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

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Received 2008 November 24; accepted 2009 April 9; published 2009 April 30

ABSTRACT

We present visual-wavelength photometry and spectroscopy of supernova (SN) 2008S. Based on the low peak luminosity for a SN of $M_V = -13.9$ mag, photometric and spectral evolution unlike that of low-luminosity SNe, a late-time decline rate slower than $^{56}$Co decay, and slow outflow speeds of 600–1000 km s$^{-1}$, we conclude that SN 2008S is not a true core-collapse SN and is probably not an electron-capture SN. Instead, we show that SN 2008S more closely resembles an “SN impostor” event like SN 1997bs, analogous to the giant eruptions of luminous blue variables (LBVs). Its total radiated energy was $\sim 10^{57.8}$ erg, 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, which is dominated by narrow Hα, [Ca ii], and Ca ii emission lines formed in an opaque wind. We propose a scenario where the vastly super-Eddington (Γ ≈ 40) wind of SN 2008S partly fails because of reduced opacity due to recombination, as suggested for IRC+10420. The range of initial masses susceptible to eruptive LBV-like mass loss was known to extend down to 20–25 $M_\odot$, but estimates for the progenitor of SN 2008S (and the similar NGC 300 transient) may extend this range to $\lesssim 15 M_\odot$. As such, SN 2008S may have implications for the progenitor of SN 1987A.

Key words: stars: mass loss – supernovae: individual (SN 2008S)

1. INTRODUCTION

The class of Type IIn supernovae (SNe IIn) is surprisingly diverse compared to other spectral types. 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) challenge our understanding of massive star evolution.

We also know of remarkably faint SNe IIn. It is unclear if these belong to a tail of the core-collapse SN distribution (e.g., Pastorello et al. 2004), or if they mark a different kind of outburst. Among low-luminosity SNe IIn is an observed class of objects 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). These are non-terminal outbursts related to historical eruptions of η Car, P Cyg, SN 1961V, and SN 1954C (see Humphreys et al. 1999). The physical cause of the outbursts is unknown, but since the stars are observed to survive in some cases (Van Dyk et al. 2002; Van Dyk et al. 2005; Smith et al. 2001), they are thought to be distinct from core-collapse SNe. For distant objects, however, the case is not always clearly proven (e.g., Stockdale et al. 2001; Chu et al. 2004). Conversely, Woosley et al. (2007) proposed that even the most luminous SNe IIn may be non-terminal events.

The underlying trigger of these outbursts remains unexplained, but the observed outflow is generally thought to be caused by violating the classical Eddington luminosity and thereby initiating severe mass loss (Owocki et al. 2004; Smith & Owocki 2006). These “impostors” exceed their pre-outburst states by several magnitudes, with typical peak absolute visual magnitudes of −11 to −14. The class is heterogeneous, but a representative example of a SN impostor is SN 1997bs (Van Dyk et al. 2000), which was the first “SN” detected by the Lick Observatory SN Search (Filippenko et al. 2001). Van Dyk (2005) discussed additional examples.

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 February 1.8 UT (Arbour & Boles 2008). It is of particular interest because Prieto et al. (2008) found an associated infrared (IR) source in pre-explosion Spitzer images. IR data and visual upper limits suggest 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). Prieto et al. (2008) favor a mass at the lower end of this range, with certain assumptions. 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. We find that despite the unusual low-luminosity progenitor, the outburst resembles known SN impostors, but is unlike any other objects that have been proposed as weak core-collapse SNe or electron capture SNe.

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 described by Li et al. (2006). Final photometry of SN 2008S is reported in Table 1.

Notes. 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.

* Julian Date – 2,454,000; add 3 for days since discovery.

† 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.

Our spectra have insufficient dispersion to infer the local reddening of SN 2008S using Na I D absorption, and this would be problematic anyway because the line changes to emission at late times. In this paper, we draw attention to the remarkable similarity between the spectrum of SN 2008S and that of the Galactic hypergiant star IRC+10420; the basis for and implications of this comparison will be discussed in more detail below (see Figure 2). For now, we mention the spectroscopic similarity only as a basis for assuming that the intrinsic values of $T_{\text{eff}}$ for these two objects are similar, in order to constrain the reddening. The spectral type of IRC+10420 is M 13 (e.g., Oudmaijer 1998). Thus, with $T_{\text{eff}} \approx 7500$ 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 in Figure 2 (this extinction or the intrinsic $T_{\text{eff}}$ seems to vary as the object evolves). This local reddening is consistent with the $B-V$ color near maximum light: an intrinsic $B-V$ color of $-0.2$ mag for 7500 K accounts for the corrected $B-V$ in Figure 1.

3. BASIC PARAMETERS

The extinction-corrected light curve in Figure 1 shows a peak $M_R = -13.9$ mag, corresponding to $L_{\text{peak}} = 3 \times 10^7 L_\odot$ with zero bolometric correction. For $T_{\text{eff}} = 7500$ K, the
emitting radius at peak is $2.3 \times 10^{14}$ cm or 15 AU. Modest expansion speeds of (full width at half-maximum intensity [FWHM] $\lesssim 1000$ km s$^{-1}$) near peak are indicated by Hα and Ca ii lines, while [Ca ii] lines are narrower, appearing unresolved even in our higher-resolution LRIS spectra with FWHM $\lesssim 240$ km s$^{-1}$. The broader line wings of Hα and Ca ii likely arise from multiple scattering by thermal electrons in the dense wind (e.g., Chugai 2001). Integrating the light curve in Figure 2 and assuming zero bolometric correction, the total radiated energy in the first 270 days is $E_{\text{rad}} = 10^{47.8}$ erg, between those of SN 1995J ($10^{47.3}$ erg) and P Cyg's 1600 outburst ($10^{48.8}$ erg) (Humphreys et al. 1999).

The peak of SN 2008S approaches the bottom end of the luminosity distribution for core-collapse SNe II. This low end constitutes a subset of low-luminosity SNe II-P thought to have kinetic energies $\lesssim 10^{50}$ erg, including objects such as SNe 1994N, 1999br, 1999eu, 2001gc, and 2005cs (see Pastorello et al. 2004). Aside from the partial overlap in peak luminosity, however, SN 2008S shares little else in common with this class. Their light curves all exhibit flat plateaus, ending with a sharp decline at $t = 100$–120 days to a $^{56}$Co decay tail, marking their transition from photospheric to nebular phases. SN 2008S, in contrast, shows a relatively linear decline from peak with no clear transition of this type. Moreover, the color evolution of SN 2008S is nothing like this class of low-luminosity SNe II-P (Figure 1), whose color evolution is like that of the more normal-luminosity SNe II-P, with little dispersion in the group (see Pastorello et al. 2004). The late-time $R$-band decline of SN 2008S (Figure 1) roughly matches the rate of 0.01 mag day$^{-1}$ that one expects for $^{56}$Co decay from 0.002 $M_\odot$ of $^{56}$Ni. However, Figure 1 shows only the $R$ magnitude with no bolometric correction. The day 270 spectrum has a very red continuum peaking at $\gtrsim 1$ $\mu$m even after correcting for reddening, so the substantial bolometric correction raises the luminosity by $\sim 0.5$ mag and makes the true decay rate about 0.06 mag day$^{-1}$—almost half that of $^{56}$Co. The late-time decline rate of a SN can be faster than the $^{56}$Co decay rate with energy leakage, but it cannot be slower if radioactivity is the source. It is therefore unlikely that the late-time luminosity of SN 2008S is powered by radioactive decay.

Furthermore, the spectral evolution of SN 2008S is unlike those of the class of weak core-collapse SNe, all of which exhibit remarkably homogeneous spectral properties (Pastorello et al. 2004). The observed ejecta speeds in faint SNe II are slower than those of normal SNe II-P, typically declining from 5000 to 3000 km s$^{-1}$ in the first months, and reaching 1000–1500 km s$^{-1}$ by day 100. The speeds seen in SN 2008S were even slower, however, dropping from $\sim 1000$ km s$^{-1}$ at early times to below 600 km s$^{-1}$ (Figure 2). The smooth continuum and bright narrow emission lines of H and Ca ii at all times in SN 2008S are quite unlike the strong absorption lines and broad P Cyg profiles observed in the photospheres of faint core-collapse SNe (see SN 2005cs in Figure 2). Finally, SN 2008S did not show the characteristic transition from photospheric to nebular phases seen in the low-luminosity SNe II; instead, its day 270 spectrum was almost identical to, although redder than, its spectrum near peak. Thus, we find that the spectrum of SN 2008S did not arise from a recombination front receding through expanding and cooling ejecta, as in weak core-collapse SNe II. Its spectrum points to a different mechanism.

Thompson et al. (2008) raised the question of whether SN 2008S and the NGC 300 transient may have been electron-capture SNe (ecSNe) from stars of initial mass $\sim 9 $ $M_\odot$. While it is admittedly unclear exactly what the observed properties of ecSNe should be, one might expect an ecSN from a $9 M_\odot$ super-asymptotic giant branch star to resemble a weak core-collapse SN in a 10 $M_\odot$ red supergiant (RSG), since both have rapidly expanding H envelopes with similar mass. Indeed, some authors have proposed that the class of weak SNe II-P may be ecSNe (Chugai & Utrobin 2000; Hendry et al. 2005; Kitaura et al. 2006). Since the observed parameters of SN 2008S are quite distinct from those of the weak SNe II, as discussed above, we consider it unlikely that SN 2008S was an ecSN.

On the other hand, the low peak luminosity of SN 2008S is consistent with the observed range for SN impostors. Despite differences in the progenitor stars, the light curve of SN 2008S closely matches that of the SN impostor SN 1997bs (Figure 1), for which the progenitor and surviving star were detected (Van 2004). Indeed, Pastorello et al. (2004) suggest that their spectral homogeneity is sufficient to infer the phase in cases when the explosion date is not known. 6 It is hard to definitively eliminate the possibility that SN 2008S arose from a very weak ($<10^{49}$ erg) core-collapse SN shock interacting with dense circumstellar material (CSM), as in more luminous SNe IIIn, but this scenario would require the underlying SN photosphere to be at least a factor of 100 fainter than a normal SN II-P and it would be indistinguishable from CSM interaction caused by a non-terminal explosion.
Dyk et al. 2000; but see Li et al. 2002). Similarly, the slow expansion speeds, strong Balmer lines, and smooth continuum match those observed in nearby LBVs and other SN impostors, supporting our earlier conjecture that SN 2008S was not a core-collapse SN (Steele et al. 2008). The Eddington parameter, \( \Gamma = \left( \kappa_e L / (4\pi G M c) \right) \), 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 \( L_{\text{peak}} = 3 \times 10^7 L_\odot \), SN 2008S would have \( \Gamma \approx 40 \left( M/20 M_\odot \right)^{-1} \). This huge Eddington parameter is a factor of \( \sim 10 \) higher than that of \( \eta \) Car during its 1843 eruption, when the star shed \( \sim 10 M_\odot \) in a few years (Smith et al. 2003). This high Eddington ratio may hint that the SN 2008S event was explosive, although that does not necessarily imply that it was not an LBV-like event. For example, the same 1843 eruption of \( \eta \) Car produced a fast blast wave of \( \sim 5,000 \text{ km s}^{-1} \) and \( \sim 10^{50} \text{ erg} \) (see Smith 2008).

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 star IRC+10420 (see Figure 2). Both objects exhibit a smooth continuum dominated by narrow H\( \alpha \), [Ca\( \alpha \)]\, and Ca\( \alpha \) emission. Such strong, narrow Ca\( \alpha \) emission lines have not been seen before in a SN or SN impostor, and are extremely rare among known stars. The strong Ca\( \alpha \) and [Ca\( \alpha \)] lines have not been seen in SNe IIn where the radiation is produced by shock interaction with a dense CSM. IRC+10420 is an evolved massive star in a yellow (spectral type \( \approx G5 \)) region of mid-A) hypergiant phase with strong mass loss (Humphreys et al. 2002). This phase may be a counterpart to the LBVs at cooler \( T_{\text{eff}} \) (Smith et al. 2004).

This spectral similarity between SN 2008S and IRC+10420 does not necessarily mean that the objects are in the same evolutionary phase. Although IRC+10420 has experienced strong variability in the past 30 years, it is not currently in a giant eruption. Nevertheless, the similarity does indicate similar values of \( T_{\text{eff}} \) for SN 2008S in outburst and IRC+10420 in its current quiescent state. It also demonstrates that the observed spectrum of SN 2008S can plausibly originate in an opaque and turbulent wind, because this is known to be the case for IRC+10420, whereas no such precedent exists for core-collapse SNe. IRC+10420’s mass-loss rate is estimated as \( \sim 10^{-4} M_\odot \text{ yr}^{-1} \) (see Humphreys et al. 2002). The Ca\( \alpha \) lines imply that both IRC+10420 and the progenitor of SN 2008S are (or were) obscured by dust (Jones et al. 1993; Prieto et al. 2008), since one potential explanation for the unusually strong Ca\( \alpha \) lines is that radiation from SN 2008S might have vaporized grains that were previously in equilibrium around a less luminous progenitor.

Effective temperatures around 7500 K in both objects imply an interesting regime where H is recombining, with serious consequences in a wind driven by radiation force. As such, the classical electron-scattering Eddington limit may be altered in the outermost layers of the star or inner wind. 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, as has been suggested for IRC+10420 (Humphreys et al. 2002).

Recent numerical simulations of super-Eddington winds show a complex pattern of outflow and infall (van Marle et al. 2008). The general character of the winds in these simulations closely matches the situation we envision for SN 2008S, although it is difficult to evaluate this comparison quantitatively. If our suggested picture of a failed super-Eddington wind is applicable, we might expect high-resolution spectra of the H\( \alpha \) and Ca\( \alpha \)\, 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. These have in fact been seen in IRC+10420 (Oudmaijer 1998; Humphreys et al. 2002). Following our initial prediction, these types of line profiles were indeed shown in higher-resolution spectra of the related transient in NGC 300 (Berger et al. 2009; Bond et al. 2009). Unfortunately, our low-dispersion spectra do not resolve the detailed line-profile shapes in SN 2008S itself. A super-Eddington wind with \( \Gamma > 10 \) can drive strong mass loss, with rates up to \( \sim 0.1 M_\odot \text{ yr}^{-1} \) (Owocki et al. 2004). If the ratio of radiated energy to kinetic energy is near unity, as in \( \eta \) Car (Smith et al. 2003; Smith 2006), then we might expect an ejected mass of \( \sim 0.16 \pm 0.05 M_\odot \).

The LBV outburst phenomenon has been observed to occur in stars with initial masses down to about 20 \( M_\odot \) (e.g., Smith et al. 2004). For the lower mass range, the instability is thought to result from heavy mass loss as a RSG, so that the stars have high \( L/M \) ratios in post-RSG blue loops (see Smith et al. 2004). If a similar mechanism operates in SN 2008S, as we suggest, then the relatively low initial mass of \( 10–20 M_\odot \) inferred for the progenitor star by Prieto et al. (2008) has important implications. It tells us that the phenomenon of episodic pre-SN mass loss seen in LBVs can extend to even lower-mass stars than previously thought, perhaps down to \( 15 M_\odot \) or less. At such low masses, it is not at all clear that the star needs to be a blue supergiant to experience a similar type of non-terminal outburst. The mass loss that caused the self-obscuration may have occurred as a RSG with a high \( L/M \) value (Heger et al. 1997), possibly initiating the star’s consequent instability, whereas it seems likely that the high luminosity of the event itself evaporated most of that dust. The expected short duration of \( \lesssim 10^4 \text{ yr} \) for that preceding phase (Heger et al. 1997) satisfies the expectations of Thompson et al. (2008) that these obscured phases would be short lived. If SN 2008S was a super-Eddington event in a \( M_{\text{ZAMS}} \lesssim 20 M_\odot \) 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 to include progenitors with lower luminosity than previously thought. Since the underlying mechanism that triggers LBV eruptions is still not diagnosed, it is difficult to be certain about the difference in these perspectives. We suspect that SN 2008S and the transient in NGC 300 are special cases where the progenitors were highly obscured because of recent mass loss and because of their relatively low progenitor mass. The scenario of a non-terminal explosion or “SN impostor” predicts that the star will be detectable again, although it may take decades before the star recovers to thermal equilibrium.

N.S. acknowledges interesting discussions concerning the nature of SN 2008S with J. Prieto and T. Thompson, and of super-Eddington winds with S. Owocki. Some of the data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California
Institute of Technology, the University of California, and NASA; the observatory was made possible by the generous financial support of the W. M. Keck Foundation. We thank the Lick and Keck Observatory staffs for their dedicated help, as well as the following for their assistance with some of the observations: C. Anderson, A. Barth, J. Chu, J. Leja, B. Macomber, B. Tucker, and J. Walsh. N.S. was partially supported by NASA through grants GO-10241 and GO-10475 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555, and through Spitzer grants 1264318 and 30348 administered by JPL. A.V.F.’s supernova group at U.C. Berkeley is supported by NSF grant AST-0607485, NASA/Spitzer grant 1322321 administered by JPL, and the TABASGO Foundation. We acknowledge the use of public data from the Swift archive.

**Facilities:** Keck I (LRIS), Lick 3 m (Kast), Lick 1 m, Lick KAIT, Swift UVOT.

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