind because it assumes that the opacity is dominated by electron scattering in fully ionized gas. However, if H recombines in the outflow, the opacity will drop and the radiation field may no longer be able to effectively impart momentum to the outflowing material. An inhomogeneous wind may stall or partly fail, and some material may fall back onto the star.[5]

In fact, recent numerical simulations probe the regime

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[4] Broader wings at ±1000 km s^{-1} are likely due to electron scattering; see Dessart et al. (2008).

[5] H recombination also dominates the photospheres of normal SNe II, of course, but this does not impede SN mass ejection because it is not a radiation-driven wind.

of super-Eddington winds under somewhat different circumstances (i.e., not including recombination effects), but a complex pattern of outflow and infall is seen (van Marle, Owocki, & Shaviv 2008). In fact, the general character of the winds in these simulations closely matches the type of situation we envision for SN 2008S. If our suggested picture of a failed super-Eddington wind is applicable, we might expect high-resolution spectra of the Hα and Ca II lines to reveal signatures of simultaneous outflow and infall such as inverse P Cyg features, and asymmetric or double-peaked profiles caused by self absorption, as seen in IRC+10420 (Oudmaijer 1998; Humphreys et al. 2002). Unfortunately, our low-dispersion spectra do not resolve the detailed line profile shapes in SN 2008S. For the observed outflow speeds of $\lesssim$600 km s^{-1} in SN 2008S, the star's surface escape speed should be at least a few $\times 10^2$ km s^{-1}. This is consistent with a blue supergiant (BSG), but is too fast for a red supergiant (RSG).

A super-Eddington wind with $\Gamma > 10$ can drive strong mass loss, with rates of $\sim$0.1 M$_\odot$ yr $^{-1}$ (Owocki et al. 2004). Indeed, if the ratio of radiated energy to kinetic energy is near unity, as in η Car (Smith et al. 2003; Smith 2006), then we might expect an ejected mass of $\sim$0.16 $M_\odot$. It may be considerably less, however, if recombination causes part of the wind to stall as speculated above.

The properties of the SN 2008S outburst seem consistent with a BSG mass as low as 20 M$_\odot$. Prieto et al. (2008) find upper limits of 12 M$_\odot$ for a RSG progenitor or $\sim$20 M$_\odot$ for a BSG, the latter of which is more consistent with our conclusions. These upper limits assume that the progenitor suffers the same amount of extinction as the outburst, but given the possibility of circumstellar dust evaporation evidenced by the strong Ca II emission, these upper limits to the mass could increase. The strong mass loss that caused the self-obscuration may have occurred as a RSG with a high L/M value (Heger et al. 1997), perhaps initiating a blue loop and the star's consequent instability that led to the outburst. The expected short duration of $\lesssim 10^4$ yr for that preceding phase (Heger et al. 1997) satisfies the expectations of Thompson et al. (2008) that these obscured stars would be short-lived. The classical LBV phenomenon has been observed in stars down to initial masses of 20–25 M$_\odot$ (Smith et al. 2004), where the instability and high L/M arise from previous strong RSG mass loss. If SN 2008S was a super-Eddington outburst of a $M_{\rm ZAMS} \approx 20$ M$_\odot$ star, it strengthens the hypothesis that the progenitor of SN 1987A ejected its nebula in a similar outburst (Smith 2007).

Thompson et al. (2008) proposed that SN 2008S and the similar event in NGC 300 represent a new class of transients, while our observations of the SN 2008S outburst itself imply the somewhat different interpretation that they extend the parameter space of the already diverse class of SN impostor outbursts. We suspect that they are special cases where the progenitors were highly obscured because the outburst occurred soon after a blue-loop transition away from a RSG phase. In the scenario of a SN impostor, the star is not destroyed in the event. This predicts that the star will be detectable again, although it may take decades before the star fully recovers to thermal equilibrium.

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