

A NEW CLASS OF LUMINOUS TRANSIENTS AND A FIRST CENSUS OF THEIR MASSIVE STELLAR PROGENITORS

TODD A. THOMPSON^{1,2,4}, JOSÉ L. PRIETO^{1,2}, K. Z. STANEK^{1,2}, MATTHEW D. KISTLER^{2,3}, JOHN F. BEACOM^{1,2,3}, AND CHRISTOPHER S. KOCHANEK^{1,2}

¹ Department of Astronomy, The Ohio State University, 140 W. 18th Ave., Columbus, OH 43210, USA; thompson@astronomy.ohio-state.edu, prieto@astronomy.ohio-state.edu, kstanek@astronomy.ohio-state.edu, ckochanek@astronomy.ohio-state.edu

² Center for Cosmology & Astro-Particle Physics, The Ohio State University, 191 W. Woodruff Ave., Columbus, OH 43210, USA

³ Department of Physics, The Ohio State University, 191 W. Woodruff Ave., Columbus, OH 43210, USA; kistler@mps.ohio-state.edu, beacom@mps.ohio-state.edu

Received 2008 September 3; accepted 2009 September 8; published 2009 October 21

ABSTRACT

The progenitors of SN 2008S and the 2008 luminous transient in NGC 300 were deeply dust-enshrouded massive stars, with extremely red mid-infrared (MIR) colors and relatively low bolometric luminosities ($\approx 5 \times 10^4 L_{\odot}$). The transients were optically faint compared to normal core-collapse supernovae (ccSNe), with peak absolute visual magnitudes of $-13 \gtrsim M_V \gtrsim -15$, and their spectra exhibit narrow Balmer and [Ca II] emission lines. These events are unique among transient–progenitor pairs and hence constitute a new class. Additional members of this class may include the M85 transient, SN 1999bw, 2002bu, and others. Whether they are true supernovae or bright massive-star eruptions, we argue that their rate is of order $\sim 20\%$ of the ccSN rate in star-forming galaxies. This fact is remarkable in light of the observation that a *very* small fraction of all massive stars in any one galaxy, at any moment, have the infrared colors of the progenitors of SN 2008S and the NGC 300 transient. We show this by extracting MIR and optical luminosity, color, and variability properties of massive stars in M33 using archival imaging. We find that the fraction of massive stars with colors consistent with the progenitors of SN 2008S and the NGC 300 transient is $\lesssim 10^{-4}$. In fact, only $\lesssim 10$ similar objects exist in M33 (and perhaps $\lesssim 1$)—all of which lie at the luminous red extremum of the asymptotic giant branch sequence. That these transients are simultaneously relatively *common* with respect to supernovae, while their progenitors are remarkably *rare* compared to the massive star population, implies that the dust-enshrouded phase is a short-lived phenomenon in the lives of many massive stars. This shrouded epoch can occur only in the last $\lesssim 10^4$ yr before explosion, be it death or merely eruption. We discuss the implications of this finding for the evolution and census of “low-mass” massive stars (i.e., $\sim 8\text{--}12 M_{\odot}$), and we connect it with theoretical discussions of electron-capture supernovae (ecSNe) near this mass range. Other potential mechanisms, including the explosive birth of massive white dwarfs and massive star outbursts, are also discussed. A systematic census with (warm) *Spitzer* of galaxies in the local universe ($D \lesssim 10$ Mpc) for analogous progenitors would significantly improve our knowledge of this channel to massive stellar explosions, and potentially to others with obscured progenitors.

Key words: stars: evolution – supernovae: general – supernovae: individual (SN 2008S, 1999bw) – surveys

Online-only material: machine-readable table

1. INTRODUCTION

Identifying the progenitors of core-collapse supernovae (ccSNe), the outbursts of luminous blue variables (LBVs), and other massive-star transients is essential for understanding the physics, demographics, variability, evolution, and end states of massive stars. The problem of identifying the progenitors of bright transients from massive stars is difficult, and traditionally limited to serendipitous archival imaging of nearby galaxies in the optical and near-infrared (NIR, e.g., Van Dyk et al. 2003; Smartt et al. 2004; Li et al. 2007; see the extensive summary in Smartt et al. 2009). Progenitor searches are complemented by statistical studies of supernova environments within their host galaxies, which provide indirect evidence for associations between certain types of supernovae and broad classes of progenitors (e.g., James & Anderson 2006; Kelly et al. 2008; Prieto et al. 2008a; Anderson & James 2008).

A much more direct method for understanding the relation between types of massive stars and their transients is to catalog all of the massive stars in the local universe ($D \lesssim 10$ Mpc) before explosion. While surveys for bright optical transients in

the local universe are well developed (e.g., Li et al. 2001, 2003), a fairly complete census of the massive stars in nearby galaxies has only recently been proposed and undertaken (Massey et al. 2006; Kochanek et al. 2008). Despite the technical challenges required by the depth, area, and cadence of the observations, these surveys are critical for our understanding of the one-to-one correspondence between massive stars and their end states, whether they are successful or failed explosions (e.g., Kochanek et al. 2008). The long-term promise of these surveys is to produce a catalog within which the characteristics of progenitors of future supernovae are listed pre-explosion, as in the case of SN 1987A (West et al. 1987; Menzies et al. 1987). They will provide an essential mechanism for understanding the direct causal mapping between individual progenitor types and their transients (see, e.g., Gal-Yam et al. 2007).

Here, we describe a new link in this causal mapping. The discovery by Prieto et al. (2008a) and Prieto (2008, hereafter P08) of the dust-obscured progenitors of the luminous outbursts in NGC 6946 (SN 2008S; Arbour & Boles 2008) and in NGC 300 (Monard 2008) with *Spitzer* opens up qualitatively new possibilities in the study of the connection between massive stars and their explosions. We show that these discoveries allow us to make a strong—and perhaps unprecedented—connection

⁴ Alfred P. Sloan Fellow.

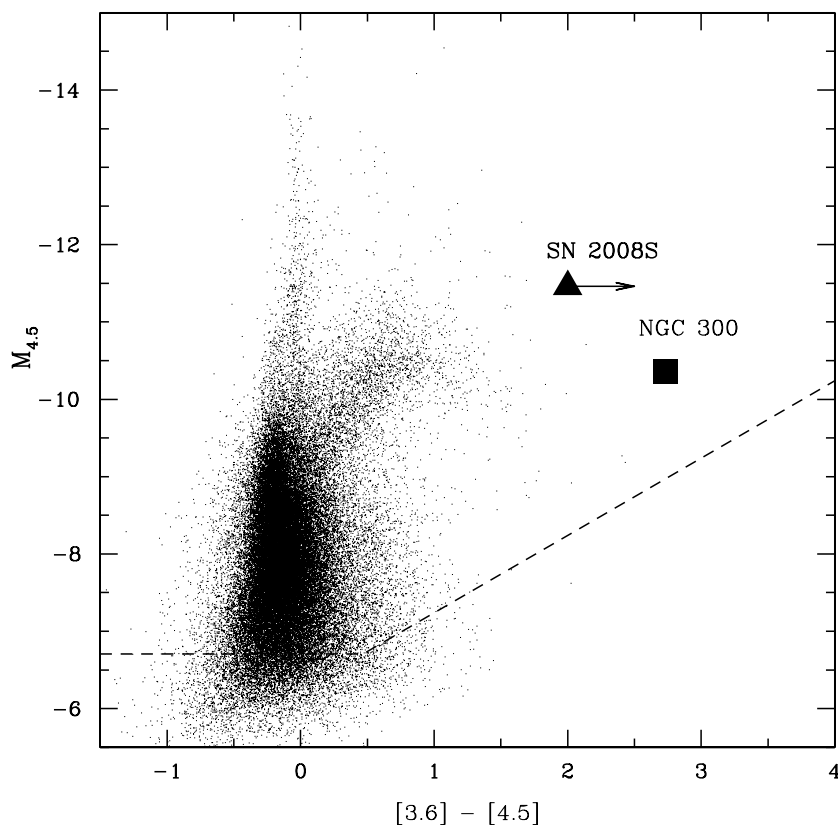


Figure 1. MIR CMD for M33. Absolute magnitude at $4.5 \mu\text{m}$ is plotted vs. $[3.6] - [4.5]$ color for all detected sources (3σ limits denoted by dashed lines; see Section 4.1; Table 1). For comparison, the positions of the progenitors of NGC 300 (filled square) and SN 2008S (filled triangle; lower limit) are also plotted (P08, P08b). Stars analogous to these progenitors are exceedingly rare. Compare with Figure 2. The main sequence, AGB, and EAGB stars are clearly visible. Note the “spur” in the data extending to fainter $M_{4.5}$ and redder color at $[3.6] - [4.5] \approx 1$ and $M_{4.5} \approx -10.5$, originating at the red extremum of the AGB population. To our knowledge, this is the first time that such a feature has been identified in a MIR CMD.

between a dust-enshrouded sub-population of massive stars and a new relatively common class of bright transients.

The argument presented in this paper can be summarized in four points as follows.

1. *The transients SN 2008S and NGC 300⁵ constitute a class.* Both have peak absolute V -band magnitude $M_V \approx -14 \pm 1$ (≈ 2 – 3 mag fainter than normal ccSNe; e.g., Richardson et al. 2002), strong evidence for internal extinction in their spectra, narrow emission lines (similar to low-luminosity Type II supernovae; e.g., Filippenko 1997), and progenitors that are optically obscured and deeply dust embedded (dust-reprocessed emission giving blackbody temperatures $\lesssim 500$ K), and with bolometric luminosities of $\sim 5 \times 10^4 L_\odot$. In addition, they show little infrared variability on a few-year baseline. The details of this unique class of progenitor–transient pairs and its members, as well as a comparison with other classes of optical transients are presented in Section 2. An in-depth search for analogs to the progenitors of SN 2008S and NGC 300 in M33 is presented in Section 4.
2. *Transients of this type are relatively common with respect to ccSNe.* A total of ≈ 22 ccSNe or supernova-like transients have been discovered within ≈ 10 Mpc since 1999. Sixteen were confirmed supernovae, two were luminous blue variable (LBV) eruptions, one was a Type II supernova (SN 2002bu in NGC 4242, $D \approx 8$ Mpc; Puckett

& Gauthier 2002), whose relatively low peak magnitude ($M_V \approx -15$; Hornoch 2002) suggests a close similarity with the remaining two bright transients (see Section 2.5), which are of primary interest in this paper: SN 2008S ($D \approx 5.6$ Mpc) and NGC 300 ($D \approx 1.9$ Mpc), whose physical nature is uncertain. They may be either true (but optically subluminous) supernovae, or a new class of massive star eruptions. Taken at face value, these numbers imply that the rate of SN 2008S-like transients is of order $\sim 10\%$ of the supernova rate.⁶ Because of incompleteness, the true rate is likely higher, and we adopt a nominal value of 20%. We discuss the frequency of these events in detail in Section 3.

3. *The progenitors of this class are extremely rare among massive stars at any moment, in any star-forming galaxy.* Although the bolometric luminosities of the progenitors of SN 2008S and NGC 300 are unremarkable for massive stars ($\sim 5 \times 10^4 L_\odot$), their colors put them in a class consisting of less than 10^{-4} of all massive stars ($[3.6] - [4.5] \mu\text{m}$ color $\gtrsim 2.0$ and ≈ 2.7 , respectively). In a mid-infrared (MIR) color–magnitude diagram (CMD; see Figures 1 and 2), these progenitors lie at the extremum of the asymptotic giant branch (AGB) sequence in both luminosity and MIR color. We refer to them as “extreme-AGB” (EAGB) stars throughout this work. Because of their relatively low bolometric luminosities, they are not η Carinae, cool hypergiant, or classical LBV analogs (see, e.g., Smith 2008).

⁵ Throughout this paper, we denote “the transient in NGC 300” as “NGC 300” (e.g., “the progenitor of NGC 300”) unless we specifically refer to the host galaxy.

⁶ Throughout this paper, we use “supernova rate” to mean the ccSN rate unless we specifically mention the contribution from Type Ia supernovae.

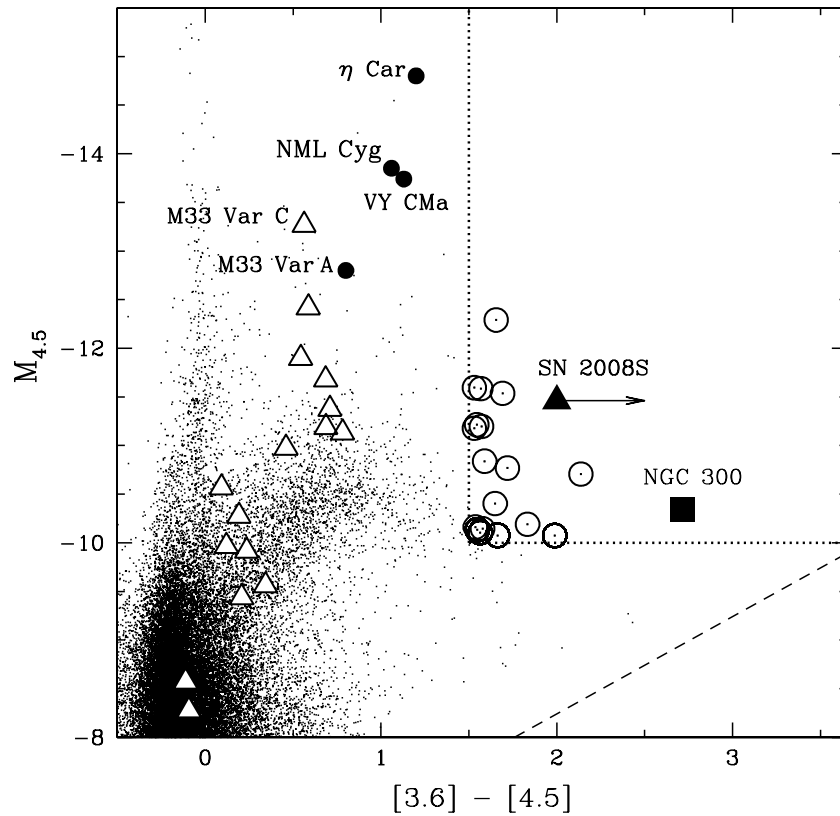


Figure 2. Same as Figure 1, but focused on the red and bright region of interest. Here, the $[3.6]-[4.5] > 1.5$ and $M_{4.5} < -10$ selection for extremely red and bright objects is shown explicitly by the dotted lines, as are the 18 EAGB sources in M33 that meet these criteria (large open circles; see Section 4.2). We denote them “S1–S18,” ordered by color. The reddest source, S1, is shown in Figure 3. Most of these sources are highly variable (see Figures 7, A1, and A2). SEDs are shown in Figure 5 (see Table 2). The EAGB population is clearly distinct from the optically luminous LBV candidates from the catalog of M07, shown by the open triangles (see Section 4; Table 3). Most of the LBV candidates are considerably more bolometrically luminous and much less variable at $4.5 \mu\text{m}$ than the EAGB sample (see Figures 5, 7, A3, and A4). A number of cool hypergiants such as VY CMa, NML Cyg, and M33 Var A, as well as η Carina, are shown for comparison. The brightest LBV candidate is M33 Var C. The LBV candidates appear to be bimodal in MIR color (right panel of Figure 5).

They are thus distinct from the “supernova impostors,” produced by bright outbursts of optically luminous LBVs (e.g., SN 1997bs; Van Dyk et al. 2000, 2003). In Section 4, we present results from a comprehensive survey of M33 for massive stars with properties similar (in bolometric luminosity, obscuration, and variability) to the progenitors of SN 2008S and NGC 300. We find remarkably few. We compare with MIR surveys of the LMC, SMC, and NGC 300.

4. *Conclusion: a large fraction of all massive stars undergo a dust-enshrouded phase within $\lesssim 10^4$ yr of explosion.* This is the most natural explanation for the facts of points (2) and (3) above. If these transients have a rate comparable to the supernova rate ($\sim 10\%$ – 20% ; point 2), then the timescale for the obscured phase is determined by the ratio of the number of dust-obscured massive stars relative to the entire population ($\lesssim 10^{-4}$; see Sections 4, 5) times the average lifetime of a massive star ($\sim 10^7$ yr). Importantly, from the rarity of SN 2008S-like progenitors alone ($\sim 10^{-4}$ of massive stars; point 3), one would naively expect a comparable fraction of supernovae to have progenitors of this type, if the dust-obscured phase occurs at a random time in the life of a massive star. However, the relative frequency of these explosions (point 2) shows that this phase must come in the last $\lesssim 10^4$ yr, just before explosion. Thus, there must be a causal relation between the occurrence of the highly dust-enshrouded phase and eruption. We emphasize that even if the rate of SN 2008S-like explosions is significantly less

than 20% of the supernova rate, our qualitative conclusion is unchanged. These points, together with a discussion of the theory of the evolution of massive stars, the potential connection with ecSNe, white dwarf birth, and other hypotheses for the physical mechanism of 2008S-like explosions, as well as a call for a more comprehensive *Spitzer* survey for analogous sources within $D \approx 10$ Mpc, are presented in Section 5.

2. THE CLASS

We start by listing the objects we view as likely to represent this new class of SN 2008S-like transients and progenitors. The two objects that define the class—SN 2008S (Section 2.1) and NGC 300 (Section 2.2)—are unique among transient–progenitor pairs. The progenitors have relatively low luminosity, low variability, and are deeply dust embedded on ~ 100 AU scales. The transients have low luminosity, with spectra exhibiting both narrow Balmer lines (similar to low-luminosity II n 's and impostors), and [Ca II] in emission, and have rapidly decaying light curves compared to IIP supernovae. The transient in M85 (Section 2.3) and SN 1999bw (Section 2.4) may also be members of the same class, but we cannot confirm the existence of a dust-obscured progenitor similar to SN 2008S/NGC 300. In Section 2.5, we contrast this class with other peculiar outbursts, such as the supernova impostors and low-luminosity Type IIP supernovae, and we note a number of other transients that are not excluded as members of the SN 2008S-like class.

2.1. SN 2008S

SN 2008S in NGC 6946 ($D \approx 5.6$ Mpc; Sahu et al. 2006) was discovered February 1.79 UT (Arbour & Boles 2008). Because of the presence of narrow Balmer lines (FWHM ≈ 1000 km s⁻¹), it was initially classified as a young Type II_n supernova. Stanishev et al. (2008) reported strong Na D absorption with equivalent width of 5 Å, indicating a high degree of internal extinction. On the basis of its relatively low luminosity ($M_V \simeq -14$) and peculiar spectrum (including the presence of strong and narrow [Ca II] 730 nm doublet in emission), Steele et al. (2008) proposed that SN 2008S was a *supernova impostor* such as SN 1997bs (Van Dyk et al. 2000). Botticella et al. (2009) present the late-time light curve of SN 2008S, which shows evidence for a power-law time dependence with a slope indicative of being powered by the radioactive decay ⁵⁶Co. Following the suggestion by Prieto et al. (2008b, hereafter P08b) and the discussion presented in Section 5, Botticella et al. argue that SN 2008S may have been an ecSN.

P08b used a deep pre-explosion archival Large Binocular Telescope (LBT) image of NGC 6946 to put stringent upper limits on the optical emission from the site of the supernova (3σ limits of $M_U > -4.8$, $M_B > -4.3$, and $M_V > -3.8$). The failure to detect a progenitor in the optical led P08b to examine archival *Spitzer* IRAC imaging of NGC 6946 from the SINGS Legacy Survey (Kennicutt et al. 2003) for the progenitor. A point source at the location of SN 2008S was detected at 4.5, 5.8, and 8 μm , but undetected at 3.6 μm and 24 μm , leading to a lower limit on the [3.6]–[4.5] color of $\gtrsim 2$. The best-fitting blackbody temperature to the spectral energy distribution (SED) was ≈ 440 K.⁷ The integrated luminosity was $\approx 3.5 \times 10^4 L_\odot$, consistent with a relatively low-mass massive-star progenitor with a zero-age main sequence (ZAMS) mass of $M \approx 10 M_\odot$. The progenitor SED is shown in the left panel of Figure 5. Simple arguments suggest that the obscuration was circumstellar, with an optical depth at visual wavelengths larger than a few on a physical scale of order 150 AU (P08b). The explosion itself was also serendipitously observed by *Spitzer* 5 days after discovery (Wesson et al. 2008), with an infrared luminosity ~ 50 times larger than the progenitor, suggesting a substantial amount of dust reprocessing (see Figure 2 of Prieto et al. 2008c, hereafter P08c). The lack of variability of the progenitor on a ~ 3 yr timescale argues that the obscuring medium was either a continuous wind with a steady photosphere or a (implausibly?) slowly ($\lesssim 10$ km s⁻¹) expanding shell.

2.2. NGC 300

A luminous optical transient ($M_V \simeq -13$) in the nearby galaxy NGC 300 ($D \approx 1.9$ Mpc; Gieren et al. 2005) was discovered by Monard (2008) and reported by Berger & Soderberg (2008). The latter used archival imaging with Advanced Camera for Surveys/Wide Field Planetary Camera (ACS/WFC) on-board the *Hubble Space Telescope* (*HST*) to put very tight limits on the optical emission (see Figure 5). These limits led them to suggest that the NGC 300 transient was analogous to the outburst V838 Monocerotis (Bond et al. 2003).

Similar to the case of SN 2008S, P08 discovered a deeply embedded source in archival *Spitzer* imaging (PI: R. Kennicutt) at the location of the transient. The source was detected in all IRAC bands, as well as in MIPS 24 μm , and had a [3.6]–[4.5] color of ≈ 2.7 . The SED implies a ≈ 330 K blackbody (as with

⁷ A blackbody provides a rather poor fit to the SED, perhaps indicating an interesting grain size distribution in the obscuring material (P08b).

SN 2008S, a blackbody is a fairly poor fit to the SED) with a bolometric luminosity of $\approx 5.6 \times 10^4 L_\odot$. This finding confirms the massive stellar origin of the NGC 300 transient, and is consistent with a relatively low-mass massive star (see Figure 5). Importantly, depending on the details of stellar models for ZAMS masses in the range of $\sim 10 M_\odot$, at fixed final bolometric luminosity, the inferred initial progenitor mass may be multiply valued, and a luminosity of $\approx 5.6 \times 10^4 L_\odot$ can imply a ~ 5 , ~ 8 or $\sim 11 M_\odot$ progenitor (see Smartt et al. 2009, their Figure 2; Section 5.2).⁸

The luminosity and blackbody temperature of the progenitor of NGC 300 suggest an obscuring medium with a physical scale of order 300 AU. The deep limits on the optical emission from the progenitor with the *HST* suggest an optical depth at V considerably larger than unity (~ 8 – 10).⁹

The fact that the transients in NGC 300 and SN 2008S were similar, both in their luminosities (both relatively faint with respect to typical supernovae with $M_V \approx -14$) and spectra (with narrow Balmer lines and strong [Ca II] 730 nm doublet in emission; Bond et al. 2008), and that their progenitors were similar (highly dust-obscured, relatively modest bolometric luminosities) led P08 to propose that NGC 300 and SN 2008S share a common origin: the explosion—whether supernova or outburst—of a massive star enshrouded in its own dust. As we show below, the fact that their progenitors are so rare among massive stars implies that just two events (although see Sections 2.3 and 2.4) are sufficient to define a class.

2.3. M85

The optical transient in the Virgo galaxy M85 (NGC 4382) was discovered in early 2006 by the Lick Observatory Supernova Search Team (KAIT; Li et al. 2001) and discussed in Kulkarni et al. (2007) and Pastorello et al. (2007) and may also be a member of the class defined by SN 2008S and NGC 300. The transient had peak R -band absolute magnitude of ≈ -12 with a ~ 80 – 100 day plateau, similar to low-luminosity Type IIP supernovae. Optical limits constrain the progenitor to be less than $\approx 7 M_\odot$ or highly obscured (Ofek et al. 2008; see also Pastorello et al. 2007).¹⁰ The low optical luminosity, plateau, and redward spectral evolution of the transient led Kulkarni et al. (2007) to propose that it was analogous to the outburst V838 Mon. In contrast, Pastorello et al. (2007) argued that it was a low-luminosity Type IIP supernova (see Section 2.5).

P08c again searched archival *Spitzer* imaging and discovered an infrared source at the site of the optical transient, but, by chance, taken 8.8 days before the discovery in the optical by KAIT. The source was detected in all IRAC bands and was associated with the transient itself, and not with the progenitor, since archival *Spitzer* imaging from 2004 (PID 3649; PI: P. Côté) does not reveal a point source at the location of the M85 transient. Using these images, we derive 3σ upper limits of $4 \times 10^5 L_\odot$ and $2 \times 10^5 L_\odot$ at 3.6 μm and 4.5 μm , respectively, for the progenitor. The transient was also detected in the MIR seven months after the initial discovery by Rau et al. (2007), the fluxes having decreased by a factor of ≈ 5

⁸ P08 assumed standard singly valued masses, and given the measured luminosity of the progenitor of NGC 300 quoted ($\sim 10^5 L_\odot$) they inferred an initial progenitor mass of ~ 15 – $20 M_\odot$.

⁹ Assuming a spherical homogeneous medium and a Galactic dust-to-gas ratio, this optical depth at V requires a total mass of obscuring material of roughly $\sim 2 \times 10^{-3} M_\odot$ on a scale of 300 AU.

¹⁰ Ofek et al. (2008) quote a limiting absolute magnitude at F850LP(z) with the *HST* of > -6.2 .

over that time. The bright infrared transient discovered by P08c is adequately fit by a blackbody with temperature of ≈ 800 K and luminosity $\approx 2 \times 10^6 L_{\odot}$. The optical and photometry of Kulkarni et al. (2007) indicate a second component to the SED with a blackbody temperature of ≈ 3900 K and with a luminosity of $\approx 5 \times 10^6 L_{\odot}$.

The cooler re-radiated dust emission arises from a region of order 300–400 AU in the physical scale. Assuming that the optical emission did not vary in the ≈ 8.8 days between the IR discovery and the optical discovery, the ratio of the power in these two blackbody components implies that the optical depth at V (τ_V) is less than unity. The physical scale of the obscuring medium indicates that it is likely circumstellar, and the result of a mass-loaded wind. In addition, the luminosity of the transient suggests that any pre-existing dust within ~ 100 – 200 AU would have been destroyed during the explosion. Given the fact that the optical depth to the source scales as r^{-1} in a freely expanding wind, it is not implausible that τ_V to the progenitor was a factor of ~ 10 – 20 larger before explosion. These estimates suggest a pre-explosion obscuring medium similar in its gross properties to the SN 2008S and NGC 300 progenitors.

The M85 transient also showed narrow Balmer lines in emission, as well as some Fe II lines, similar to SN 2008S and NGC 300. Because of the strong evidence for obscuration of the progenitor, as evidenced by the bright IR transient, and the similarity of the spectra, P08c proposed that these outbursts share a common origin and that their obscured progenitors may give rise a new class of 2008S-like transients.

We emphasize that because the character of the progenitor is not known (except for the optical and IR limits), the connection to SN 2008S- and NGC 300-like events is plausible rather than certain. Nevertheless, if the M85 transient was associated with an embedded massive star, the IR limits we derive are consistent with the luminosities derived for the 2008S and NGC 300 progenitors.

2.4. SN 1999bw

The Lick Observatory Supernova Search reported in 1999 April the discovery of a possible supernova in the galaxy NGC 3198 (Li 1999). The optical spectrum of the transient, dominated by narrow Balmer lines in emission (Garnavich et al. 1999; Filippenko et al. 1999), and its low V -band absolute magnitude at maximum of ≈ -13 ($D \approx 13.7$ Mpc; Freedman et al. 2001) led Li et al. (2002) to propose that this transient was an LBV-like outburst. Like SN 2008S and NGC 300, its spectrum showed [Ca II] in emission. Additionally, an infrared source coincident with the optical position of the transient was detected in archival *Spitzer* imaging obtained with IRAC by the SINGS Legacy Survey five years after the discovery of SN 1999bw (Sugerman et al. 2004). The source was detected in all IRAC bands, and the SED was well fit by a 450 K blackbody with an integrated luminosity of $\approx 1.4 \times 10^5 L_{\odot}$, which translates into a blackbody scale of ~ 300 AU.¹¹ We have checked archival IRAC images obtained in 2005 December (PID 20320; PI: B. Sugerman), 1.5 yr after the detection in the SINGS images, and we confirm that the MIR source is indeed the transient, since the fluxes have declined by a factor of more than 3 during this time.

The combination of a low optical luminosity at maximum, an optical spectrum dominated by narrow Balmer lines in emission, the presence of [Ca II] emission, and a luminous infrared

emission detected with *Spitzer*, make SN 1999bw similar to SN 2008S, NGC 300, and the transient in M85. However, as in the case of M85, we emphasize that because there is no information on the progenitor, we cannot be sure that SN 1999bw was of the same class as SN 2008S and NGC 300.

2.5. The Connection to Other Transients

As we discuss in detail in Section 4, perhaps the primary distinguishing characteristic of this class of transients is their deeply embedded progenitors. Since we are unable to confirm the presence of such progenitors for the M85 transient or SN 1999bw, we are unable to make a direct analogy with SN 2008S and NGC 300, and instead rely on the fact that the transients themselves provide strong evidence for obscuration on few-hundred AU scales.

In our effort to understand which cataloged transients might belong to the SN 2008S/NGC 300-like class, we have examined archival imaging of many recent supernovae, as well as archetypal peculiar supernovae, including supernova impostors, LBV outbursts, and low-luminosity Type IIP supernovae. Here, we provide a brief discussion in an effort to orient the reader.

As we mentioned in Section 1 (point 2), the low-luminosity Type IIn SN 2002bu is an interesting transient that may be a member of the class defined by SN 2008S and NGC 300. We checked archival *Spitzer* data of the host galaxy NGC 4242 (PID 69; PI: G. Fazio) taken two years after discovery, and we find a bright infrared point source detected in all IRAC bands within $0''.6$ of the supernova position. Also, two epochs of MIPS data (PID 40204; PI: R. Kennicutt), obtained in 2008, six years after explosion, and separated by just six days, reveal a $24 \mu\text{m}$ source at the position of the supernova. This is qualitatively similar to the case of M85 and SN 1999bw, but because only a single post-explosion IRAC epoch exists, and because the two MIPS epochs are separated by such a short time, we are unable to definitively confirm that the MIR source is associated with SN 2002bu.

SN 1997bs is an intriguing example of an object that does not fit into this class, although its peak absolute magnitude, light curve, color, and some spectral features are comparable to SN 2008S and NGC 300. In this case, a luminous unobscured progenitor has been identified in the optical ($M_V \approx -7$), and the transient itself has been argued to be the outburst of an LBV (Van Dyk et al. 2003). Of interest is the fact that no object has been subsequently identified in the optical at the site of the transient (Van Dyk 2005). We have checked archival *Spitzer* data of the host galaxy (NGC 3627) obtained in 2004 (~ 7 yr after discovery) by SINGS, and do not detect a bright MIR source at the site of SN 1997bs, in contrast with SN 2008S, M85, and SN 1999bw. The event SN 2003gm is also interesting in this context, since it had photometric and spectroscopic evolution similar to SN 1997bs, and also showed an optically luminous progenitor ($M_V \approx -7.5$; Maund et al. 2006). The fact that both SN 1997bs and 2003gm had bright unobscured progenitors is our primary reason for excluding them from the class defined by SN 2008S and NGC 300.

Historical LBV eruptions in nearby galaxies that have been initially classified as supernovae are also worth mentioning here. These include SN 1954J (e.g., Smith et al. 2001) and SN 2002kg (e.g., Maund et al. 2006; Van Dyk et al. 2006) in NGC 2403, SN 1961V (e.g., Humphreys 2005) in NGC 1058, and SN 2000ch in NGC 3432 (Wagner et al. 2004). As in the cases of SN 1997bs and SN 2003gm, a very important common difference between these objects and SN 2008S or NGC 300 is that they

¹¹ The luminosity and blackbody scale have been adjusted to the distance employed here.

all had optically luminous progenitors with absolute magnitudes $\lesssim -6$, consistent with originating from very massive stars. These transients also have other properties that are not consistent with SN 2008S-like explosions: (1) their peak absolute magnitudes range between $-18 \gtrsim M_V \gtrsim -9$, (2) the transient timescales vary widely from a few days to years, and (3) they are not luminous MIR sources in archival *Spitzer* data.

Other optical transients classified as subluminescent Type IIP supernovae that might potentially fall into the class defined by SN 2008S and NGC 300 include SN 1994N, SN 1997D, SN 1999eu, 1999br, 2001dc, 2003Z, and 2005cs (e.g., Pastorello et al. 2004, 2006). We note, however, that there are fundamental differences in the spectra of low-luminosity Type IIP SNe compared with SN 2008S-like transients. In particular, subluminescent Type IIP SNe show Balmer lines with strong P Cygni absorption profiles and velocities of a few thousand km s^{-1} , as is observed in more luminous Type IIP SNe. This stands in sharp contrast with the Balmer lines in SN 2008S-like transients, which are fairly narrow (FWHM $\sim 1000 \text{ km s}^{-1}$) and which do not show strong P Cygni absorption features. In this way, SN 2008S-like transients most closely resemble the spectra of low-luminosity Type IIn SNe and LBV outbursts.

In addition to the very interesting case of 2002bu, there were five other low-luminosity transients classified as “impostors” or “unknown” that could have been LBV outbursts, but for which no progenitor has been identified, and which might be 2008S-like: NGC 4656, SN 2001ac, 2006bv, 2006fp, and 2007sv (see Section 3). However, as we have emphasized and as the sources discussed above imply, the properties of the progenitor cannot be deduced from the character of the optical outburst alone (e.g., contrast SN 1997bs and SN 2003gm with SN 2008S). Thus, in order to understand the causal mapping between progenitor and explosion, a census of the progenitors must first be completed. What is clearly needed is a comprehensive survey for bright MIR sources in all nearby galaxies ($\lesssim 10 \text{ Mpc}$) with (warm) *Spitzer*, analogous to the survey proposed by Kochanek et al. (2008) in the optical. In the following section, we discuss our search for deeply embedded progenitors in M33. We discuss a more complete census in Section 5.

3. RATES

The absolute rate of transients analogous to NGC 300 and SN 2008S is uncertain. Current samples of supernovae over the last decade in the local volume within 10, 20, and 30 Mpc allow us to make only a rough estimate of the true rate. A systematic transient search in the local volume is crucial to solidify these numbers. Nevertheless, we estimate that 2008S-like transients occur with a frequency equivalent to $\sim 20\%$ of the Type II supernova rate. We discuss the observed rates in Section 3.1 below, and then we enumerate several arguments suggesting that the sample of SN 2008S-like transients may be highly incomplete in the local universe (Section 3.2).

3.1. Observed Counts

3.1.1. $D \lesssim 10 \text{ Mpc}$

In addition to SN 2008S and NGC 300, ≈ 20 other ccSNe or supernova-like transients have been discovered within $\approx 10 \text{ Mpc}$ since 1999.¹² Sixteen were confirmed supernovae; they are SN 1999em, 1999ev, 1999gi, 1999gq, 2002hh, 2002ap, 2003gd, 2004am, 2004dj, 2004et, 2005af, 2005at, 2005cs,

2007gr, 2008bk, and 2008ax. Two were bona-fide LBV eruptions (SN 2000ch, Wagner et al. 2004; 2002kg, Schwartz et al. 2003; Weis & Bomans 2005; Maund et al. 2006; Van Dyk et al. 2006). One was a Type IIn supernova potentially of the SN 2008S class (SN 2002bu in NGC 4242, $D \approx 8 \text{ Mpc}$; Puckett & Gauthier 2002; Hornoch 2002). Finally, the transient in NGC 4656 also had some of the spectral characteristics of low-luminosity IIn supernovae (e.g., narrow H α in emission), but only reached an absolute magnitude of ≈ -11.5 (Rich et al. 2005; Elias-Rosa et al. 2005).

Taken at face value, with no correction for incompleteness, these numbers imply that $2/22 \approx 9\%$ or $3/22 \approx 14\%$ (including SN 2002bu) of all optically bright transients are SN 2008S-like. Removing the two bona-fide LBV outbursts (2000ch and 2002kg) for comparison with the supernova sample proper, if SN 2008S and NGC 300 are supernovae, they represent $\approx 10\%$ and $\approx 15\%$ (again, with SN 2002bu) of the sample.

3.1.2. $D \lesssim 20 \text{ Mpc}$

A similar exercise can be carried out within the larger volume of $\sim 20 \text{ Mpc}$. With a peak absolute magnitude of ~ -14 , SN 2008S-like transients would have an apparent magnitude of 17.5 at $D = 20 \text{ Mpc}$, without including a correction for extinction intrinsic to the transient. In fact, SN 2008S and NGC 300 had $A_V \approx 1.2$ (P08b) and $A_V \sim 0.3-1.2$ (Bond et al. 2008), respectively.

Using the Smartt et al. (2009) compilation, we find 29 IIP, 4 I Ib, 15 Ib/c, 2 IIn (1998S & 2002bu), and 2 IIL supernovae in the last decade. There are six classified as “LBV eruptions/impostors” (1999bw, 2000ch, 2002kg, 2003gm, 2007sv, and NGC 4656¹³), but only 2000ch and 2002kg have strong evidence for an LBV progenitor. Whether the yellow supergiant progenitor of 2003gm survived the explosion, and hence whether 2003gm was in fact a supernova, has not yet been definitively established (Maund et al. 2006). Similarly, although SN 2007sv, which reached an absolute magnitude of ≈ -14 , bears some similarity to 1997bs, the nature of its progenitor has not been established (Duszanowicz et al. 2007; Harutyunyan et al. 2007). Finally, there are three events whose nature is classified in Smartt et al. (2009) as unknown: M85, NGC 300, and SN 2008S.

With no correction for incompleteness, and taking only NGC 300 and SN 2008S, this compilation implies an overall rate of $2/61 \approx 3.3\%$ within 20 Mpc. Including M85 and 2002bu in the sample of 2008S analogs doubles the rate. Including 1999bw, 2007sv, and NGC 4656 brings the overall observed rate of SN 2008S-like transients to $\sim 10\%$ within $D \lesssim 20 \text{ Mpc}$.

3.1.3. $D \lesssim 30 \text{ Mpc}$

With a limiting magnitude of $\approx 18-19$, amateur and professional supernova surveys could in principle find SN 2008S-like transients with $M_V \approx -14$ to a luminosity distance of $\sim 25-40 \text{ Mpc}$ (again assuming no extinction). Objects of interest discovered over the last $\sim 10 \text{ yr}$ with faint absolute magnitudes in this distance range, and with the spectral characteristics of IIn supernovae analogous to SN 2008S include 2001ac, 2006bv, and 2006fp.

A total of 92 ccSNe and seven LBV eruptions appear in the recent compilation of Smartt et al. (2009). Three events—M85, NGC 300, and SN 2008S—are classified as “unknown.” Of the seven “LBV eruptions,” only 2000ch, 2002kg, and 2003gm

¹² Throughout the discussion here we exclude Type Ia supernovae.

¹³ Note that NGC 4656 is not included in Smartt et al. (2009).

have LBV-like progenitors. The remainder—1999bw, 2001ac, 2006fp, and 2007sv—have little or no progenitor information, spectra that resemble IIn's, and *may* be SN 2008S analogs. Given the number of confirmed NGC 300 and SN 2008S-like analogs (just 2) and those suspected of belonging to this class (M85, 1999bw, 2002bu), as well as those traditionally labeled “LBV outbursts,” but with no strong confirmation (4656, 2001ac, 2006bv, 2006fp, 2007sv) the overall rate ranges from $2/102 \approx 2\%$ to $10/102 \approx 10\%$ when measured within 30 Mpc.

3.2. Arguments for Incompleteness and Some Implications

To summarize the previous subsections, conservatively taking NGC 300 and SN 2008S as the only examples of their type ever observed (that is, excluding all other low-luminosity transients), the observed rate is $\sim 9\%$, $\sim 3\%$, and $\sim 2\%$ within 10, 20, and 30 Mpc volumes, respectively, with respect to all bright optical transients when averaged over the last 10 years.

It is difficult to estimate the degree of uncertainty in these numbers, since the surveys that find local supernovae are a combination of professional and amateur, with complicated and unquantified selection functions for transient identification. Most surveys responsible for transient discoveries in the local universe do not have detailed descriptions of completeness in the literature. On the contrary, the large majority of the transients in the local volume are first discovered by amateurs.¹⁴ Nevertheless, it is possible to make an estimate of completeness that gives a sense of how large the correction to the rate of SN 2008S-like transients may be.

As an example, B. Monard typically quotes $\pm 0.15\text{--}0.2$ mag (unfiltered) photometric errors on discovery observations of SNe detected at $\approx 16\text{--}17$ mag (e.g., Monard 2006). This photometric error translates to a signal-to-noise ratio of $S/N \approx 5$ (the error associated with calibration is subdominant). In order to estimate a lower limit on the incompleteness, we can compare this value for S/N with the mean detection efficiency for Type Ia supernovae in the SDSS-II Supernova Survey, which employs a well-tested photometric pipeline that uses difference imaging to subtract off the host galaxy (see Dilday et al. 2008). Their Figure 7 shows that for $S/N \approx 5$, the detection efficiency is ≈ 0.5 in Sloan *gri*. The detection efficiency drops to $\sim 0.1\text{--}0.2$ for $S/N \approx 2$, corresponding to a photometric error of ± 0.4 mag.

Momentarily ignoring the difference in the shape of Type Ia light curves with respect to those of 2008S and NGC 300, the results of Dilday et al. (2008) imply that surveys achieving limiting magnitudes of $\approx 18\text{--}19$ are of order $\sim 10\%$ complete for SN 2008S-like transients with $M_V \approx -14$ at 25–40 Mpc ($S/N \sim 1\text{--}2$). Thus, a factor of ~ 10 correction should be applied to the 30 Mpc sample in Section 3.1.3 from the Smartt et al. (2009) catalog for the true rate of low-luminosity IIn supernovae like SN 2008S. Within 20 Mpc the correction for incompleteness is likely a factor of ~ 5 , and within 10 Mpc the incompleteness is probably closer to a factor of ~ 2 . Similar corrections should be applied to the observed rate of true LBV eruptions.

There is another argument for incompleteness at the factor of ~ 2 level within 10 Mpc for SN 2008S-like transients. As summarized by Horiuchi et al. (2009, Section II.B), the observed rate of supernovae of all types within 30 Mpc yields a ratio

of Type Ia supernovae to ccSNe that is significantly in excess of the cosmic ratio measured at high redshift ($0.5 \lesssim z \lesssim 1$; Dahlen et al. 2008). Indeed, the ratio within 30 Mpc is large enough that we would expect to have seen several Type Ia supernovae within 10 Mpc in the last 10 years. Yet, none have been found. This fact implies that the ratio of Ia to ccSNe has been overestimated within 30 Mpc because normal ccSNe are intrinsically fainter than Type Ia's. Thus, the sample of *normal* ccSNe is incomplete within 30 Mpc at the factor of $\sim 1.5\text{--}2$ level, even though these objects typically have peak absolute visual magnitudes of $M_V \approx -16$ to -18 . Naively, analogs to SN 2008S with $M_V \approx -14$ would be ~ 6 times *more* incomplete than normal supernovae at $D \approx 30$ Mpc. Of course, the actual incompleteness correction depends on the overall extinction correction for the transient population and on the cadence of the observations since the light curve declines much faster for 2008S-like transients than for supernova of type IIP. This implied nearly order-of-magnitude incompleteness correction at $D \approx 30$ Mpc for 2008S-like events strongly indicates that the sample is incomplete at order unity within $D \approx 10$ Mpc.

Additionally, a plot of the discovery rate of all supernovae (Ia's included) within 30 Mpc over the last 10 years shows an *increasing* trend, super-Poisson variance, and strong dependence on the results and observing strategy of a single survey (LOSS; Li et al. 2000). There is also an asymmetry between the rate of discovery in the northern and the southern sky in excess of a simple extrapolation of star formation from the catalog of Karachentsev et al. (2004). Finally, there is an unquantified bias against small star-forming galaxies in the local universe. These points further solidify the case that the normal ccSN rate is incomplete, which implies that we are missing 2008S analogs in abundance in the local universe.

Taking yet another angle on the question of overall rate, we may consider the a posteriori statistics of the events SN 2008S and NGC 300 themselves. Taking the overall supernova rate as $\sim 1\text{--}2 \text{ yr}^{-1}$ within 10 Mpc implies a probability of $\sim (4\text{--}8) \times 10^{-4}$ of seeing two events in a single year if the overall rate of 2008S-like transients is 2% of the supernova rate. We consider this uncomfortably small. Similarly, if we were to take the true SN 2008S-like transient rate to be $\sim 100\%$ of local supernova rate, we would be forced to explain the fact that only ~ 2 such events have been seen within 10 Mpc in the last 10 years. Given the discussion of incompleteness above, an overall rate of $\sim 20\%$ with respect to supernovae gives a reasonable chance of seeing two in one year and of seeing only a handful on a 10 year baseline.

Taken together, these arguments imply that the sample of transients in the local universe *when averaged over the last 10 years* is highly incomplete. We suggest that the incompleteness correction is a factor of ~ 2 , ~ 5 , and ~ 10 for $M_V \approx -14$ transients at 10 (≈ 16.0 mag), 20 (≈ 17.5 mag), and 30 Mpc (≈ 18.4 mag), even before accounting for the potentially higher average extinction of these transients relative to normal supernovae. These estimates are consistent with the Richardson et al. (2002), who conclude that low-luminosity supernovae with $M_B \gtrsim -15$ may constitute more than 20% of the overall supernova population (for related arguments, see Schaefer 1996; Hatano et al. 1997; Pastorello et al. 2004). There are several immediate implications as follows.

1. The true rate of SN 2008S-like transients is $\sim 20\%$ of the ccSN rate. However, we emphasize that lower and higher values at the factor of ~ 2 level are not excluded until a more thorough census has been made.

¹⁴ Of the 13, 17, and 13 local ($D \lesssim 30$ Mpc) supernovae (including Type Ia's) discovered in 2006, 2007, and 2008, only one, four, and four were discovered by professional searches. We are unable to confirm which of these would have been independently discovered by a professional supernova search.

2. The true rate of massive star eruptions (LBV-like and otherwise) is similarly incomplete. The observed rate of “LBV eruptions” within 10 and 20 Mpc in Sections 3.1.1 and 3.1.2 implies that they are $\sim 1\text{--}3$ times more common than SN 2008S-like transients. Thus, the true rate of massive LBV eruptions is likely $\sim 20\%\text{--}60\%$ of the ccSN rate.¹⁵
3. The observed rate of ccSNe is incomplete at the factor of ~ 2 level for $D \lesssim 30$ Mpc.

4. A FIRST CENSUS

Because of the implied frequency of events similar to SN 2008S and NGC 300 (Section 1, point 2) and the interesting character of their progenitors, we searched for analogous sources in archival *Spitzer* imaging of nearby galaxies. Our goal was to identify the underlying subpopulation of massive stars from which these progenitors emerge, to characterize their properties and frequency, and to catalog them for future study.

The key characteristics of the progenitors of SN 2008S and NGC 300 are that they are optically obscured and deeply embedded, with very red MIR colors, that their bolometric luminosities are indicative of relatively low-mass massive stars ($L \approx 4 \times 10^4$ and $\approx 5.6 \times 10^4 L_\odot$, respectively), and that the several epochs on NGC 6946 revealed that the progenitor of SN 2008S was not highly variable in the ≈ 3 yr before explosion (P08b). We discuss the variability of the progenitor of NGC 300 in Section 4.4 below based on just two pre-explosion epochs. Although we are only able to derive a lower limit to its RMS variation at $4.5 \mu\text{m}$, like the progenitor of SN 2008S, we find that it too is consistent with a low level of variability.

For a first census, we searched for the deepest archival *Spitzer* observations of a nearby relatively massive bright star-forming galaxy, with already extant optical catalogs. The Triangulum galaxy M33 is a perfect test case. It has an absolute B -band magnitude of $M_B \approx -19.2$, a distance of ≈ 0.96 Mpc (distance modulus $\mu = 24.92$; Bonanos et al. 2006), and it has extensive optical (e.g., Hartman et al. 2006; Massey et al. 2006, hereafter M06), $H\alpha$ (Massey et al. 2007, hereafter M07), and MIR and FIR imaging (McQuinn et al. 2007, hereafter Mc07). A similarly rich data set exists for several other local galaxies, including the Magellanic Clouds (e.g., Blum et al. 2006; Bolatto et al. 2007) and M31 (e.g., Mould et al. 2008). An analysis similar to that described below will be the subject of future work (but, see Section 4.5).

In this section, we present the MIR color–magnitude and color–color diagrams for all cataloged point sources in M33 obtained from multi-epoch archival *Spitzer*/IRAC (Fazio et al. 2004) observations (PI: R. Gehrz; PID 5). This data set allows us to search for and identify stars analogous to the progenitors of SN 2008S and NGC 300. We also present a variability study for both the reddest sources we find in M33 (all extreme-AGB “EAGB” stars) and for the optically selected LBV candidates from M07, which are detected in the MIR imaging. We find that the population of the reddest sources—those most likely to be true analogs of the progenitors of SN 2008S and NGC 300—is completely distinct from the population of LBV candidates in the primary metrics of color, magnitude, and variability. Indeed, we find very few sources with the properties of the SN 2008S and NGC 300 progenitors.

Section 4.1 describes our procedure for extracting point sources and the resulting catalog. In Section 4.2, we present

Table 1
MIR Catalog for 53,194 Point Sources in M33

| R.A. (deg) | Decl. (deg) | [3.6] (mag) | $\sigma_{3.6}$ | [4.5] (mag) | $\sigma_{4.5}$ |
|---------------|----------------|----------------|----------------|----------------|----------------|
| 23.03815 | 30.82294 | 18.70 | 0.21 | 18.19 | 0.12 |
| 23.04489 | 30.82397 | 17.67 | 0.07 | 18.24 | 0.10 |
| 23.04532 | 30.81396 | 18.15 | 0.14 | 18.59 | 0.15 |
| 23.04906 | 30.81863 | 15.69 | 0.05 | 16.19 | 0.07 |
| 23.04955 | 30.82077 | 17.52 | 0.08 | 17.82 | 0.13 |
| 23.05103 | 30.82549 | 16.79 | 0.06 | 17.13 | 0.07 |
| 23.05131 | 30.81658 | 17.96 | 0.09 | 18.33 | 0.12 |
| 23.05277 | 30.79529 | 16.50 | 0.07 | 17.13 | 0.07 |
| 23.05287 | 30.80321 | 17.45 | 0.06 | 17.94 | 0.09 |
| 23.05303 | 30.82159 | 16.96 | 0.05 | 17.38 | 0.07 |
| 23.05314 | 30.78955 | 18.73 | 0.11 | 18.41 | 0.19 |
| 23.05333 | 30.81954 | 18.14 | 0.07 | 18.13 | 0.11 |
| 23.05470 | 30.79727 | 17.57 | 0.06 | 18.04 | 0.12 |
| 23.05473 | 30.81597 | 17.84 | 0.07 | 18.29 | 0.10 |
| 23.05481 | 30.80367 | 17.86 | 0.06 | 18.14 | 0.10 |
| ... | ... | ... | ... | ... | ... |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

the CMD for M33, and discuss the reddest sources vis à vis the optically selected LBV candidates from M07. In Sections 4.3 and 4.4, we discuss their SEDs and variability, respectively. Finally, in Section 4.5, we discuss a preliminary search for similar sources in the NGC 300, LMC, and SMC.

4.1. Catalog

We co-added six epochs of MIR imaging of M33 obtained between 2004 January 9 and 2006 February 4 with IRAC (3.6–8.0 μm ; see Mc07 for details of the observing program). We produced the co-adds in all four IRAC channels from the flux-calibrated mosaics provided by the Spitzer Science Center (post-BCD data). Our final mosaics cover an area of $\sim 33' \times 33'$ (1650×1650 pixels, with $1/2 \text{ pix}^{-1}$) centered on M33, this is approximately within $R_{25} (\simeq 35')$; de Vaucouleurs et al. 1991). We performed source detection and point-spread function (PSF) fitting photometry on the co-adds using the DAOPHOT/ALLSTAR package (Stetson 1992). The PSF magnitudes obtained with ALLSTAR were transformed to Vega-calibrated magnitudes using simple zero-point shifts derived from aperture photometry (using a $12''$ radius), performed in the original images, of 10–20 bright and isolated stars in each band. We estimate errors in the photometric transformations to the Vega system of 0.04 mag in 3.6 μm , 0.05 mag in 4.5 μm , 0.07 mag in 5.8 μm , and 0.07 mag in 8.0 μm channels. For the 3.6 and 4.5 μm bands, the detection limits (3σ) in the co-adds are $[3.6] \simeq 18.9$ mag and $[4.5] = 18.2$ mag, respectively. The sample becomes incomplete at $[3.6] \simeq [4.5] > 17.1$, approximately 0.5 mag deeper than Mc07. A total of $\approx 80,000$ sources are detected in either 3.6 or 4.5 μm . We cross-matched the two catalogs using a 0.5 pixel ($0''.6$) matching radius to obtain a final catalog with $\approx 53,200$ individual sources detected at both 3.6 and 4.5 μm (see Table 1).

There are several reasons for producing a new point source and variability (see Section 4.4) catalogs, given the already existing catalog from Mc07: (1) because we are specifically looking for objects with extreme colors, we wanted to be able to relax the criterion for point source detection in all IRAC bands (in the figures that follow, all sources of interest are

¹⁵ We thank the anonymous referee for pointing this out.

detected with 3σ confidence); (2) we wanted to be able to derive our own upper limits in each band for the same reason; (3) we wanted full IRAC SEDs, whereas the catalog of Mc07 does not provide data at $5.8\ \mu\text{m}$; (4) we wanted to combine the images used by Mc07 with a sixth archival epoch (PI: R. Gehrz; PID 5); (5) for the reddest stars, we wanted to derive full six-epoch light curves for a more complete measure of variability. The resulting MIR CMD looks different from that in Mc07. Of the 18 sources we discuss extensively below, only two were detected at both 3.6 and $4.5\ \mu\text{m}$ in the catalog of Mc07.

4.2. The Color–Magnitude Diagram

The primary result of this effort on M33 was the production of the MIR CMD, shown in Figure 1, which shows the $[3.6]\text{--}[4.5]$ color for all the sources detected at both 3.6 and $4.5\ \mu\text{m}$ as a function of absolute magnitude at $4.5\ \mu\text{m}$, $M_{4.5}$. The dashed line marks the 3σ completeness limit in this plane. The *Spitzer* colors and magnitudes of the progenitors of SN 2008S and NGC 300 are shown for comparison (filled triangle and filled square, respectively; P08, P08b). Note that there are remarkably few objects inhabiting the bright and (very) red region of the CMD. Among the $\sim 5 \times 10^4$ massive stars in M33 (see Section 5), ≈ 18 , 186, and 567 have both $M_{4.5} < -10$ and $[3.6]\text{--}[4.5]$ color larger than 1.5, 1.0, and 0.7, respectively, which correspond to blackbody temperatures of ≈ 500 , 700, and 1000 K, respectively. A total of 2264 point sources are detected with $[3.6]\text{--}[4.5] \leq 0.7$ and $M_{4.5} < -10$.

Figure 2 shows an expanded view of the brightest MIR sources. In addition to the progenitors of SN 2008S and NGC 300, we include several well-studied LBVs (e.g., η Carina), and a number of cool hypergiants (VY CMa, NML Cyg, and Var A in M33) for comparison. The MIR magnitudes and colors for η Carina, VY CMa, and NML Cyg were synthesized from *Infrared Space Observatory* spectra (Sloan et al. 2003). The magnitudes of M33 Var A were obtained from Humphreys et al. (2006). Also included are the 16 sources matched between the catalog of MIR sources presented here and the LBV sample of M07, obtained from narrow-band $H\alpha$ imaging, using a $0''.6$ matching radius. The larger circles within the dotted lines show the EAGB stars, which we discuss in detail below.

The primary point of Figures 1 and 2 is to show that there are *very few* massive stars with the colors and MIR luminosities of the progenitors of SN 2008S and NGC 300. Although it is difficult to identify a quantitative criterion for inclusion in the class defined by the progenitors of SN 2008S and NGC 300, it is clear from Figure 1 that the number of analogs in color and magnitude is very small with respect to the total number of massive stars in M33. For example, if to be included as an analog to the SN 2008S and NGC 300 progenitors, we require that $M_{4.5}$ be brighter than or equal to the progenitor of NGC 300 and that the color be redder than the lower limit on the progenitor of SN 2008S, we find a *single* source. If we require $M_{4.5} < -10$ and color redder than SN 2008S, we find just two sources. Casting the net more widely, for the purpose of having a sample larger than one or two objects and in an effort to be conservative, we use $M_{4.5} < -10$ and $[3.6]\text{--}[4.5] > 1.5$ to identify a sample of 18 EAGB stars (large open circles). As an example, we show an image of our reddest EAGB star (S1) in Figure 3 at 3.6 and $4.5\ \mu\text{m}$ (as well as in V and I ; see Section 4.3). We discuss the spectra and variability properties of these sources in Sections 4.3 and 4.4.

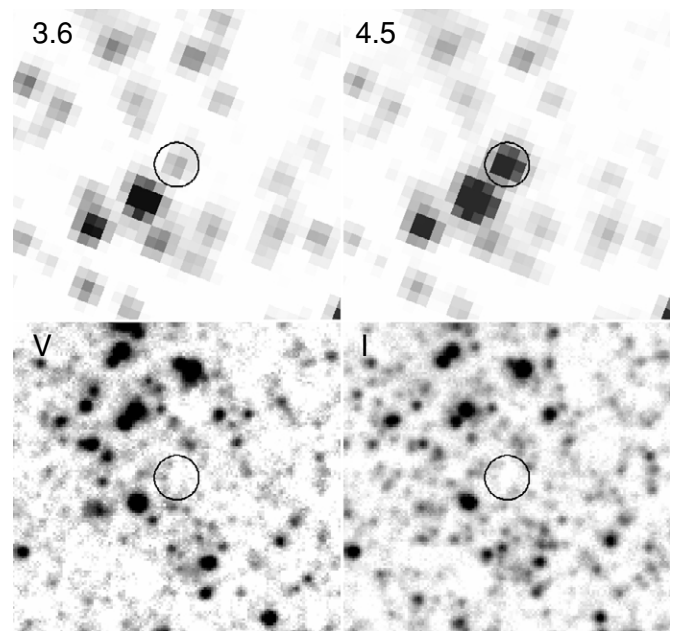


Figure 3. Image showing the point source S1 at $3.6\ \mu\text{m}$, $4.5\ \mu\text{m}$, as well as V and I band (M06). This is the reddest of the 18 sources in $[3.6]\text{--}[4.5]$ color selected in Figure 1. It is optically obscured (see Figure 5). S1 is also highly variable in color and $4.5\ \mu\text{m}$ magnitude (see Figures 6 and 7).

Our choice of the cuts $M_{4.5} < -10$ and $[3.6]\text{--}[4.5] > 1.5$ to identify objects of interest is somewhat arbitrary. Because our argument in this paper relies on the fact that analogs to the progenitors of SN 2008S and NGC 300 are intrinsically rare (Sections 1 and 5), this issue deserves discussion. The magnitude limit is straightforward: it is meant to select objects that have bolometric luminosities indicative of massive stars ($\gtrsim 8 M_{\odot}$). In Section 4.3 below, we show that $M_{4.5} < -10$ is conservative; only half of the 18 sources selected have bolometric luminosities large enough to be massive stars. Note that had we required $M_{4.5}$ to be brighter than or equal to the NGC 300 progenitor, we would exclude eight of our 18 sources (see Figure 5). Our goal was to not miss any deeply embedded massive stars, and the criterion $M_{4.5} < -10$ accomplishes that goal.

The cut on color is more complicated. We were motivated by several factors. First, we wanted to avoid the AGB sequence blueward of 1.5, where the density of points increases dramatically and where the sample would consist largely of Carbon stars (see Figures 1 and 2). Second, this cut essentially eliminates contamination from background active galaxies (Stern et al. 2005). Third, the $[3.6]\text{--}[4.5] > 1.5$ cut gives us a reasonable number of objects to assess individually—it is neither too many nor too few (again, had we taken $[3.6]\text{--}[4.5] > 2.0$, the sample would consist of just one or two objects).

These considerations leave us open to the potential criticism that optically obscured massive stars may exist in the region $M_{4.5} < -11.5$ (again, avoiding the AGB feature in the CMD) and with $0.5 < [3.6]\text{--}[4.5] < 1.5$. To address this, we have examined the 45 sources that occupy this region of the CMD. Four are identified with the LBV candidate catalog from M07, which we discuss more below. Sixteen of the remaining 41 sources have bright optical counterparts from the catalog of M06. Of the 25 sources that do not appear in M06, 16 are optically detected, but at flux levels where the M06 catalog is highly incomplete. That leaves nine optically obscured sources that have MIR luminosities indicative of massive stars. Like

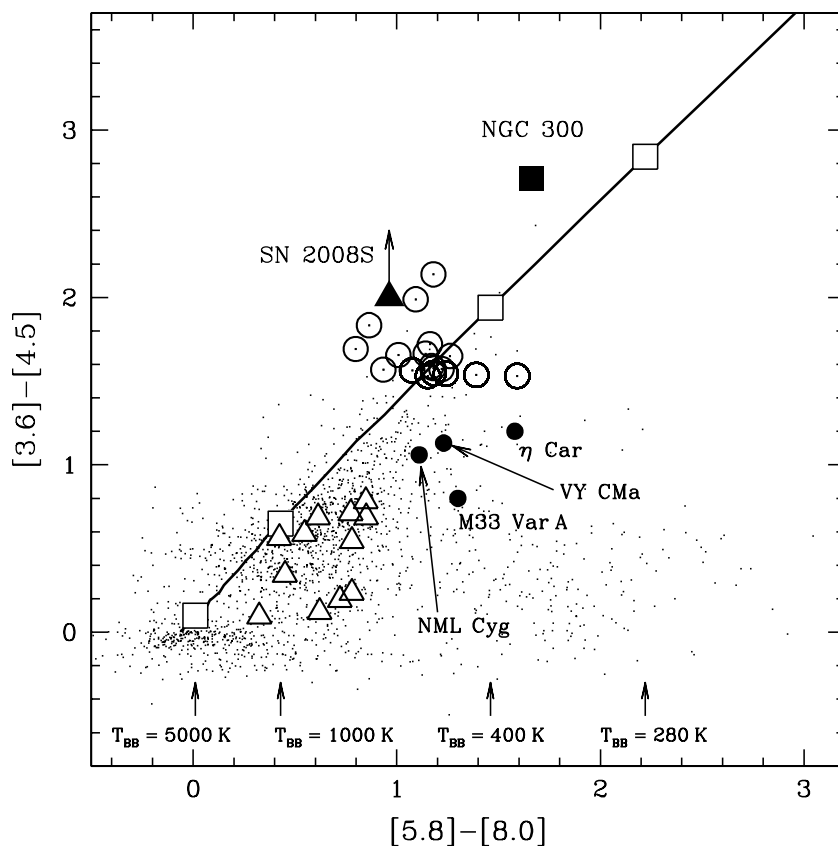


Figure 4. Color-color diagram showing $[5.8]-[8.0]$ vs. $[3.6]-[4.5]$ colors for all (≈ 1800) the sources detected in all four IRAC bands. Symbols are the same as in Figure 1. The solid line and open squares show the expectation for a blackbody of temperature $T_{\text{BB}} = 5000, 1000, 400,$ and 280 K. The small filled points with $[5.8]-[8.0] \approx 1.6-1.8$ and $[3.6]-[4.5] \gtrsim 2$ are not sufficiently bright at $4.5 \mu\text{m}$ ($M_{4.5} < -10$) to be included in the sample defined by the dotted lines in Figure 2.

the very brightest of the 18 sources within the dotted lines in Figure 2, about half of these have very large MIR luminosities, considerably larger than the progenitors of SN 2008S and NGC 300. We conclude that in this region there is just a handful of sources that might be true analogs to these progenitors—and we note that these have colors $\sim 0.5-1.0$ mag bluer than the lower limit on the progenitor of SN 2008S. Indeed, self-obscuration to the extent of the NGC 300 and SN 2008S progenitors is exceedingly rare for the most luminous stars, as evidenced by the lack of objects in the upper-right corner of Figures 1 and 2.

Finally, we note that we have searched for $4.5 \mu\text{m}$ sources without $3.6 \mu\text{m}$ detections that would lie within the dotted lines in Figure 2, and we find just one source. Close inspection of the images reveals a marginal $3.6 \mu\text{m}$ detection and $[3.6]-[4.5] \approx 1.5$.

Despite this long discussion of color and magnitude selection, the primary point of Figures 1 and 2 still stands: there are remarkably few massive stars in M33 that have the color and luminosity of the progenitors of SN 2008S and NGC 300. As we discuss in Section 4.3, all are consistent with relatively low-mass massive stars.

The second point to note from Figures 1 and 2 is that the EAGB stars we have selected are not optically luminous LBVs, η Carina analogs, or cool hypergiants. Indeed, all of the LBV candidates (open triangles) have $[3.6]-[4.5] \lesssim 0.8$, and about half have colors $\lesssim 0.3$. The cool hypergiants and η Carina-like objects are also bluer than the EAGB population, and considerably brighter than the progenitors of SN 2008S and NGC 300. Indeed, the latter are most naturally associated

in this diagram with the luminous red extremum of the AGB population, hence our use of “EAGB” stars.

The color-color diagram for all the sources detected in the four IRAC bands is shown in Figure 4. The symbols are the same as in Figure 2. The small points with extremely red $[5.8]-[8.0]$ colors are relatively dim, with $M_{4.5} > -10$ and are likely young stellar objects (YSOs; e.g., Bolatto et al. 2007). The strong deviation of the SN 2008S and NGC 300 progenitors from the blackbody curve (solid line) reinforces the fact that the SEDs of these sources are not well fit by a simple blackbody (P08b). Despite this, the SN 2008S and GC 300 progenitors, EAGBs, LBV candidates, and cool hypergiants do not stand out as separate populations in $[5.8]-[8.0]$ color. This is important because it means that $[5.8]-[8.0]$ color alone cannot be used as a metric for inclusion or exclusion from the class of SN 2008S/NGC300-like progenitors.

4.3. Spectral Energy Distributions

The limits on the optical emission from the progenitors of NGC 300 and SN 2008S are tight, and effectively rule out an optically unobscured massive star (Berger & Soderberg 2008; P08b; Figure 5). For the purposes of finding analogs to these sources, it is critical to derive the optical luminosities and/or upper limits for the 18 EAGBs identified in Section 4.2. Here, we present these results and compare the derived optical-to-MIR SEDs of the EAGBs to the optically bright (narrow band $H\alpha$ -selected) LBV candidates from M07.

As part of the *Survey of Local Group Galaxies Currently Forming Stars* (SLGG), M06 presented a catalog of $\sim 150,000$ point sources in M33 with well-calibrated *UBVRI* photometry

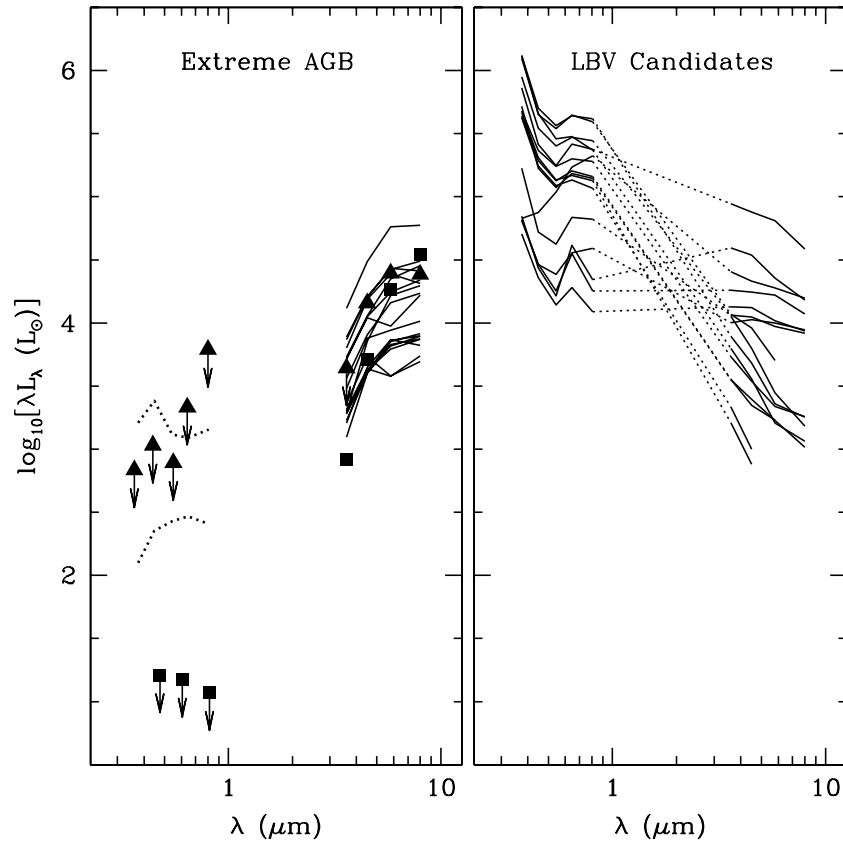


Figure 5. Left panel: SEDs of the 18 EAGB stars in M33 with $[3.6]-[4.5] > 1.5$ and $M_{4.5} < -10$ (see Figure 2; Table 2). The lower dotted line shows the best lower limits obtained in the optical, whereas the upper dotted line shows the worst lower limits at U and I and the two BVR detections (see discussion Section 4.3; Table 2). The SEDs of the SN 2008S (filled triangles) and NGC 300 (filled squares) progenitors are also shown. For all the sources in M33, we assume a total extinction of $E(B - V) = 0.1$ mag. Right panel: SEDs of the 16 LBVs detected in MIR from the $H\alpha$ -selected catalog of M07 (see Figure 2; Table 3). The relative increase in λL_λ in the R band ($0.6 \mu\text{m}$) is due to the presence of strong $H\alpha$ emission.

obtained from observations at the KPNO 4 m telescope with the Mosaic imager. We use the published photometric catalog and images from M06 to complement the *Spitzer* MIR photometry described in Section 4.2.

We first cross-matched the positions of the EAGB stars with the M06 photometric catalog. Importantly, we do not find any optical counterpart to the EAGB sources using a matching radius of $0''.5$. Since the completeness of the M06 catalog starts to decline rapidly at $V \simeq 22$ mag, we analyze the images independently to look for faint optical counterparts to the EAGB stars. We use SExtractor (Bertin & Arnouts 1996) with a low detection threshold (2σ above the local background) to detect and measure aperture photometry (using a small aperture of 3 pixels radius) of all the sources detected in the KPNO/Mosaic $UBVRI$ images of M33 from M06. We calibrate the photometry relative to the magnitudes in the catalog of M06. Using a radius of $0''.5$ to cross-match the MIR positions of the EAGB stars with our multi-band catalogs of faint optical sources, we only detect two EAGB stars in the BVR bands (again, 2σ). The remaining 16 sources do not have optical counterparts. We estimate 3σ upper limits on the $UBVRI$ magnitudes using the local background RMS at the positions of the EAGB stars. The median 3σ upper limits are: $U = 24.0$, $B = 24.0$, $V = 23.5$, $R = 23.0$, and $I = 22.5$. The data for each of the 18 EAGB stars are listed in Table 2.

In order to convert MIR and optical magnitudes to fluxes, we used zero points in Reach et al. (2005) and Cohen et al. (2003) for the EAGBs and LBV candidates, respectively. The

luminosities of all sources were calculated assuming a constant reddening of $E(B - V) = 0.15$ mag and a distance of $\mu = 24.92$ (Bonanos et al. 2006). The reddening correction is motivated by the uncorrected $B - V$ CMD of M06, which shows that the bluest sources only reach $B - V \approx -0.2$, instead of ≈ -0.33 , as would be expected from an unreddened massive star. In addition, Bonanos et al. (2006) also quote an average reddening correction of 0.1 mag to massive stars for M33. A larger adopted reddening correction increases our upper limits for the optical fluxes of the EAGB stars.

The primary result of this procedure is Figure 5, which shows the SEDs of the EAGB stars (left panel) and LBV candidates (right panel). The dotted lines in the left panel show the range of upper limits (and one BVR detection, as described above) for the 18 EAGB stars at $UBVRI$ (see Table 2). The filled triangles show the optical and $3.6 \mu\text{m}$ upper limits for the progenitor of SN 2008S. The solid squares show the MIR detections and optical upper limits for the NGC 300 progenitor. These sources should be contrasted with the optically luminous LBV candidates from M07 (right panel). Note that three of the LBVs do not have 5.6 and $8.0 \mu\text{m}$ detections. The fact that one of the non-detections would appear to have a 5.6 and $8.0 \mu\text{m}$ flux larger than some of the other detections is a consequence of the locally higher MIR diffuse flux near that particular object.

There are a number of points to take away from the two panels of Figure 5. First, nine of the 18 EAGB stars we identified in Figure 1 do not have bolometric luminosities indicative of massive stars; they have $L_{\text{bol}} \lesssim 2 \times 10^4 L_\odot$.

Table 2
Photometry for the 18 EAGBs in M33

| Name | R.A. (deg) | Decl. (deg) | U^a (mag) | B^a (mag) | V^a (mag) | R^a (mag) | I^a (mag) | [3.6] (mag) | [4.5] (mag) | [5.8] (mag) | [8.0] (mag) |
|------|---------------|----------------|--------------------|--------------------|--------------------|--------------------|--------------------|----------------|----------------|----------------|----------------|
| S1 | 23.45485 | 30.85704 | 23.47 | 23.76 | 23.37 | 22.90 | 22.47 | 16.35 | 14.21 | 12.55 | 11.37 |
| S2 | 23.44397 | 30.79731 | 23.96 | 24.15 | 23.55 | 23.15 | 22.47 | 16.84 | 14.85 | 13.52 | 12.42 |
| S3 | 23.56813 | 30.87755 | 23.91 | 23.97 | 23.48 | 23.10 | 22.50 | 16.56 | 14.73 | 13.42 | 12.55 |
| S4 | 23.43452 | 30.57106 | 23.87 | 23.74 | 23.21 | 22.71 | 22.02 | 15.87 | 14.15 | 13.23 | 12.07 |
| S5 | 23.40436 | 30.51738 | 22.99 | 23.10 | 22.97 | 22.71 | 22.10 | 15.08 | 13.38 | 12.12 | 11.32 |
| S6 | 23.49194 | 30.82791 | 24.10 | 23.84 | 23.42 | 22.89 | 22.09 | 16.51 | 14.84 | 13.46 | 12.32 |
| S7 | 23.55640 | 30.55211 | 24.52 | 24.50 | 23.86 | 23.31 | 22.75 | 14.29 | 12.63 | 11.18 | 10.17 |
| S8 | 23.46408 | 30.64138 | 22.79 ^b | 23.11 ^b | 22.32 ^b | 21.75 ^b | 20.96 ^b | 16.17 | 14.52 | 14.14 | 12.87 |
| S9 | 23.53817 | 30.73269 | 21.75 ^b | 21.93 ^b | 22.14 ^b | 22.10 ^b | 21.89 ^b | 15.67 | 14.08 | 12.69 | 11.51 |
| S10 | 23.29877 | 30.59901 | 24.31 | 23.97 | 23.67 | 23.30 | 22.75 | 16.35 | 14.78 | 13.55 | 12.37 |
| S11 | 23.29777 | 30.50744 | 23.82 | 23.64 | 23.53 | 23.05 | 22.83 | 15.30 | 13.72 | 12.47 | 11.26 |
| S12 | 23.55236 | 30.90564 | 24.20 | 23.96 | 23.50 | 23.21 | 22.62 | 14.90 | 13.33 | 12.01 | 11.08 |
| S13 | 23.37907 | 30.70096 | 24.05 | 24.14 | 23.60 | 23.03 | 22.41 | 16.38 | 14.82 | 13.44 | 12.36 |
| S14 | 23.26238 | 30.34469 | 23.96 | 23.95 | 23.48 | 23.03 | 22.47 | 16.33 | 14.79 | 13.61 | 12.43 |
| S15 | 23.39709 | 30.67737 | 24.13 | 24.02 | 23.29 | 22.80 | 22.23 | 15.25 | 13.71 | 12.22 | 10.97 |
| S16 | 23.43722 | 30.64242 | 23.75 | 23.39 | 22.79 | 21.99 | 21.39 | 16.30 | 14.76 | 14.15 | 12.76 |
| S17 | 23.47176 | 30.67430 | 23.81 | 23.67 | 23.03 | 22.51 | 21.60 | 15.27 | 13.74 | 13.15 | 11.56 |
| S18 | 23.34248 | 30.64602 | 24.21 | 23.95 | 23.65 | 23.22 | 22.63 | 14.86 | 13.32 | 12.03 | 10.88 |

Notes.

^a Except where otherwise noted, all *UBVRI* data in this table are upper limits.

^b Source detections. Magnitudes from M06.

Thus, these are not likely to be true analogs to the SN 2008S and NGC 300 progenitors. Second, all of the sources are highly optically obscured, with $\lambda L_\lambda[V]/\lambda L_\lambda[4.5\ \mu\text{m}] \sim 10^{-2}$. Third, these sources are qualitatively different from the more bolometrically luminous LBV candidates (right panel). The LBVs are interesting in their own right, dividing approximately into two classes: (1) relatively optically dim with a strong MIR excess and (2) optically bright with little MIR excess, if at all. This division is also evidenced by their positions in the CMD (Figure 1), which indicates a bimodality in MIR color. For a possible analog to LBVs with a MIR excess, see Smith (2007).

4.4. Variability

Because four epochs of archival *Spitzer* data were available for NGC 6946 in the three years prior to the discovery of SN 2008S, P08b investigated potential variability of the progenitor. They found that there was remarkably little and showed that this fact could be used to constrain the motion of the obscuring medium, under the assumption of a geometrically thin, but optically thick shell (see Section 2; P08b).

Motivated by this result, and by the fact that six epochs of archival data over two years exist for M33, we investigated the MIR variability of all the sources detected at 3.6 and 4.5 μm . To generate light curves, we used the difference imaging analysis package ISIS, based on the techniques of Alard & Lupton (1998) and Alard (2000).¹⁶ For a discussion, see Hartman et al. (2004).

There is a striking difference between the 4.5 μm light curves of the 18 EAGB stars and the LBV candidates from M07. Most of the EAGB stars are highly variable, both in magnitude ($0.1 \lesssim \text{RMS}(\text{mag}) \lesssim 0.8$) and in [3.6]–[4.5] color. In contrast, the majority of the LBVs are not variable ($\text{RMS} \lesssim 0.1$ mag); only two sources show clear variability (both are blue in [3.6]–[4.5]). To illustrate these differences, we

show in Figure 6 the light curve at 4.5 μm and color variations of the reddest source in our EAGB sample S1 (left panel) and an LBV candidate (right panel). For completeness, we present all of the 4.5 μm light curves and color variations of the 18 EAGB stars in Appendix A (Figures A1 and A2) and of the LBVs in Appendix B (Figures A3 and A4).

Figure 7 summarizes these findings. It shows the measured RMS at 4.5 μm as a function of [3.6]–[4.5] color for all the bright sources with $M_{4.5} < -10$. The symbols are the same as in Figures 2 and 4. There is a clear correlation evident between the RMS (or amplitude) and color for the AGB stars (see also Mc07).

For comparison, the RMS variation of the progenitor of SN 2008S derived from its three-year light curve is also shown. In the case of the NGC 300 progenitor, we can only put a lower limit on its RMS variation, because only two epochs of archival *Spitzer* imaging exist. Nevertheless, it is striking that both the SN 2008S and the NGC 300 progenitors are consistent with very little variation in the few years preceding their explosions. In particular, SN 2008S is inconsistent with the clear trend among the AGB stars to become more variable as they become redder. Only a handful of the EAGB stars vary so little, which suggests that a *lack of variability among an otherwise variable EAGB star population* may be used as a selection criterion for analogs to the SN 2008S and NGC 300 progenitors. As an example, requiring the RMS to be $\lesssim 0.3$ mag, we find five sources. They are S12, S7, S9, S17, and S8, in order of increasing RMS (see Table 2). Sources S8 and S9 are among the lower luminosity sources in the left panel of Figure 5, and are therefore not likely true SN 2008S analogs. In contrast, S7 is the brightest of our EAGB stars. Finally, the least variable source (S12) has $M_V \approx -11.6$, which is quite close to the SN 2008S progenitor, even though it is ~ 0.5 mag bluer.

Although we have identified a few rare and interesting sources, the sparsity of data in Figures 2 and 7 with [3.6]–[4.5] > 1.5 makes it difficult to construct a strict quantitative joint criterion in the space of luminosity, color, and variability for

¹⁶ See <http://www2.iap.fr/users/alard/package.html>.

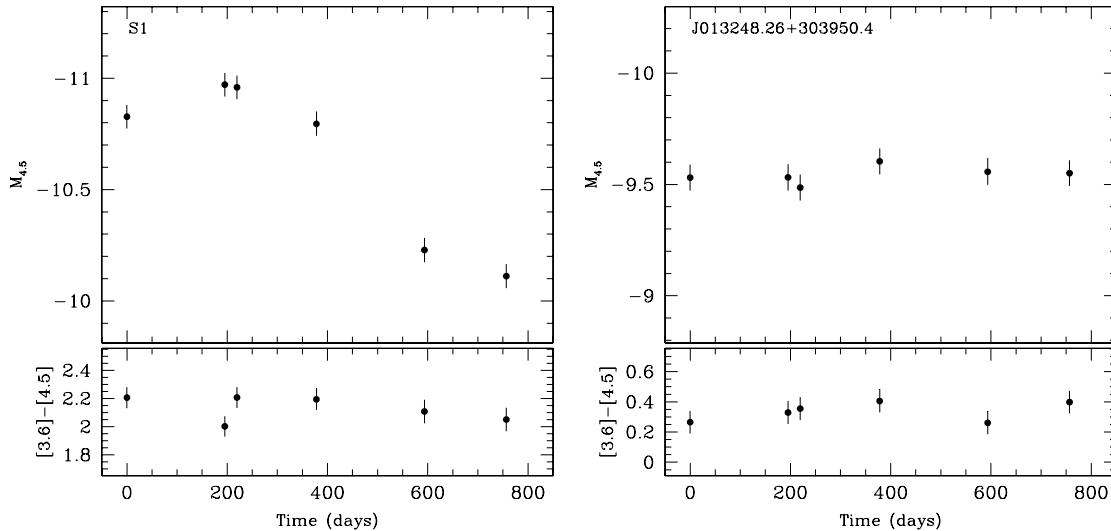


Figure 6. Left panel: light curve for S1 (see Figure 3), the reddest of the 18 EAGB stars selected in Figure 2. Note the high degree of variability, which for this source, is *inconsistent* with the progenitor of SN 2008S and (potentially) NGC 300 (see Figure 7). Light curves for all of the EAGB stars are shown in Figures A1 and A2. Although not strong in this example, most of the sources exhibit correlated color–magnitude variations. Right panel: 4.5 μm light curve for one of the LBV candidates from M07 (see Figures A3 and A4 for the complete set). The large majority of the 16 LBV candidates are not highly variable at 4.5 μm , although there are two exceptions (Figure 7).

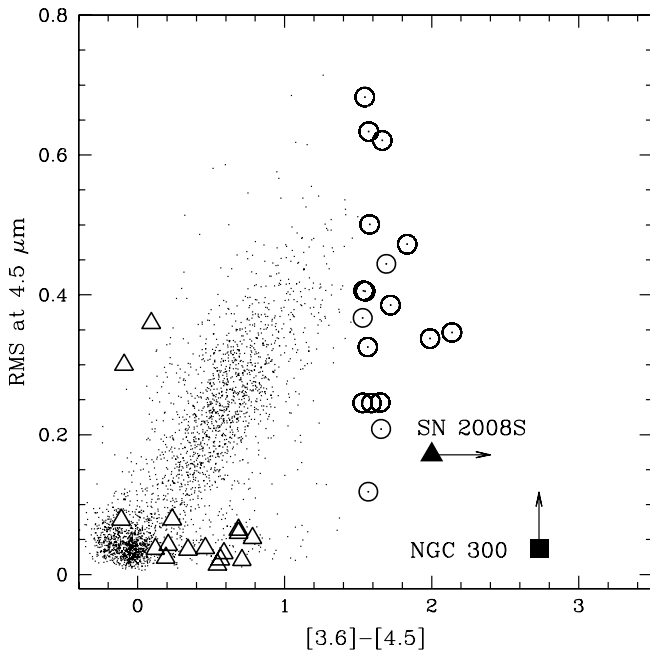


Figure 7. RMS variation in 4.5 μm magnitude as a function of [3.6]–[4.5] color for all of the sources detected in 3.6 μm and 4.5 μm with $M_{4.5} < -10$ (points) and the 16 LBV candidates (open triangles). As in Figure 2, the 18 EAGB stars are denoted with larger open circles. As noted in Figures A1 and A2, as well as A3 and A4, the extreme-AGB stars are highly variable, whereas all but two of the LBV candidates are not. Variability of the progenitors of SN 2008S and NGC 300 is also shown. For the former, the data are taken from P08b (their Figure 2). For NGC 300 only two epochs are available and hence the value of the RMS (≈ 0.05) is a lower limit on the variability of the progenitor.

inclusion in the class of SN 2008S-like progenitors. Based on the discussion above, as in Sections 4.2 and 4.3, we expect a total of ~ 1 –10 in M33. A more complete multi-epoch survey of EAGB stars in the local universe may fill in the region in Figure 7 between the AGB locus and the SN 2008S and NGC 300 progenitors. Most importantly, it might make clear a quantitative criterion for “SN 2008S-like” in the RMS–color plane.

4.5. Other Galaxies

Blum et al. (2006) and Bolatto et al. (2007) present *Spitzer* point source catalogs for the LMC and SMC, respectively. We have searched these catalogs for sources that satisfy the selection criteria $M_{4.5} < -10$ and $[3.6] - [4.5] > 1.5$ used to identify the 18 EAGB stars discussed throughout this section. In the catalog of Blum et al. (2006), we find nine sources. Three are coincident with Two Micron All Sky Survey sources, and five appear in the *IRAS* catalog. Although more careful follow-up is clearly required, a subset of these nine sources may be EAGB stars. In the catalog of Bolatto et al. (2007) for the SMC, we find a single source that satisfies $M_{4.5} < -10$ and $[3.6] - [4.5] > 1.5$. Finally, we have also completed a cursory search for EAGB stars in archival imaging of NGC 300 (PI: R. Kennicutt; ID 40204), and we find just four potential sources.

In sum, even the relatively conservative criteria $M_{4.5} < -10$ and $[3.6] - [4.5] > 1.5$ pick out remarkably few stars in any galaxy—M33 is not peculiar in this regard. Given the fact that we expect only a fraction of the 18 sources in M33 to be bona-fide analogs to the progenitors of SN 2008S and the transient in NGC 300 (based on luminosity, color, and variability; see Sections 4.3 and 4.4), a more careful look at the sources of interest in the LMC (≈ 9), SMC (≈ 1), and NGC 300 (≈ 4) is likely to further decrease the total number of sources of interest in these systems. As emphasized in Sections 1 and 5 below, the scarcity of SN 2008S-like progenitors with respect to the total massive star population is remarkable in light of the fact that SN 2008S-like transients are likely to be relatively common with respect to the overall supernova rate.

5. DISCUSSION

We have shown that in the primary metrics of color, luminosity, and variability, stars analogous to the progenitors of SN 2008S and NGC 300 are exceedingly rare in star-forming galaxies. They have luminosities characteristic of low-mass massive stars, are deeply dust-obscured with extremely red MIR colors, and show little MIR variability (see Figures 1, 2, 5, and 7). In luminosity and color, they are distinct from the population of

optically luminous LBV candidates selected from M06. Although many of the reddest objects selected as EAGB stars in Figure 2 are highly variable, the few (~ 1 – 5) least-variable sources most closely resemble the SN 2008S and NGC 300 progenitors. In this way (but in only this way), they are similar to the LBV candidates.

In this section, we discuss the implications of our finding that stars with characteristics analogous to the progenitors of SN 2008S and NGC 300 are rare. In Section 5.1, we estimate the overall fraction of massive stars that are deeply dust-embedded and the lifetime of stars in that state. In Section 5.2, we connect with the evolution of massive stars, including the possibility that SN 2008S-like transients are the result of ecSNe or massive white dwarf birth. Section 5.3 discusses how many EAGB stars can be found within the local universe ($D \lesssim 10$ Mpc) using *Spitzer*.

5.1. Numbers & Rates

The total number of analogs to the progenitors of SN 2008S and NGC 300 in M33 is uncertain. This uncertainty comes primarily from the fact that we are unable to identify an absolute quantitative criterion for inclusion into this progenitor class based on our three primary metrics: color, luminosity, and variability. To be conservative, we have identified 18 sources in the region $M_{4.5} < -10$ and $[3.6]$ – $[4.5] > 1.5$ of the CMD that satisfy the minimal criteria of being bright and extremely red (larger open circles in Figure 2). However, a very strict cut in color and magnitude (i.e., all sources redder than the lower limit to SN 2008S and brighter than NGC 300) yields just two sources. Among the 18 selected sources, we have shown that roughly half do not have bolometric luminosities indicative of massive stars. That is, they do not have luminosities as large as one would expect for stars who are traditionally thought to end their lives as supernovae ($L_{\text{bol}} \gtrsim 4 \times 10^4 L_{\odot}$). It is important to note, however, that at fixed final luminosity of a massive star, its initial ZAMS stellar mass may be multi-valued, implying progenitors with either ~ 5 – 7 , ~ 8 – 9 , and ~ 11 – $14 M_{\odot}$ for $L \approx (5$ – $10) \times 10^4 L_{\odot}$. (see Figure 2 of Smartt et al. 2009; Section 5.2; see footnote 8). Of course, the explosions SN 2008S and NGC 300 may not be true supernovae, but rather a new class of bright eruptions from obscured massive stars (see Section 5.2). Nevertheless, comparing these 18 sources to the progenitors of SN 2008S and NGC 300 in Figure 5, we would argue that only roughly half belong to this progenitor class based on SED alone. Finally, Figure 7 shows that only ≈ 1 – 5 of the 18 sources vary as *little* as the progenitors of SN 2008S and (potentially) NGC 300. Importantly, 16 of the 18 sources satisfy the criterion of being highly optically obscured (see Table 2).

In summary, very few massive stars have the color, luminosity, and variability of the SN 2008S and NGC 300 progenitors. Our best guess is that the number of true analogs may be as few as zero and as large as ~ 10 – 20 . We denote this number in M33—the number of *true* analogs—as N_{EAGB} . A larger sample of stars, culled from a larger multi-epoch study of local star-forming galaxies (see Section 5.3), is clearly needed to fill in the parameter space in the extreme red and bright side of the CMD. This is the most robust way to understand N_{EAGB} and its uncertainty.

In order to evaluate the *fraction* of stars in M33 that might be analogs to the progenitors of SN 2008S and NGC 300, and so constrain the rate of production of such objects, we must first estimate the total number of massive stars in M33 (N_{\star} ; i.e., with

$M_{\text{ZAMS}} \gtrsim 8 M_{\odot}$). This number can be estimated in several ways: (1) extinction-corrected $H\alpha$ luminosity (e.g., Hoopes et al. 2001; Hoopes & Walterbos 2000), (2) dust-reddening-corrected UV continuum luminosity (for *GALEX* observations, see Thilker et al. 2005), (3) total number of main-sequence optical point sources detected with $M_V \lesssim -2$ (appropriate for stars with ZAMS masses above ≈ 9 – $10 M_{\odot}$; Lejeune & Schaerer 2001), or (4) total number of red supergiants (RSGs; $M_V \lesssim -3.5$; M06) times the ratio of the lifetime of a massive star to the time spent as an RSG ($t_{\star}/t_{\text{RSG}} \approx 10$; e.g., Schaller et al. 1992). Using the latter method and selecting RSGs with $V - R > 0.5$ and $M_V < -3.5$ from the catalog of M06, we find ≈ 5400 sources, implying $N_{\star} \approx 5.4 \times 10^4$. Taking a more conservative color cut of $V - R > 0.7$ and $M_V < -3.5$, we find that $N_{\star} \approx 3.5 \times 10^4$. Similar estimates in the range of $N_{\star} \approx (3$ – $6) \times 10^4$ are obtained using method (3) with the M06 catalog, although this estimate suffers significantly from incompleteness. We take $N_{\star} = 5 \times 10^4$ as a fiducial number and include it in our scalings below. Note that estimates of the total star formation rate in M33 range from ~ 0.3 to $\sim 0.7 M_{\odot} \text{ yr}^{-1}$, consistent with the UV, $H\alpha$, and FIR luminosities (e.g., Gardan et al. 2007 and references therein), implying a supernova rate for the galaxy of $\sim 0.005 \text{ yr}^{-1}$ (e.g., Gordon et al. 1998).

Taking $N_{\text{EAGB}} \sim 5$ and $N_{\star} \approx 5 \times 10^4$, we find that a fraction

$$f_{\text{EAGB}} = \frac{N_{\text{EAGB}}}{N_{\star}} \sim 1 \times 10^{-4} \left[\frac{N_{\text{EAGB}}}{5} \right] \left[\frac{5 \times 10^4}{N_{\star}} \right] \quad (1)$$

of the massive stars in M33 may be analogs of the progenitors of SN 2008S and NGC 300.

As noted in Sections 1 (point 2) and 3, only a fraction of all massive stars go through this highly dust-enshrouded phase and produce transients like SN 2008S and NGC 300. Since, by assumption, roughly all of the massive stars in any galaxy become normal ccSNe (but, see Kochanek et al. 2008), the rate of SN 2008S-like explosions can be characterized by their fractional rate with respect to the overall supernova rate. This fraction is determined by dividing the observed rate of SN 2008S-like transients by the total number of supernovae within some volume, times an incompleteness correction that accounts for the fact that SN 2008S-like transients are intrinsically less optically luminous. Based on the numbers presented in Section 3, we estimate that $f_{\text{SN}} \approx 0.2$, although higher and lower values are not excluded. For example, it is possible that SN 2008S-like transients are intrinsically rare, and the fact that NGC 300 and SN 2008S occurred in the same year was simply a chance. Although we cannot exclude this possibility, we note that such an explanation appears improbable in the face of what is known about the rarity of their progenitors (f_{EAGB} ; Equation (1)). Conversely, it is possible that the incompleteness correction exceeds the factor of ~ 2 advocated in Section 3 within 10 Mpc and that such transients are indeed common with respect to supernovae. However, it then becomes increasingly difficult to explain why no more SN 2008S-like transients were observed within 10 Mpc in the last 10 years. There is no way to circumvent these uncertainties without a more complete census of progenitors and outbursts.

As stated in Section 1, the simplest explanation for the fact that SN 2008S- and NGC 300-like transients are simultaneously common with respect to supernovae ($f_{\text{SN}} \sim 0.2$) and that their progenitors are very rare by a number at any moment, in any star-forming galaxy ($f_{\text{EAGB}} \sim 10^{-4}$) with respect to massive stars, is that a significant fraction of all massive stars (~ 0.2) go

Table 3
Photometry for the 16 LBV Candidates in M33 from M07

| Identifier (From M07) | <i>U</i> (mag) | <i>B</i> (mag) | <i>V</i> (mag) | <i>R</i> (mag) | <i>I</i> (mag) | [3.6] (mag) | [4.5] (mag) | [5.8] (mag) | [8.0] (mag) |
|--------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|----------------|----------------|------------------|------------------|
| J013248.26+303950.4 | 16.13 | 17.32 | 17.25 | 17.01 | 16.89 | 15.70 | 15.36 | 15.02 | 14.57 |
| J013324.62+302328.4 | 18.66 | 19.49 | 19.58 | 19.27 | 19.53 | 14.26 | 13.55 | 13.04 | 12.27 |
| J013333.22+303343.4 | 18.30 | 19.30 | 19.40 | 18.44 | 18.89 | 13.09 | 12.50 | 12.20 | 11.65 |
| J013335.14+303600.4 | 15.54 | 16.53 | 16.43 | 16.30 | 16.14 | 14.45 | 14.35 | 14.48 | 14.15 |
| J013341.28+302237.2 | 15.18 | 16.24 | 16.29 | 16.28 | 16.32 | 15.08 | 14.96 | 15.07 | 14.45 |
| J013350.12+304126.6 | 15.76 | 16.85 | 16.82 | 16.43 | 16.30 | 12.22 | 11.65 | 11.06 | 10.64 |
| J013406.63+304147.8 | 15.12 | 16.26 | 16.08 | 15.86 | 15.76 | 14.41 | 13.95 | 13.83 | ... ^a |
| J013410.93+303437.6 | 15.13 | 16.13 | 16.03 | 15.87 | 15.70 | 14.84 | 14.65 | 14.69 | 13.97 |
| J013416.10+303344.9 | 16.32 | 17.17 | 17.12 | 16.96 | 16.85 | 15.69 | 15.48 | 15.01 | ... ^a |
| J013422.91+304411.0 | 16.36 | 17.28 | 17.21 | 17.14 | 17.07 | 16.24 | 16.35 | ... ^a | ... ^a |
| J013424.78+303306.6 | 16.21 | 16.97 | 16.84 | 16.72 | 16.54 | 15.24 | 15.00 | 14.74 | 13.97 |
| J013426.11+303424.7 | 18.38 | 19.23 | 18.97 | 18.59 | 18.27 | 14.57 | 13.79 | 13.09 | 12.24 |
| J013429.64+303732.1 | 16.24 | 17.12 | 17.11 | 17.05 | 16.93 | 16.55 | 16.64 | ... ^a | ... ^a |
| J013442.14+303216.0 | 18.35 | 18.20 | 17.34 | 16.89 | 16.44 | 13.56 | 13.02 | 12.39 | 11.62 |
| J013459.47+303701.9 | 17.35 | 18.59 | 18.37 | 17.88 | 17.69 | 14.42 | 13.73 | 13.16 | 12.31 |
| J013500.30+304150.9 | 18.37 | 19.22 | 19.30 | 18.60 | 19.11 | 13.93 | 13.24 | 12.54 | 11.93 |

Notes. ^a Non-detection.

through a brief evolutionary epoch in which they are highly dust-obscured, just before explosion. Taking the average lifetime of massive stars with ZAMS masses in the range of 9–10 M_{\odot} to be $t_{\star} \approx 3 \times 10^7$ yr (e.g., Schaller et al. 1992), we find that the duration of this dust-obscured phase is

$$t_{\text{EAGB}} \sim 1 \times 10^4 \left[\frac{t_{\star}}{10^{7.5} \text{ yr}} \right] \left[\frac{N_{\text{EAGB}}}{5} \right] \left[\frac{5 \times 10^4}{N_{\star}} \right] \left[\frac{0.20}{f_{\text{SN}}} \right] \text{ yr.} \quad (2)$$

We consider the uncertainty in f_{SN} to be at the factor of 2 level, but we emphasize that even if f_{SN} were a factor of 10 smaller than our nominal value of 0.2 (see Section 3), our qualitative conclusion would be unchanged: the dust-enshrouded phase is a short-lived phenomenon in the lives of many massive stars just before a SN 2008S-like explosion. In addition, as we have stressed, N_{EAGB} may be as much as a factor of 5 or more lower ($t_{\text{EAGB}} \lesssim 10^3$ yr), or a factor of ~ 2 –4 higher ($t_{\text{EAGB}} \sim 6 \times 10^4$ yr) than our fiducial value.¹⁷ To improve these numbers significantly, a careful monitoring program for optical transients like SN 2008S within the local universe ($D \lesssim 10$ Mpc), coupled with a survey of all local galaxies for bright MIR point sources with (warm) *Spitzer* (see Section 5.3) should be undertaken. The combination of watching for more transients of this type and associating them with individual progenitors whose luminosities and variability have been cataloged will significantly decrease the uncertainty in both f_{SN} and N_{EAGB} , and significantly increase our understanding of the causal mapping between progenitors and their outbursts.

5.2. Connection to The Evolution of Massive Stars

The relation between final luminosity and initial stellar mass may be triply valued (Smartt et al. 2009) at ~ 5 –7, ~ 8 –9, and ~ 11 –14 M_{\odot} for $L \approx (5$ – $10) \times 10^4 L_{\odot}$. This relation is of course uncertain, particularly in the mass range singled out by the bolometric luminosity of the 2008S and NGC 300 progenitors near $\sim 10 M_{\odot}$. It is likely further complicated by binarity, and by the mass-loss history, metallicity, and rotation of massive stars. Because the absolute rate of these outbursts as well as whether

or not they should be associated with the death of the progenitor is still uncertain, we consider a number of potential scenarios below. We list a subset of the possibilities in order of increasing progenitor mass.

5.2.1. Massive White Dwarf Birth: $M \approx 6$ –8 M_{\odot}

We have referred to the progenitors of SN 2008S and NGC 300 throughout this work as extreme (“E”) AGB stars because they lie at the red extremum of the AGB sequence in the MIR CMD (Figures 1 and 2). Taken literally, these stars may indeed be the progenitors of the most massive O–Ne–Mg white dwarfs, undergoing explosive core–envelope separation as they transition to protoplanetary nebulae (e.g., Riera et al. 1995; García-Hernández et al. 2007). Perhaps the 2008S and NGC 300 progenitors were then akin to the most massive highly evolved carbon- or oxygen-rich AGB stars (Kwok 1993).

Based on analogy with local protoplanetary nebulae, we would expect bipolar explosion morphology and eventually the emergence of a hot ionizing continuum source as the newly born white dwarf begins its cooling phase (perhaps similar to Hen 3-1475/*IRAS* 17423-1755; Riera et al. 2003). The initial luminosity of the central source would be of order $\sim 5 \times 10^4 L_{\odot}$ for a white dwarf near the Chandrasekhar mass, and it should cool on a timescale comparable to $\sim 10^5$ yr. Thus, the bolometric luminosity of the transient should eventually decrease back to approximately pre-outburst levels. The primary distinguishing characteristic of this particular scenario is the (eventual) emergent hot continuum source and emission lines, bi-polar morphology, and the fact that the bolometric luminosity should not decrease to pre-outburst levels in the next decades (e.g., Kwok 1993).

5.2.2. Electron-capture Supernova: $M \approx 9 M_{\odot}$

The timescale estimated in Equation (2) is of the right order of magnitude to be associated with the onset of carbon burning in relatively low-mass massive stars. This is traditionally a very difficult phase to model (see the summary in Woosley et al. 2002; Siess 2006; Poelarends et al. 2008).

One of the most intriguing explanations for the physics of SN 2008S-like transients is that they result from ecSNe of O–Ne–Mg cores of relatively low-mass massive stars (Miyaji

¹⁷ In comparison with the uncertainty in f_{SN} and N_{EAGB} , we consider the uncertainty in N_{\star} to be at the level of a factor of 1.5.

et al. 1980). While speculative, this explanation accounts for many of the observed characteristics of both the transients and their progenitors. In particular, it accounts for the fact that the progenitors of NGC 300 and SN 2008S were relatively low luminosity and deeply embedded. Here we follow the scenario detailed by Poelarends et al. (2008) (see also Nomoto 1984, 1987; Ritossa et al. 1996, Siess 2006, 2007; as well as Chugai 1997; Wheeler et al. 1998; Woosley et al. 2002; Eldridge et al. 2007; Wanajo et al. 2009).

We know from the properties of the observed progenitors and our analysis of the luminous stars in M33 that the progenitors are extreme AGB stars. In these systems, the combination of thermal pulses due to He shell burning and dredge-up produces a massive, dusty wind (for lower luminosity and less enshrouded analogs, see the work on carbon stars in the Magellanic clouds by Groenewegen et al. 2007, as well as van Loon et al. 2005, 2006). In the Poelarends et al. (2008) models, the mass loss peaks at nearly $10^{-4} M_{\odot} \text{ yr}^{-1}$ for stars of mass $M \simeq 9 M_{\odot}$ and luminosity $L \simeq 10^5 L_{\odot}$, and then drops precipitously for slightly more massive stars which can support core Neon burning, and which eventually become normal iron-core ccSNe (see Figure 13 from Poelarends et al. 2008). The thermal pulses driving the mass loss occur at very high rates for the EAGB stars (on timescales of years), suggesting that mass loss may appear as a steady wind, as seems to be required for the small variability in the light curves of the SN 2008S and NGC 300 progenitors (see Figure 7; discussion in P08b), rather than as impulsive ejections of optically thick shells expected for normal carbon stars. The low degree of variability seen in SN 2008S (particularly when contrasted with the EAGB stars in Figure 7) might also be explained by the onset of *core* carbon burning as the final phases of stellar evolution commence. Note that the work of Nomoto (1984) and (1987) implies that the EAGB envelope and mass-loss would be carbon-enhanced.

For a narrow mass range near $9 M_{\odot}$, the balance between mass loss and the growth of the core allows the core to become unstable to collapse without igniting core Neon burning, leading to an ecSNe. This occurs only for a small model-dependent mass range near $9 M_{\odot}$ (see also, e.g., Nomoto 1984; Siess 2006, 2007). Poelarends et al. (2008) estimated a mass range of $M_{\min} \simeq 9 M_{\odot}$ to $M_{\max} \simeq 9.25 M_{\odot}$. For a standard Salpeter IMF, and assuming that all stars from M_{\max} to $20 M_{\odot}$ form ccSNe, the ecSN fraction is just $\approx 6\%$ ($9.0 M_{\odot} \leq M \leq 9.25 M_{\odot}$). This is below our (albeit, uncertain) fiducial estimate for the rate of SN 2008S-like transients relative to the normal ccSN rate, $f_{\text{SN}} \sim 0.2$. However, other studies have found somewhat broader mass ranges for ecSNe. For example, Siess (2007) find that $M_{\max} - M_{\min} \approx 1-1.5 M_{\odot}$, which implies a fractional rate for ecSNe more in accord with our nominal estimate for f_{SN} .

While the observed rate of SN 2008S-like transients is uncertain, we have argued that they represent a modest fraction of the normal ccSN rate, consistent with a limited progenitor mass range. The relatively low luminosity of their progenitors implies that they are low-mass massive stars, potentially near the boundary between electron-capture and normal ccSNe. In addition, Kitaura et al. (2006) argue that ecSNe should be subluminous compared to normal ccSNe, because of their low Ni yields, potentially explaining the low luminosity of SN 2008S-like transients. Finally, for the fiducial ecSN model of Poelarends et al. (2008, see also Nomoto 1984), the AGB phase lasts for $\approx 4 \times 10^4$ yr, which, although short with respect to the lifetime of the star itself, is of order t_{EAGB} in Equation (2) based on the number of analogs to the SN 2008S and NGC 300 progenitors in M33. Of course, these timescales need not be

identical, since the fiducial ecSN progenitors of Poelarends et al. may evolve significantly in color as a result of mass-loss during their super-("extreme") AGB phase, becoming increasingly like the SN 2008S and NGC 300 progenitors as they approach the end of their lives.

Fortunately, this speculative explanation has at least one simple and testable prediction: there should be no surviving progenitor once the transient fades. This may be testable in the optical, since most of the dust enshrouding the progenitor was likely destroyed by the explosion, but observations in the MIR will be required to be certain that a new shroud has not formed. A second test is to find strong evidence in the late-time light curve for synthesized ^{56}Ni . This may be difficult that both because ecSN may produce little ^{56}Ni (Kitaura et al. 2006), and because dust, whether that remaining from the EAGB phase or dust formed in the ejecta (e.g., P08c for M85), may make it difficult to correctly measure the late-time decay rate. *Spitzer* may again be key in constraining the nature of these events because of this obscuration. A third test is to ensure that *Spitzer* has surveyed all the nearby galaxies, so that future examples of these transients can be causally connected to their deeply obscured progenitors. Finally, as with ccSNe, very nearby ecSNe ($D \lesssim 300$ kpc) should produce neutrino signatures characteristic of neutron star formation, which detectors such as SuperKamiokande and its successors would observe (see, e.g., Thompson et al. 2003; Kistler et al. 2008).

The recent paper by Botticella et al. (2009) in part corroborates the interpretation discussed in Prieto et al. (2008a) and proposed here that SN 2008S may be an electron-capture supernova. They present the late-time quasi-bolometric light curve of SN 2008S, which shows evidence for a power-law time dependence with a slope indicative of being powered by the radioactive decay ^{56}Co . Although this need not uniquely signal ecSN as the physical mechanism (see Section 5.2.3), it provides some evidence for core collapse, and something perhaps akin to normal neutron star formation (Kitaura et al. 2006). A light curve with similar cadence and photometric coverage has recently been published in Bond et al. (2009) for NGC 300.

5.2.3. Intrinsically Low-luminosity Iron Core-collapse Supernova: $M \sim 10-12 M_{\odot}$

Heger et al. (1997) discuss a mechanism for generating a potentially obscuring "superwind" via pulsational mass loss in red supergiants between 10 and $20 M_{\odot}$ during the last 10^4 yr before explosion. The prediction of enhanced AGB-like obscuration (they compare directly with luminous OH/IR stars), the evolutionary timescale (compare their 10^4 yr with our Equation (2)), and the secular *increase* in the fundamental mode pulsation period as the star approaches death (see their Figure 7) are all in good agreement with the requirements on the 2008S and NGC 300 progenitors we discuss in this paper.

The physical mechanism of iron ccSNe is unknown (Rampp & Janka 2000; Liebendörfer et al. 2001; Thompson et al. 2003; Buras et al. 2003; Burrows et al. 2006). Recent observations hint that low-luminosity Type IIP supernovae may be more common than previously thought (e.g., Chugai & Utrobin 2000; Pastorello et al. 2004, 2007), particularly when one accounts for the incompleteness corrections discussed in Section 3. Because the mechanism of supernovae has yet to be conclusively identified, it is difficult to interpret the diversity in inferred ^{56}Ni yield physically. In fact, this diversity may be larger than previously thought, and we are only now appreciating the existence of a very low-luminosity tail to the Type IIP luminosity

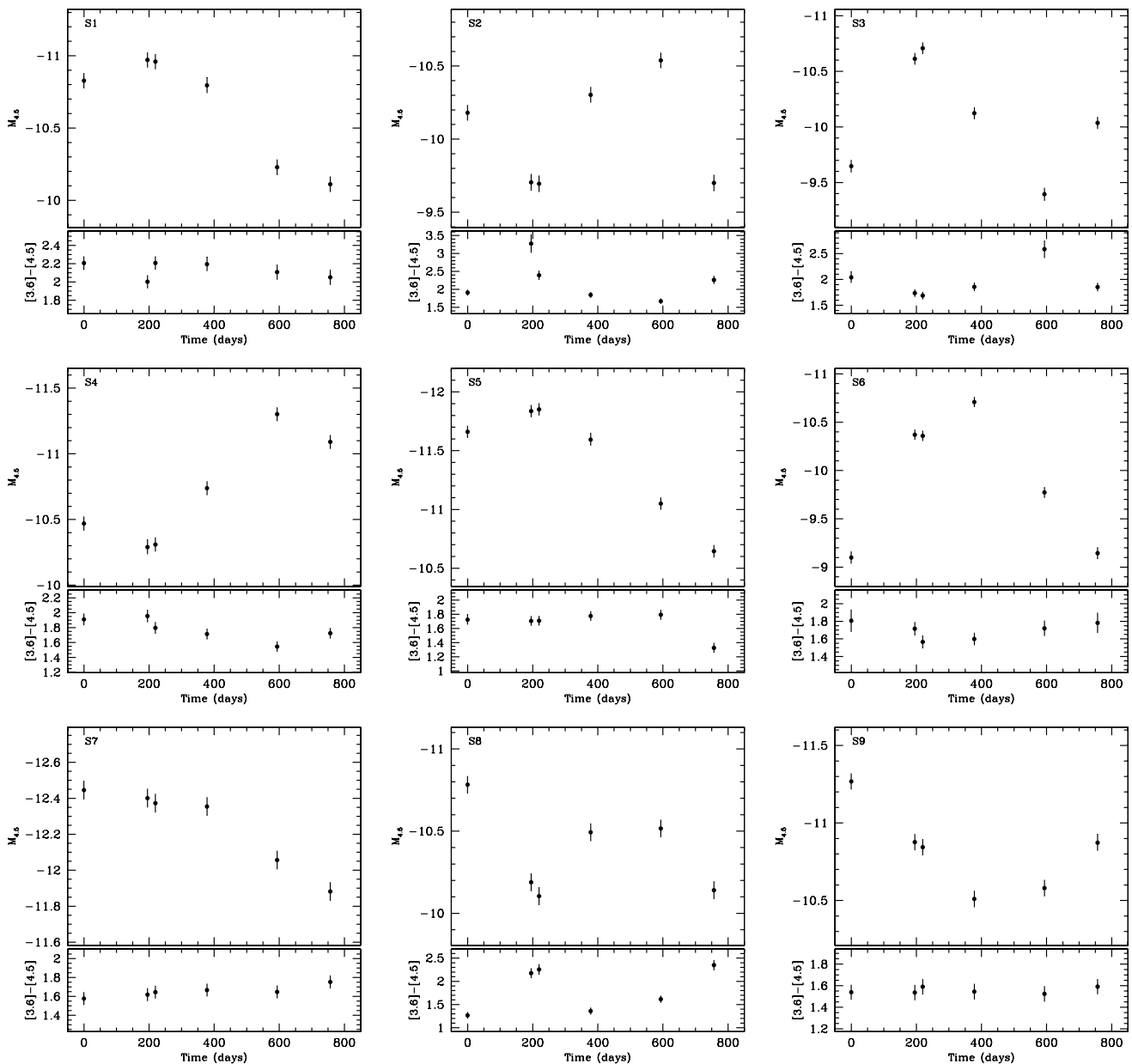


Figure A1. Light curves for sources S1–S9 of the 18 reddest sources (sorted by color) with $M_{4.5} < -10$ and $[3.6] - [4.5] > 1.5$ in the M33 MIR CMD (open circles in Figure 2; remaining source light curves are shown in Figure A2). For each source, the top and bottom panels show the absolute $4.5 \mu\text{m}$ magnitude and the $[3.6] - [4.5]$ color variation, respectively, as a function of time. More than a magnitude variation on a timescale of 100–1000 days is common. Local minima in $4.5 \mu\text{m}$ luminosity generally correspond to local maxima in color, although there are deviations from this trend. Colors can vary by more than a magnitude, with the largest excursions reaching $[3.6] - [4.5] \approx 2.5$. In just one source (S2), and in at just one epoch, we find a $[3.6] - [4.5]$ color as large as the progenitor of NGC 300 (≈ 2.7 ; Figures 1 and 2).

function. If so, it is natural to imagine that these low-luminosity core-collapse events might have analogs that occur in the very dusty circumstellar medium of their massive stellar progenitors, as in Heger et al. (1997), and thus may give rise to events like SN 2008S and NGC 300.

This scenario yields many of the predictions of the ecSN scenario discussed in Section 5.2.2. Indeed, even with a complete sampling of “ec-” and “cc-” supernovae, it may be difficult to disentangle the two populations since many of the predictions—radioactive decay powered lightcurves, potentially embedded progenitor, no “postgenitor”—are the same in both.

5.2.4. Massive Star Outburst: $M \approx 10\text{--}15 M_{\odot}$

On the basis of the relatively low luminosity of their progenitors, we view the ecSN and massive white dwarf birth scenarios

discussed above as the most probable explanation SN 2008S and NGC 300. Nevertheless, there is of course the possibility that they are instead a new class of outbursts from relatively low-mass massive stars, potentially analogous to the pulsational instabilities discussed in Poelarends et al. (2008) or Heger et al. (1997). The majority of the true “LBV” eruptions with documented progenitors (e.g., 1997bs, 2002kg) came from optically bright massive stars significantly more bolometrically luminous than the progenitors of SN 2008S and NGC 300. As we have shown in Figures 2 and 5, the EAGB population is separate from the sources traditionally classified as LBVs: they are less bolometrically luminous and much more dust-obscured. These facts suggest that if these transients were the outbursts of massive stars then they are distinct from the classical supernova impostors. If these events are not supernovae, but merely outbursts, then their existence is likely connected to the physics

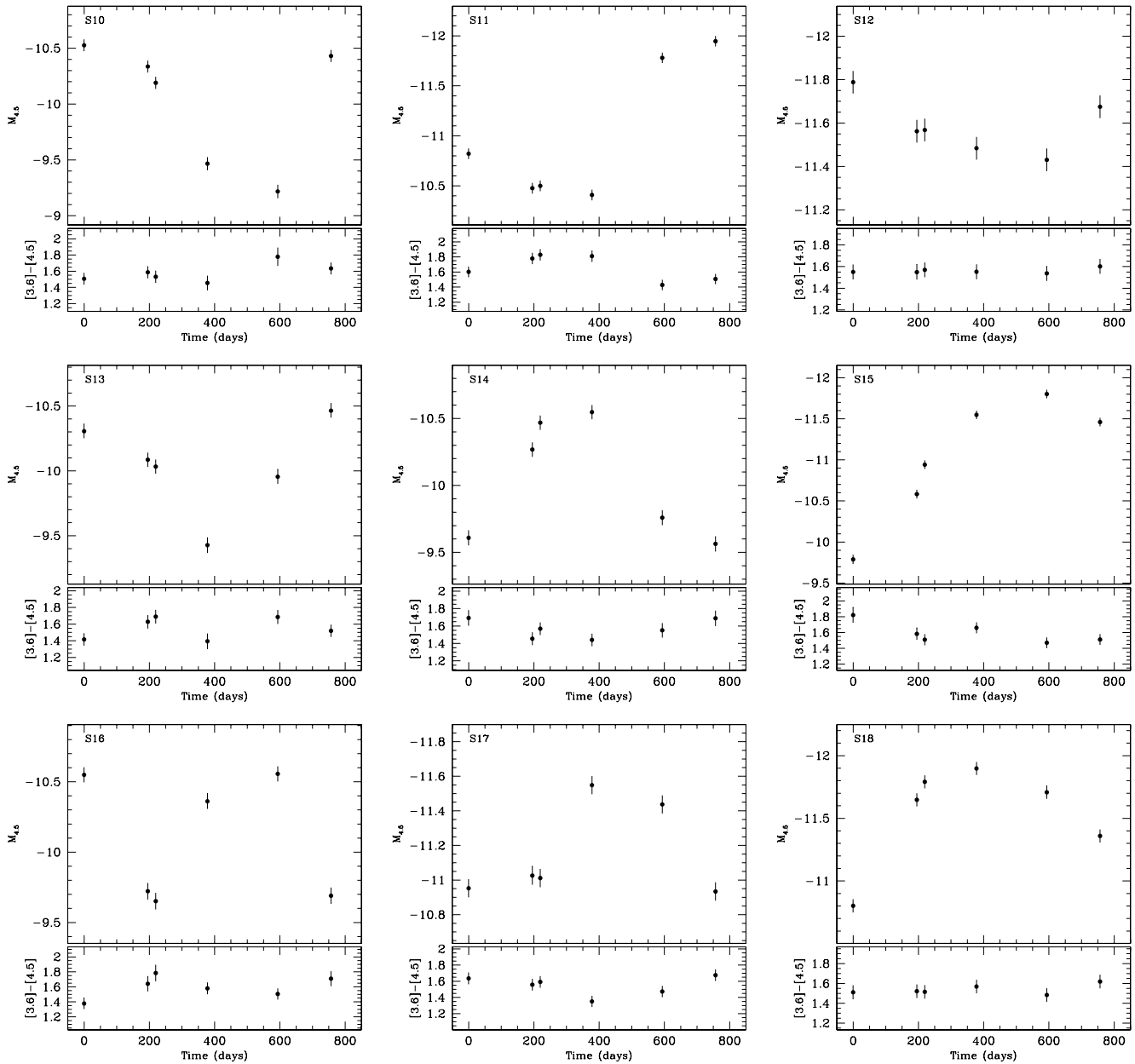


Figure A2. Same as Figure A1, but for sources S10–S18 of the 18 reddest sources with $M_{4.5} < -10$ in the M33 MIR CMD (see Figures 2 and 5).

of the transition between stars that become ecSNe and/or cc-SNe, and those that do not. The degree of dust obscuration at outburst is a crucial clue to their evolution. A simple prediction of this possibility is that the progenitors of SN 2008S and NGC 300 should eventually be rediscovered in the optical and/or infrared after the outburst emission has faded. For further arguments on the nature of SN 2008S and NGC 300 related to this discussion, see Bond et al. (2008), Smith et al. (2009), and Berger et al. (2009).

5.3. A More Complete Census

Equation (1) implies that a fraction $\sim 1 \times 10^{-4}$ of the massive star population in any given galaxy appears to be in the evolutionary state that led to the explosions observed as SN 2008S and NGC 300. The simplest explanation, adopted throughout this work, is that the deeply dust-enshrouded phase marks the last $t_{\text{EAGB}} \lesssim 10^4$ yr (Equation (2)) in the life of a fraction $f_{\text{SN}} \approx 0.2$ of the massive star population.

Compilations of star formation and supernova rates in the local universe (e.g., Ando et al. 2005) suggest that the latter is $\approx 2 \text{ yr}^{-1}$ within 10 Mpc (see Section 1, point 2), implying that there are $\sim 5 \times 10^6$ massive stars and $\lesssim 10^3$ EAGB stars within this volume. If the lifetime in the pre-explosion, highly dust-obscured phase is t_{EAGB} (Equation (2)), we would expect to see one SN 2008S-like transient every few years, in accord with our estimate for f_{SN} .

A multi-epoch survey of all the local star-forming galaxies within 10 Mpc with *Spitzer* would allow for a comprehensive census of EAGB stars. It would significantly increase our knowledge of the variability properties and SED evolution of these objects, and it might allow us to define more strict criteria for inclusion in the class of SN 2008S/NGC 300-like progenitors. It would therefore decrease the considerable uncertainty in N_{EAGB} in Equations (1) and (2). Coupled with the supernova surveys in the local volume, such a study would improve our knowledge of the fraction f_{SN} of stars that eventually

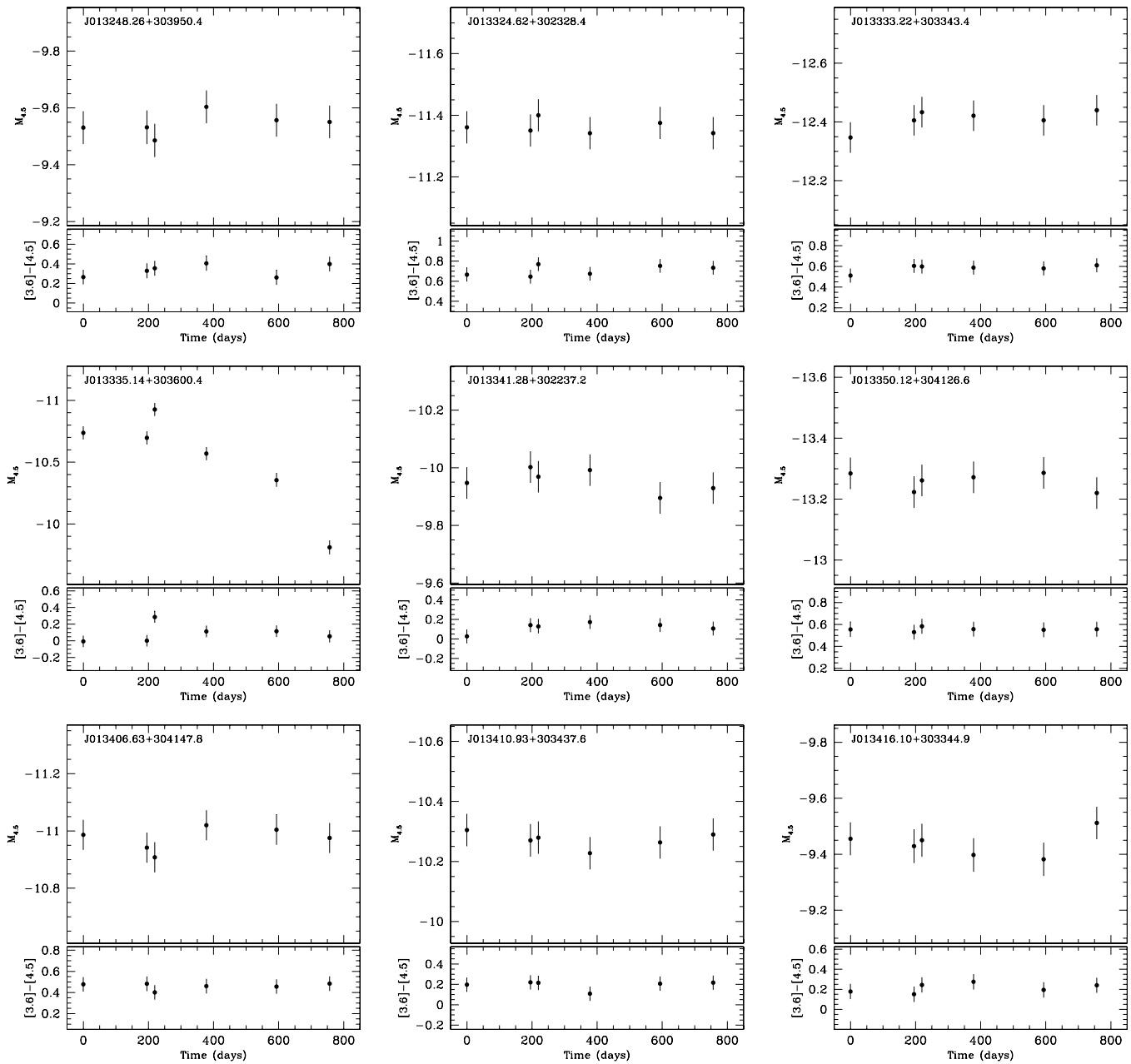


Figure A3. Light curves at $4.5 \mu\text{m}$ for nine of the 16 LBV candidates of M07. Although there are several exceptions (notably J013335.14+303600.4 above and J013429.64+303732.1 in Figure A4), the LBV candidates do not vary significantly in absolute magnitude or color (see also Figure 7). As shown in Figure 2 (open triangles), the LBV candidates with high luminosities at $4.5 \mu\text{m}$ are characteristically more red than those with larger $M_{4.5}$.

go through the deeply embedded phase just before explosion. Of course, the most intriguing possibility is that the number of true analogs to the progenitors of SN 2008S and NGC 300 is in fact $N_{\text{EAGB}} \sim 0\text{--}1$ in M33 and that $t_{\text{EAGB}} \lesssim \text{few} \times 10^3 \text{ yr}$.¹⁸ If so, the final catalog of EAGB stars that would be produced by a *Spitzer* survey would have just $\sim 50\text{--}100$ members. These could be followed up repeatedly, since, given these numbers one would expect to wait just ~ 10 yr before one of these individual sources exploded. This would give a direct observational link in the causal mapping between a subpopulation of massive stellar progenitors and their explosions, connecting them with a short timescale. Indeed, the ability to identify an individual

star as marked for imminent death (or eruption) would be an astonishing consequence of this work.

We thank B. Monard, H. Yüksel, A. Gal-Yam, N. Smith, R. Humphreys, J. J. Eldridge, K. Sellgren, and A. Gould for helpful conversations, and the anonymous referee, whose comments materially improved the manuscript. We extend our gratitude to the SINGS Legacy Survey for making their data publicly available. This work is based in part on archival data obtained with the *Spitzer Space Telescope*, which is operated by the JPL, Caltech under a contract with NASA. This research has made use of NED, which is operated by the JPL and Caltech, under contract with NASA and the HEASARC Online Service, provided by NASA's GSFC. T.A.T. gratefully acknowledges the Aspen Center for Physics where a portion of this work

¹⁸ The lower limit here comes from the fact that pre-explosion imaging of the SN 2008S and NGC 300 progenitors establishes a few year baseline.

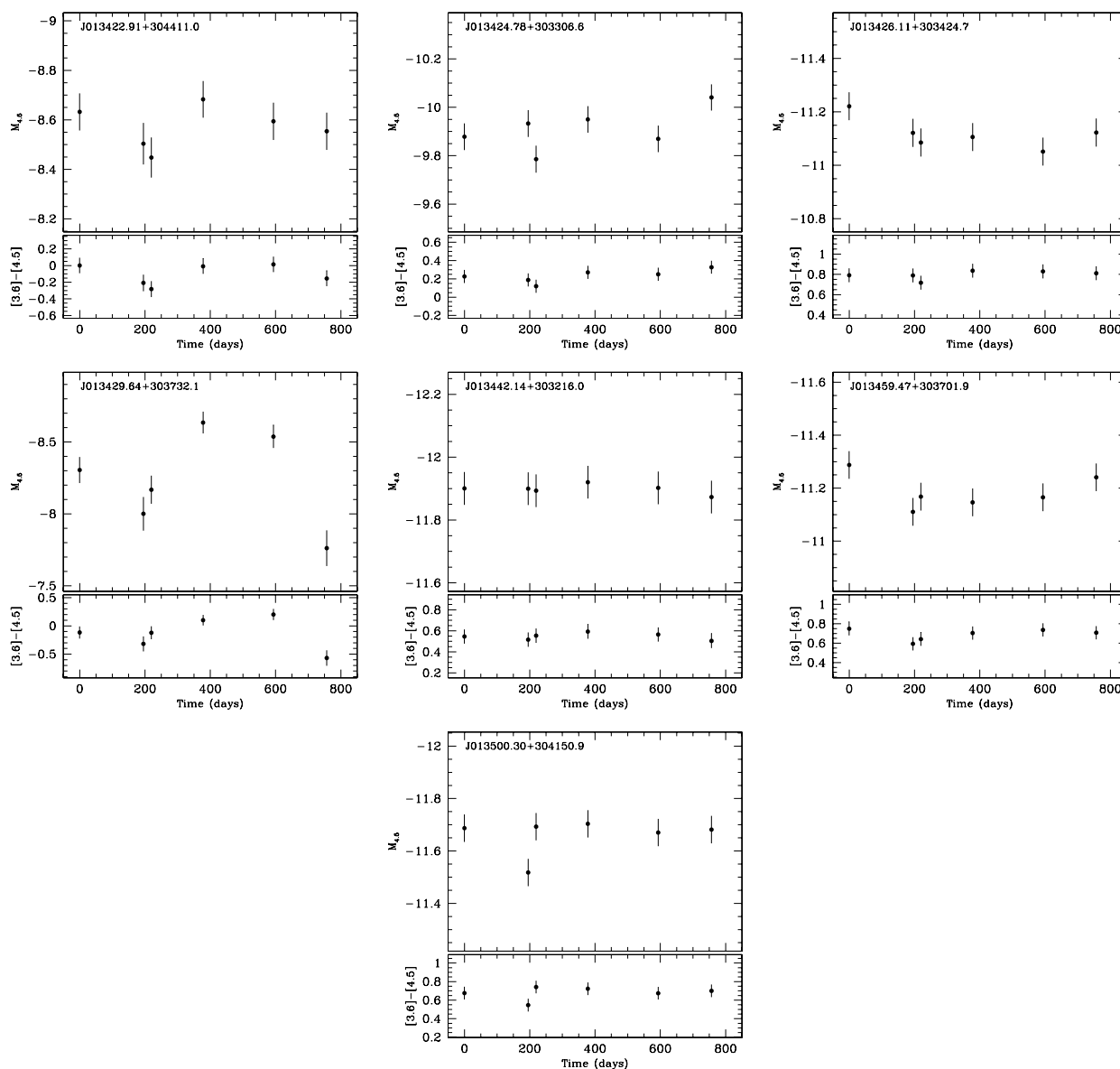


Figure A4. Same as Figure A3, but for the remaining seven LBV candidates of M07, matched to our 4.5 μm catalog.

was completed and an Alfred P. Sloan Fellowship for financial support. J.L.P. and K.Z.S. are supported by NSF grant AST-0707982. M.D.K. and J.F.B. are supported by NSF CAREER grant PHY-0547102. This research is supported in part by NSF grant AST-0908816.

APPENDIX A

EXTREME-AGB STAR VARIABILITY

Section 4.4 presents a discussion of the variability of the 18 reddest sources selected as EAGB stars (see Table 2 for their photometry). In this appendix (in Figures A1 and A2), we present the light curves for all 18 sources. See the large open circles in Figures 2, 4, and 7, as well as the left panel of Figure 5 for a summary of their colors, SEDs, and RMS variability.

APPENDIX B

LBV CANDIDATE VARIABILITY

Like Appendix A, here we present the light curves for the 16 LBV candidates from M07 that have been matched to the

MIR point source catalog (Figures A3 and A4), as described in Section 4. Table 3 lists photometry for these sources. See Figures 2, 4, 5, and 7 for a summary of their colors, SEDs, and RMS variability properties.

REFERENCES

- Alard, C. 2000, *A&A*, 144, 363
 Alard, C., & Lupton, R. H. 1998, *ApJ*, 503, 325
 Anderson, J. P., & James, P. A. 2008, *MNRAS*, 390, 1527
 Ando, S., Beacom, J. F., & Yüksel, H. 2005, *Phys. Rev. Lett.*, 95, 171101
 Arbour, R., & Boles, T. 2008, *CBET*, 1234
 Berger, E., & Soderberg, A. 2008, *Astron. Tel.*, 1544, 1
 Berger, E., et al. 2009, *ApJ*, 699, 1850
 Bertin, E., & Arnouts, S. 1996, *A&A*, 117, 393
 Blum, R. D., et al. 2006, *AJ*, 132, 2034
 Bolatto, A. D., et al. 2007, *ApJ*, 655, 212
 Bonanos, A. Z., et al. 2006, *ApJ*, 652, 313
 Bond, H. E., Bedin, L. R., Bonanos, A. Z., Humphreys, R. M., Monard, L. A. G. B., Prieto, J. L., & Walter, F. M. 2009, *ApJ*, 695, L154
 Bond, H. E., Walter, F. M., & Velasquez, J. 2008, *IAU Circ.*, 8946, 2
 Bond, H. E., et al. 2003, *Nature*, 422, 405
 Botticella, M. T., et al. 2009, *MNRAS*, 398, 1041

- Buras, R., Rampp, M., Janka, H.-T., & Kifonidis, K. 2003, *Phys. Rev. Lett.*, **90**, 241101
- Burrows, A., Livne, E., Dessart, L., Ott, C. D., & Murphy, J. 2006, *ApJ*, **640**, 878
- Chugai, N. N. 1997, *Astron. Rep.*, **41**, 672
- Chugai, N. N., & Utrobin, V. P. 2000, *A&A*, **354**, 557
- Cohen, M., et al. 2003, *AJ*, **125**, 2645
- Dahlen, T., Strolger, L.-G., & Riess, A. G. 2008, *ApJ*, **681**, 462
- de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G. Jr., Buta, R. J., Paturel, G., & Fouque, P. 1991, *Third Reference Catalogue of Bright Galaxies*, Vol. 1–3 (Berlin: Springer)
- Dilday, B., et al. 2008, *ApJ*, **682**, 262
- Duszanowicz, G., Boles, T., & Corelli, P. 2007, *Cent. Bur. Electron. Teleg.*, **1182**, 1
- Eldridge, J. J., et al. 2007, *MNRAS*, **376**, 52
- Elias-Rosa, N., Benetti, S., Cappellaro, E., Dolci, M., Pastorello, A., Boschin, W., & Pinilla Alonso, N. 2005, *IAU Circ.*, **8498**, 1
- Fazio, G. G., et al. 2004, *ApJS*, **154**, 10
- Filippenko, A. V. 1997, *ARA&A*, **35**, 309
- Filippenko, A. V., et al. 1999, *IAU Circ.*, **7152**, 2
- Freedman, W. L., et al. 2001, *ApJ*, **553**, 47
- Gal-Yam, A., et al. 2007, *ApJ*, **656**, 372
- García-Hernández, D. A., Perea-Calderón, J. V., Bobrowsky, M., & García-Lario, P. 2007, *ApJ*, **666**, L33
- Gardan, E., Braine, J., Schuster, K. F., Brouillet, N., & Sievers, A. 2007, *A&A*, **473**, 91
- Garnavich, P., et al. 1999, *IAU Circ.*, **7150**, 1
- Gieren, W., et al. 2005, *ApJ*, **628**, 695
- Gordon, S. M., Kirshner, R. P., Long, K. S., Blair, W. P., Duric, N., & Smith, R. C. 1998, *ApJS*, **117**, 89
- Groenewegen, M. A. T., et al. 2007, *MNRAS*, **376**, 313
- Hartman, J. D., Bakos, G., Stanek, K. Z., & Noyes, R. W. 2004, *AJ*, **128**, 1761
- Hartman, J. D., Bersier, D., Stanek, K. Z., Beaulieu, J.-P., Kaluzny, J., Marquette, J.-B., Stetson, P. B., & Schwarzenberg-Czerny, A. 2006, *MNRAS*, **371**, 1405
- Harutyunyan, A., Navasardyan, H., Benetti, S., Turatto, M., Pastorello, A., & Taubenberger, S. 2007, *Cent. Bur. Electron. Teleg.*, **1184**, 1
- Hatano, K., Fisher, A., & Branch, D. 1997, *MNRAS*, **290**, 360
- Heger, A., Jeannin, L., Langer, N., & Baraffe, I. 1997, *A&A*, **327**, 224
- Hoopes, C. G., & Walterbos, R. A. M. 2000, *ApJ*, **541**, 597
- Hoopes, C. G., Walterbos, R. A. M., & Bothun, G. D. 2001, *ApJ*, **559**, 878
- Horiuchi, S., Beacom, J. F., & Dwek, E. 2009, *Phys. Rev. D*, **79**, 083013
- Hornoch, K. 2002, *IAU Circ.*, **7923**, 5
- Humphreys, R. M. 2005, in *ASP Conf. Ser. 332, The Fate of the Most Massive Stars*, ed. R. Humphreys & K. Stanek (San Francisco, CA: ASP), **90**
- Humphreys, R. M., et al. 2006, *AJ*, **131**, 2105
- James, P. A., & Anderson, J. P. 2006, *A&A*, **453**, 57
- Karachentsev, I. D., Karachentseva, V. E., Huchtmeier, W. K., & Makarov, D. I. 2004, *AJ*, **127**, 2031
- Kelly, P. L., Kirshner, R. P., & Pahre, M. 2008, *ApJ*, **687**, 1201
- Kennicutt, R. C., et al. 2003, *PASP*, **115**, 928
- Kistler, M. D., Yuksel, H., Ando, S., Beacom, J. F., & Suzuki, Y. 2008, arXiv:0810.1959
- Kitaura, F. S., Janka, H.-T., & Hillebrandt, W. 2006, *A&A*, **450**, 345
- Kochanek, C. S., Beacom, J. F., Kistler, M. D., Prieto, J. L., Stanek, K. Z., Thompson, T. A., & Yuksel, H. 2008, *ApJ*, **684**, 1336
- Kulkarni, S. R., et al. 2007, *Nature*, **447**, 458
- Kwok, S. 1993, *ARA&A*, **31**, 63
- Lejeune, T., & Schaerer, D. 2001, *A&A*, **366**, 538
- Li, W. 1999, *IAU Circ.*, **7149**, 1
- Li, W., Filippenko, A. V., Chornock, R., & Jha, S. 2003, *PASP*, **115**, 844
- Li, W., Filippenko, A. V., Treffers, R. R., Riess, A. G., Hu, J., & Qiu, Y. 2001, *ApJ*, **546**, 734
- Li, W., et al. 2002, *PASP*, **114**, 403
- Li, W., et al. 2007, *ApJ*, **661**, 1013
- Li, W. D., et al. 2000, in *AIP Conf. Proc. 522, Cosmic Explosions*, ed. W. W. Zhang & S. S. Holt (Melville, NY: AIP), **103**
- Liebendörfer, M., Mezzacappa, A., Thielemann, F.-K., Messer, O. E., Hix, W. R., & Bruenn, S. W. 2001, *Phys. Rev. D*, **63**, 103004
- Massey, P., McNeill, R. T., Olsen, K. A. G., Hodge, P. W., Blaha, C., Jacoby, G. H., Smith, R. C., & Strong, S. B. 2007, *AJ*, **134**, 2474
- Massey, P., Olsen, K. A. G., Hodge, P. W., Strong, S. B., Jacoby, G. H., Schlingman, W., & Smith, R. C. 2006, *AJ*, **131**, 2478
- Maund, J. R., et al. 2006, *MNRAS*, **369**, 390
- McQuinn, K. B. W., et al. 2007, *ApJ*, **664**, 850
- Menzies, J. W., et al. 1987, *MNRAS*, **227**, 39
- Miyaji, S., Nomoto, K., Yokoi, K., & Sugimoto, D. 1980, *PASJ*, **32**, 303
- Monard, L. A. G. 2006, *IAU Circ.*, **8690**, 2
- Monard, L. A. G. 2008, *IAU Circ.*, **8946**, 1
- Mould, J., Barmby, P., Gordon, K., Willner, S. P., Ashby, M. L. N., Gehrz, R. D., Humphreys, R., & Woodward, C. E. 2008, *ApJ*, **687**, 230
- Nomoto, K. 1984, *ApJ*, **277**, 791
- Nomoto, K. 1987, *ApJ*, **322**, 206
- Ofek, E. O., et al. 2008, *ApJ*, **674**, 447
- Pastorello, A., et al. 2004, *MNRAS*, **347**, 74
- Pastorello, A., et al. 2006, *MNRAS*, **370**, 1752
- Pastorello, A., et al. 2007, *Nature*, **447**, 829
- Poelarends, A. J. T., et al. 2008, *ApJ*, **675**, 614
- Prieto, J. L. 2008, *ATel.*, **1550**, 1 (P08)
- Prieto, J. L., Stanek, K. Z., & Beacom, J. F. 2008a, *ApJ*, **673**, 999
- Prieto, J. L., et al. 2008b, *ApJ*, **681**, L9 (P08b)
- Prieto, J. L., et al. 2008c, *ATel.*, **1596**, 1 (P08c)
- Puckett, T., & Gauthier, S. 2002, *IAU Circ.*, **7863**, 1
- Rampp, M., & Janka, H.-T. 2000, *ApJ*, **539**, L33
- Rau, A., Kulkarni, S. R., Ofek, E. O., & Yan, L. 2007, *ApJ*, **659**, 1536
- Reach, W. T., et al. 2005, *PASP*, **117**, 978
- Rich, D., Yamaoka, H., & Itagaki, K. 2005, *IAU Circ.*, **8497**, 3
- Richardson, D., Branch, D., Casebeer, D., Millard, J., Thomas, R. C., & Baron, E. 2002, *AJ*, **123**, 745
- Riera, A., García-Lario, P., Manchado, A., Bobrowsky, M., & Estalella, R. 2003, *A&A*, **401**, 1039
- Riera, A., García-Lario, P., Manchado, A., Pottasch, S. R., & Raga, A. C. 1995, *A&A*, **302**, 137
- Ritossa, C., Garcia-Berro, E., & Iben, I. J. 1996, *ApJ*, **460**, 489
- Sahu, D. K., et al. 2006, *MNRAS*, **372**, 1315
- Schaefer, B. E. 1996, *ApJ*, **464**, 404
- Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, *A&AS*, **96**, 269
- Schwartz, M., Li, W., Filippenko, A. V., & Chornock, R. 2003, *IAU Circ.*, **8051**, 1
- Siess, L. 2006, *A&A*, **448**, 717
- Siess, L. 2007, *A&A*, **476**, 893
- Sloan, G. C., et al. 2003, *ApJS*, **147**, 379
- Smartt, S. J., Eldridge, J. J., Crockett, R. M., & Maund, J. R. 2009, *MNRAS*, **395**, 1409
- Smartt, S. J., et al. 2004, *Science*, **303**, 499
- Smith, N. 2007, *AJ*, **133**, 1034
- Smith, N. 2008, in *IAU Symp. 250, Massive Stars as Cosmic Engines*, ed. F. Bresolin, P. A. Crowther, & J. Puls (Cambridge: Cambridge Univ. Press), **193**
- Smith, N., Humphreys, R. M., & Gehrz, R. D. 2001, *PASP*, **113**, 692
- Smith, N., et al. 2009, *ApJ*, **697**, L49
- Stanishev, V., et al. 2008, *Cent. Bur. Electron. Teleg.*, **1235**, 1
- Steele, T. N., et al. 2008, *Cent. Bur. Electron. Teleg.*, **1275**, 1
- Stern, D., et al. 2005, *ApJ*, **631**, 163
- Stetson, P. B. 1992, in *ASP Conf. Ser. 25, Astronomical Data Analysis Software & Systems I*, ed. D. M. Worrall, C. Biemesderfer, & J. Barnes (San Francisco, CA: ASP), **297**
- Sugerman, B., et al. 2004, *IAU Circ.*, **8442**, 2
- Thilker, D. A., et al. 2005, *ApJ*, **619**, L67
- Thompson, T. A., Burrows, A., & Pinto, P. A. 2003, *ApJ*, **592**, 434
- Van Dyk, S. D. 2005, in *ASP Conf. Ser. 332, The Fate of the Most Massive Stars*, ed. R. Humphreys, K. Stanek (San Francisco, CA: ASP), **47**
- Van Dyk, S. D., Li, W., Filippenko, A. V., Humphreys, R. M., Chornock, R., Foley, R., & Challis, P. M. 2003, *PASP*, **115**, 1
- Van Dyk, S. D., Li, W., Filippenko, A. V., Humphreys, R. M., Chornock, R., Foley, R., & Challis, P. M. 2006, arXiv:astro-ph/0603025
- Van Dyk, S. M., et al. 2000, *PASP*, **112**, 1532
- van Loon, J. Th., Marshall, J. R., Cohen, M., Matsuura, M., Wood, P. R., Yamamura, I., & Zijlstra, A. A. 2006, *A&A*, **447**, 971
- van Loon, J. Th., et al. 2005, *A&A*, **438**, 273
- Wagner, R. M., et al. 2004, *PASP*, **116**, 326
- Wanajo, S., Nomoto, K., Janka, H.-T., Kitaura, F. S., & Müller, B. 2009, *ApJ*, **695**, 208
- Weis, K., & Bomans, D. J. 2005, *A&A*, **429**, L13
- Wesson, R., Fabbri, J., Barlow, M., & Meixner, M. 2008, *Cent. Bur. Electron. Teleg.*, **1381**, 1
- West, R. M., Lauberts, A., Schuster, H.-E., & Jorgensen, H. E. 1987, *A&A*, **177**, L1
- Wheeler, J. C., Cowan, J. J., & Hillebrandt, W. 1998, *ApJ*, **493**, L101
- Woosley, S. E., Heger, A., & Weaver, T. A. 2002, *Rev. Mod. Phys.*, **74**, 1015