THE SUPERNova IMPOSTor IMPOSTor SN 1961V: SPITZER SHOWS THAT ZWICKY WAS RIGHT (AGAIN)

C. S. KOCHANek1,2, D. M. SZCZYGIEL1,2, AND K. Z. STANEK1,2

1 Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA
2 Center for Cosmology and AstroParticle Physics, The Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA

Received 2010 October 18; accepted 2011 May 24; published 2011 August 8

ABSTRACT

SN 1961V, one of Zwicky’s defining Type V supernovae (SNe), was a peculiar transient in NGC 1058 that has variously been categorized as either a true core-collapse SN leaving a black hole (BH) or neutron star (NS) remnant, or an eruption of a luminous blue variable star. The former case is suggested by its possible association with a decaying non-thermal radio source, while the latter is suggested by its peculiar transient light curve and its low initial expansion velocities. The crucial difference is that the star survives a transient eruption but not an SN. All stars identified as possible survivors are significantly fainter, $L_{\text{opt}} \sim 10^5 L_\odot$, than the $L_{\text{opt}} \simeq 3 \times 10^6 L_\odot$ progenitor star at optical wavelengths. While this can be explained by dust absorption in a shell of material ejected during the transient, the survivor must then be present as an $L_{\text{IR}} \simeq 3 \times 10^6 L_\odot$ mid-infrared source. Using archival Spitzer observations of the region, we show that such a luminous mid-IR source is not present. The brightest source of dust emission is only $L_{\text{IR}} \simeq 10^5 L_\odot$ and does not correspond to the previously identified candidates for the surviving star. The dust cannot be made sufficiently distant and cold to avoid detection unless the ejection energy, mass, and velocity scales are those of an SN or greater. We conclude that SN 1961V was a peculiar, but real, SN. Its peculiarities are probably due to enhanced mass loss just prior to the SN, followed by the interactions of the SN blast wave with this ejecta. This adds to the evidence that there is a population of SN progenitors that have major mass-loss episodes shortly before core collapse. The progenitor is a low metallicity, $\sim 1/3$ solar, high-mass, $M_{\text{ZAMS}} \gtrsim 80 M_\odot$, star, which means either that BH formation can be accompanied by an SN or that surprisingly high-mass stars can form an NS. We also report on the mid-IR properties of the two other SNe in NGC 1058, SN 1969L, and SN 2007gr.

Key words: supernovae: individual (SN1961V, SN1969L, SN2007gr)

Online-only material: color figures

1. INTRODUCTION

We know that stars both explode, as core-collapse supernovae (SNe), and erupt in luminous transients that eject mass but do not destroy the star. In some cases, both types of transients produce similar, Type IIn spectra, where the “n” indicates that the emission lines are narrow ($\lesssim 2000$ km s$^{-1}$) compared to a normal SN (Schlegel 1990; Filippenko 1997). Type IIn SNe seem to be cases where the blast wave is interacting with a dense circumstellar medium (CSM) created either by a massive wind or mass ejected in a pre-SN eruption (see, e.g., Smith 2008; Gal-Yam et al. 2007, and references therein). The mechanism of the eruptions from luminous blue variable (LBV) stars is not well understood (see, e.g., Humphreys & Davidson 1994; Smith & Owocki 2006), but they eject material at velocities lower than normal SNe. Unfortunately, the luminosities of the faintest SN are not well separated from those of the brightest eruptions, making it difficult to safely classify transients at the boundary. These brightest of stellar eruptions are frequently referred to as SN “impostors” (Van Dyk et al. 2002). Correct classifications are important for understanding the rates and mechanisms of both processes. In particular, we note the recent debates about the nature of SN 2008S and the 2008 transient in NGC 300 (see Prieto et al. 2011, and references therein).

The most obvious difference between the two cases is that the star survives only in the eruption scenario. Thus, there have been attempts to identify the surviving star for a number of the impostors, with candidates identified for SN 1954J (Smith et al. 2001; Van Dyk et al. 2005), SN 1961V (see below), SN 1997bs (Van Dyk et al. 1999; Li et al. 2002), and SN 2000ch (Wagner et al. 2004; Pastorello et al. 2010). It is probably safe to say that none of these identifications besides SN 2000ch is certain. There is, however, a second test. Most of the candidate survivors are fainter than the progenitors, and this is expected because the surviving star lies inside a shell of ejected material that probably forms dust as it cools. For the spectacular Galactic example of η Carinae, $\sim 90\%$ of the emission is absorbed and reradiated in the mid-IR (see Humphreys & Davidson 1994). Thus, a good test for these identifications is to find the mid-IR emission from the survivor and check that it matches the absorption indicated by the difference between the luminosities of the progenitor and the survivor.5 While some SNe may be late-time IR sources, they should evolve more rapidly and are unlikely to show the balance between progenitor luminosity, optical absorption, and mid-IR emission expected for a surviving star. While frequently noted, this test seems only to have been applied to SN 1954J, where Smith et al. (2001) found evidence for a near-IR excess. Here, we apply this test to SN 1961V using archival Spitzer data.

The progenitor of SN 1961V was (likely) the brightest star in NGC 1058, with $m_{\text{pg}} \simeq 18$ in the decades before the transient (Bertola 1964; Zwicky 1964). Utrobin (1987) estimated magnitudes in 1954 December of $B = 18.2 \pm 0.1$, $V = 17.7 \pm 0.3$, and $B - V = 0.6 \pm 0.3$. Given a distance of 9.3 Mpc, the Cepheid distance to fellow group member NGC 925 (Silbermann et al. 1996), and Galactic extinction of $E(B-V) = 0.06$ mag (Schlegel et al. 1998), this corresponds...

5 There can be problems in this accounting from binary companions (see Kochanek 2009) and chance coincidences.
of the Type Ic SN 2007gr (Valenti et al. 2008), the two other
this peak, it was brighter than the maximum of the Type IIP
m
progenitor, with
1963 to 1967 where it was only moderately fainter than the
SNe in NGC 1058. It then dropped in brightness, going through
a long-lived plateau.

The horizontal, pre-transient line indicates the magnitude of the progenitor
of SN 1961V prior to (roughly) 1955. The right axis simply converts the
luminosity to absolute magnitude scale to luminosity as

\( \lambda L/\lambda L_\odot \)

for the
B
band. The post-peak
luminosity of SN 1961V is neither particularly faint nor bright compared to
other SNs showing interactions with circumstellar material. While SN 1988Z
and SN 1993J do not show the complex structures of SN 1961V, SN 2005ip also
has a long-lived plateau.

(A color version of this figure is available in the online journal.)

to

\( m_B \simeq -12 \)

making the progenitor one of the brightest stars in any galaxy. If there is additional foreground dust in
NGC 1058 or dust associated with the progenitor star, its true
luminosity is still higher and our ultimate conclusions become stronger. Detailed discussions of the light curve are presented in
Doggett & Branch (1985), Goodrich et al. (1989), Humphreys & Davidson (1994), and Humphreys et al. (1999), based on the data obtained by Zwicky (1964), Bertola (1963, 1964, 1967), Bertola & Arp (1970), and Fesen (1985). Sometime between 1955 and 1960 the star started to brighten, reaching a plateau of

\( m_{pg} \simeq 14 \)

by the summer of 1961 before briefly peaking at

\( m_{pg} \simeq 12.5 \)

in 1961 December, as shown in Figure 1. At this peak, it was brighter than the maximum of the Type IIP SN 1969L (e.g., Ciatti et al. 1971) and comparable to the peak of the Type Ic SN 2007gr (Valenti et al. 2008), the two other SNe in NGC 1058. It then dropped in brightness, going through a series of extended plateaus, including a four-year period from 1963 to 1967 where it was only moderately fainter than the progenitor, with

\( m_{pg} \simeq 19 \).

After 1968 it had faded below the point of visibility, 

\( m_{pg} \gtrsim 22 \).

Spectra of the event were also peculiar (Branch & Greenstein 1971), with relatively narrow lines (FWHM \( \simeq 2000 \) km s\(^{-1}\)), strong helium emission lines and a constant color, resembling an F star, near maximum light (Bertola 1965). Based on these peculiarities, Zwicky (1964) classified SN 1961V, along with \( \eta \) Carinae, as a “Type V” SN, although the clear presence of hydrogen in the spectra would lead to a “modern” classification of Type IIn or peculiar (Branch & Cowan 1985; Filippenko 1997).

Goodrich et al. (1989) proposed that the peculiar, extended light curve and low velocity spectra would be more easily explained if SN 1961V was actually an LBV eruption rather than an SN. They proposed that the progenitor was a hot

\( T_e > 45000 \) K, luminous (\( L_\star \simeq 10^{6.4} L_\odot \)) star that was undergoing an S Doradus outburst in the decades prior to the eruption. During such an outburst, the star has the same bolometric luminosity but a far lower photospheric temperature (\( T_e \simeq 8000 \) K; see Humphreys & Davidson 1994). Then in 1960 the star had a true eruption, leading to the luminosity peak, followed by the plateaus and a secondary peak, features that have been seen in other LBV eruptions (Humphreys & Davidson 1994; Humphreys et al. 1999). This scenario requires a surviving star, and several candidates have been identified from a sequence of steadily improving Hubble Space Telescope (HST) images by Filippenko et al. (1995), Van Dyk et al. (2002), and Chu et al. (2004) based on the accurate optical (Klemola 1986) or radio (Branch & Cowan 1985; Cowan et al. 1988; Stockdale et al. 2001) positions. All proposed candidates are significantly fainter than the progenitor, with \( V \simeq 24 \) mag.

The primary counterargument to the LBV eruption hypothesis is that SN 1961V also seems to be associated with a nonthermal radio source (Branch & Cowan 1985; Cowan et al. 1988; Stockdale et al. 2001; Chu et al. 2004) that closely resembles the properties of other radio SNe and not the fainter, thermal emission of \( \eta \) Carinae. Perhaps \( \eta \) Carinae was a nonthermal radio source when younger, but there is no nonthermal radio emission (or even a detection) from the SN impostor/LBV eruption SN 1954J even though it is almost four times closer and of similar age to SN 1961V (Eck et al. 2002). VLBI observations in 1999 by Chu et al. (2004) also resolved out the radio emission, setting a minimum radius for the radio emission of order 4 mas or about 0.17 pc. This would require an expansion velocity of \( v \simeq 4000 \) km s\(^{-1}\) that would be hard to explain with an eruption. While of finite size, it must be some kind of stellar source because of the large fractional variability (36% over 15 years). On the other hand, van Dyk (2005) reconsidered the astrometry between the radio and optical identifications and argues for a \( \simeq 2\sigma \) discrepancy between them.

We should also note that post-peak emission is seen in other SNe, where Figure 1 shows the examples of SN 1993J (Barbon et al. 1995; Richardson et al. 1996; Zhang et al. 2004), SN 1988Z (Aretxaga et al. 1999), and SN 2005ip (Smith et al. 2009), where the latter two were also compared to SN 1961V by Smith et al. (2010). Other SNe that have been compared to SN 1961V, such as SN 1978K (Ryder et al. 1993) and SN 1986J (Rupen et al. 1987), lack detailed light curves. The post-peak emission of SN 1961V is actually relatively faint compared to “typical” Type IIn SNe, although this is likely a selection effect. SNe are typically only followed until 2–3 mag fainter than peak (e.g., Li et al. 2010), so only the brightest deviations from a “normal” SN light curve are noticed and then studied in detail. The space between the two bright SNe and SN 1961V/SN 1993J is presumably fully populated. While SN 1998Z and SN 1993J do not show the complex structures of SN 1961V, SN 2005ip also appears to have a bright, long-lived plateau.

While the Spitzer Space Telescope was not intended for studies of individual stars at 10 Mpc, it should have no difficulty identifying a source with the luminosity of the SN 1961V progenitor star in the outskirts of NGC 1058. Indeed, Goodrich et al. (1989) note that in the infrared the source should be “the brightest point thermal IR source in NGC 1058.” Here we use archival Spitzer IRAC (Fazio et al. 2004) and Multiband Infrared Photometer for Spitzer (MIPS; Rieke et al. 2004) data to measure the infrared emission associated with SN 1961V. In Section 2, we discuss the available data, the astrometry relative to the HST data used to identify candidate surviving stars, and
the resulting estimates and limits on the mid-IR luminosity. We model the photometry in Section 3 to find that there is insufficient infrared emission for the progenitor star to have survived and that SN 1961V must therefore have been an SN. We note that Smith et al. (2010) have simultaneously reached this conclusion based on the gross differences between SN 1961V and other SN impostor candidates and its greater similarity to other core-collapse SNe. In Section 4, we present the photometry for SN 1969L and SN 2007gr, the other two SNe in NGC 1058. In Section 5, we discuss the consequences of SN 1961V having been an SN.

2. DATA AND INFRARED LUMINOSITY ESTIMATES

NGC 1058 has been observed twice with IRAC and MIPS, as summarized in Table 1. The total exposure times are 15 × 30 s = 450 s for the IRAC bands, 10 s + 30 s = 40 s for the MIPS 24 μm band and 3 × 3 s = 9 s for the MIPS 70 μm band. The Spitzer sensitivity estimates for these exposure times are 0.36, 0.62, 4.1, 4.7, 25, and 3400 μJy, at 3.6, 4.5, 5.8, 8.0, 24, and 70 μm, respectively. If we convert these into 3σ limits on λLλ in each band at the distance to NGC 1058, they correspond to 2400, 3300, 17,000, 14,000, 25,000, and 1.2 × 10^{16} L_{\odot} for the 3.6, 4.5, 5.8, 8.0, 24, and 70 μm bands, respectively. In practice, we would be confusion limited in the IRAC bands we were trying to reach these detection limits, but, as Goodrich et al. (1989) noted, we should have little difficulty finding the expected >10^6 L_{\odot} mid-infrared source.

We downloaded the Post-Basic Calibrated Data for these programs from the Spitzer archive. These IRAC images are two-times oversampled and have a pixel scale of 0′′.60, while the MIPS 24 μm and 70 μm images have pixel scales of 2′′.45 and 4′′.0, respectively, compared to native pixel scales of 2′′.55 and 5′′.2 (narrow field of view). We aligned and combined the data for each band using the ISIS (Alard & Lupton 1998; Alard 2000) image subtraction package. We also used ISIS to difference image between the available epochs, to search for any signs of variability, and to difference image between wavelengths. The latter technique takes advantage of the fact that all “normal” stars have the “same” mid-IR colors, so normal stars effectively “vanish” to leave only the red stars dominated by dust emission and emission by the interstellar medium (see Khan et al. 2010). This wavelength differencing procedure isolates the relatively rare, dusty stars without the crowding from the normal stars. We also obtained the HST images used by Van Dyk et al. (2002) so that we could astrometrically match the Spitzer data with the progenitors discussed by Filippenko et al. (1995), Van Dyk et al. (2002), and Chu et al. (2004). We also examined the more recent images of the area from 2007 October (Van Dyk/11119) and 2008 August (Li/10877), but these do not significantly improve on the prior data.

Figure 2 shows a wide field and close-up view of the SN 1961V region in the HST WFPC2 F606W (Illingworth/5446) and 3.6 μm reference images. Clearly, with Spitzer’s resolution we will be unable to obtain photometry for all the individual stars identified in the HST image, particularly at the longer wavelengths. We see counterparts in the 3.6 μm image to star 8, the group of stars 5/6/7/9/11 (which we will refer to as region X) and star 3. Stars 3 and 11 are not visible in the F606W image, but are detected in the F814W image. The large black circle is 2′′.4 in radius and represents one of the apertures we used for photometry.

Figure 3 shows regions around SN 1961V for all six Spitzer bands. We used black circles to mark the 2′′.4 photometric aperture we used to estimate the fluxes on IRAC images, as well as the 3′′.5 and 16′′.0 apertures used to measure fluxes in the 24.0 and 70.0 μm MIPS bands, respectively. For clarity, the alternative 3′′.6 aperture used for the IRAC bands is not shown. We also show the wavelength differentiated images between 3.6 μm and the other three IRAC bands. We see that most of the sources in the 3.6 μm image are normal stars, since they fade away at longer wavelengths and do not appear in the wavelength

### Table 1

| Date       | MJD     | PI/Program   | 3.6 μm | 4.5 μm | 5.8 μm | 8.0 μm | 24 μm | 70 μm |
|------------|---------|--------------|--------|--------|--------|--------|-------|-------|
| 2004 Aug 14| 53231.31| Fazio/69     | 150    | 150    | 150    | 150    | 0     | 0     |
| 2004 Aug 25| 53242.03| Fazio/69     | 0      | 0      | 0      | 0      | 10    | 9     |
| 2007 Sep 14| 54357.66| Kotak/40619  | 300    | 300    | 300    | 300    | 0     | 0     |
| 2007 Sep 29| 54372.22| Kotak/40619  | 0      | 0      | 0      | 0      | 30    | 0     |

Notes. Exposure times are in seconds. The IRAC frame times were 30 s in both observations.
images. This removes the flux from normal stars to leave only sources of dust. The top panels show the 3.6, 4.5, and 5.8 μm images of the region, the middle panels show the 8.0, 24, and 70 μm images of the region, and the lower panels show the [4.5]–[3.6], [5.8]–[3.6], and [8.0]–[3.6] wavelength differenced images. This removes the flux from normal stars to leave only sources of dust and PAH emission. The panels are 15′, 30′, and 60′ in size for the IRAC, 24 μm, and 70 μm bands, respectively. The large black circles in the IRAC, 24 μm, and 70 μm panels have radii of 2′, 3′, 4, and 6′, respectively, and correspond to the aperture sizes used for photometry. The smaller 1″ radius circles mark the positions of star 8 and the region X encompassing the candidate surviving stars. We also analyzed the IRAC images of the region using a 3″ radius aperture and DAOPHOT. There is some dust-related emission, much of which seems to be associated with source 8, for which we lack an optical color because it lay just off the field edge in the F814W and F450W images analyzed by Van Dyk et al. (2002), and possibly with source 10. Chu et al. (2004) identify star 7 as the only point-like source of Hα emission. The complex of sources corresponding to stars 6, 7, 9, and 11 in Van Dyk et al. (2002), which we have labeled region X in Figure 2, appears to have no significant excess emission due to dust even though they correspond to all the claimed counterparts to SN 1961V (see below).

We estimated the fluxes using two procedures. First, we simply used aperture photometry (the IRAF apphot package). We used signal aperture radii (background annuli) of 2′ and 3′ (2′–7′) for the IRAC bands, 3′ (6′–8′) for the 24 μm, and 16′ (18′–39′) for 70 μm. The background was estimated using the mode of the background pixels after 2σ outlier rejection, an approach which should work reasonably well in crowded regions. We also compensated for the presence of the edge of the 70 μm image. No source was identified at 70 μm, so we estimated a 3σ upper limit on the flux. We used the standard Spitzer corrections for these apertures.4 For the 2′ and 3′ IRAC aperture these are 1.213, 1.234, 1.379, and 1.584 (1.124, 1.127, 1.143, and 1.234) for the 3.6 μm, 4.5 μm, 5.8 μm, and 8.0 μm bands, respectively, with uncertainties of order 1%–2%. For the 24 and 70 μm apertures, they are 2.80 and 2.07 and are accurate to about 5%. The resulting flux estimates are presented in Tables 2 and 3.

While the large aperture photometry provides a conservative upper limit on the luminosity of any individual source, it is clear that the flux near SN 1961V can be divided over several sources in the IRAC images. To better account for the effects of overlapping point spread functions (PSFs) than is possible with aperture photometry, we also analyzed the region with DAOPHOT (Setton 1987), in particular dividing the IRAC flux between source 8 and the complex of sources in region X associated with the candidate surviving stars. For the still lower

4 http://ssc.spitzer.caltech.edu/irac/instrument/handbook/ and http://ssc.spitzer.caltech.edu/mips/mipsinstrument/handbook/
resolution MIPS images, no attempt was made to divide the flux over sub-components. The DAOPHOT results are also presented in Table 2. Figure 4 compares these estimates to each other as well as to the spectral energy distribution (SED) of η Carinae from Humphreys & Davidson (1994). The total flux, even in the large apertures, is far less than that of η Carinae, which roughly has the luminosity and SED we expect for SN 1961V. The sub-components are then significantly less luminous, although the DAOPHOT division into two sources does not capture all the flux in the aperture, and we again see that while star 8 has an IR excess, the region X containing all the proposed surviving stars seems not to. We also checked for variability in the IRAC and 24 μm bands, finding none to limits of roughly 10%.

We also report photometry for Stars A, B, and C in Figure 2, Van Dyk et al. (2002) star 3, SN 1969L (Ciatti et al. 1971) and SN 2007gr (Crockett et al. 2008; Valenti et al. 2008). The location of SN 1969L was only covered by some of the images and SN 2007gr is only present in the later data, so we only analyzed the relevant images but followed the same procedures. We only obtained upper limits on any flux from SN 1969L, while SN 2007gr was a very bright source. We discuss the results for these SNe in Section 4.

3. MODELS

We model the SED using DUSTY (Ivezić & Elitzur 1997; Ivezić et al. 1999; Elitzur & Ivezić 2001). We assumed a dusty shell with a density distribution ∝ 1/r² and an outer radius at twice the distance of the inner, R_{out} = 2R_{in}. This assumption has little affect on the results. The models are specified by the temperature of the illuminating blackbody, the stellar temperature T_{s}, the optical depth of the shell τ_V at V band, and the dust temperature T_d at the inner edge of the shell. We tabulated the models for Draine & Lee (1984) graphicitic and silicate dusts with the standard size distributions assumed by DUSTY for stellar temperatures of 5000, 7500, 10,000, 15,000, 20,000, 30,000, and 40,000 K, inner edge dust temperatures from 50 to 900 K in steps of 50 K, and V-band optical depths of τ_V = 0 to 6 in steps of 0.1 and τ_V = 6 to 30 in steps of 0.5. Our approach will be to normalize the models based on the pre-transient luminosity and then constrain the optical depth to match the flux of the candidate survivors, leaving as the remaining variable the dust temperature. As noted earlier, there must be little additional foreground extinction or dust associated with the progenitor or the already high estimates of the progenitor’s luminosity would quickly exceed 10^7 L_☉ after extinction corrections. Adding any additional extinction would strengthen our ultimate conclusions because the predicted mid-IR emissions would increase in proportion to the added extinction. Hence, any significant quantities of obscuring material must have been ejected in 1961.

Given the stellar luminosity, the dust temperature is determined by the shell radius, and the shell radius is closely related to the physics of the transient. If the velocity is restricted by the FWHM of the optical lines, roughly 2000 km s⁻¹ (e.g., Branch & Greenstein 1971), then the current radius of the material is

\[ R \simeq 1.4 \times 10^{17} \left( \frac{v_d}{1000 \text{ km s}^{-1}} \right) \text{ cm}, \]

where we set the elapsed time to 43 years (1961–2004) and the velocity v_d to half of the FWHM. In our standard models we consider those with inner shell radii near this value, which is mildly conservative given that the inner edge dominates the dust emission. The outer edge is then at twice this distance and so has twice the expansion velocity. As recently emphasized by Smith et al. (2010), typical LBV eruptions have much smaller line FWHM (<1000 km s⁻¹).

The only way to escape our eventual limits is to make the dust so cold that it cannot be detected given Spitzer’s diminishing sensitivity at longer wavelengths. For the dust temperature to be low, the dust must be distant, and for the simple case of radiative equilibrium for dust radiating as a blackbody, the dust temperature is

\[ T = \left( \frac{L_\ast}{16\pi \sigma R^2} \right)^{1/4} = 142 \left( \frac{L_\ast}{3 \times 10^6 L_\odot} \right)^{1/4} \left( \frac{10^{17} \text{ cm}}{R} \right)^{1/2} \text{ K} \]

(e.g., Wright 1980) corresponding to an SED peaking near λ = 20 μm that will be strongly constrained by the 24 μm data.

### Table 3

| Source          | [24] (mJy) | [70] (mJy) |
|-----------------|------------|------------|
| SN1961V area    | 0.226 ± 0.0039 | <8.0 |
| Star 3          | 0.089 ± 0.0044 | ... |
| Star A          | 0.045 ± 0.0082 | <190 |
| Star B          | 0.094 ± 0.0080 | <190 |
| Star C          | 0.027 ± 0.0049 | <178 |
| SN 2007gr       | 3.155 ± 0.0398 | ... |
| SN 1969L        | <0.063 | ... |

*Note.* Flux limits are 3σ limits.

Figure 4. Mid-IR SEDs of the SN 1961V region. The total emission is described by the large aperture MIPS fluxes and either the 3.6 (open squares) or 24′ (filled squares) IRAC apertures. With DAOPHOT we attempt to separate the fluxes of star 8 (filled triangles) and the region X (open triangles) that contains all the proposed surviving stars. For comparison, we show with open pentagons the SED of η Carinae from Humphreys & Davidson (1994), which roughly has the properties we expect for SN 1961V. The 24′ IRAC apertures combined with the 24 μm luminosity and the 70 μm upper limit will be our standard comparison SED. Note that region X has an SED dropping to longer wavelengths, indicating it is dominated by stellar emission, while star 8 has an IR excess.
DUSTY, with better dust emissivity models, usually predicts higher inner edge dust temperatures than this simple model but a similar peak emission wavelength. Lowering the dust temperature to raise the peak wavelength requires a larger dust radius, but moving the shell to a larger radius requires rapid increases in both the ejected mass and energy. The V-band optical depth of the shell is

$$\tau_V = \frac{M_d \kappa_{opt}}{4\pi R_n R_{out}} \simeq 8 \left( \frac{M_d}{M_\odot} \right) \left( \frac{\kappa_{opt}}{500 \text{ cm}^2 \text{ g}^{-1}} \right) \times \left( \frac{R_n}{R_{out}} \right) \left( \frac{10^{17} \text{ cm}}{R_{in}} \right)^2,$$

(3)

where \(\kappa_{opt} \simeq \kappa_{500} = 500 \text{ cm}^2 \text{ g}^{-1}\) is the optical opacity for a dust to gas ratio of roughly 1% (e.g., Semenov et al. 2003). \(M_{ej}\) is the ejected mass in which the dust forms, and the shell has a density profile \(\propto 1/r^2\) from \(R_{in} < R < R_{out}\). Equivalently, the required mass is

$$M_{ej} = 0.13\tau_V \left( \frac{\kappa_{500}}{\kappa_{opt}} \right) \left( \frac{R_{out}}{R_{in}} \right) \left( \frac{R_{in}}{10^{17} \text{ cm}} \right)^2 M_\odot.$$  

(4)

Assuming a thin shell with \(R_{in} \simeq R_{out} = R\) for simplicity, the kinetic energy of the ejecta,

$$E_{ej} = \frac{1}{2} M_{ej} v_{ej}^2 = 7 \times 10^{47} \tau_V \left( \frac{\kappa_{500}}{\kappa_{opt}} \right) \left( \frac{R}{10^{17} \text{ cm}} \right)^4 \text{ erg},$$

(5)

increases very rapidly with increasing shell radius because both the velocity and mass must be larger for larger distances. The kinetic energy required reaches an SN-like magnitude of \(10^{51} \text{ erg}\) for \(R \simeq 6 \times 10^{17}\tau_V^{1/4} \text{ cm}\), as does the velocity and mass. Making the dust distant enough to be cold forces the mass, velocity, and energy budgets out of the range of LBV eruptions. For example, the kinetic energy of the great eruption of \(\eta\) Carinae is \(<10^{50} \text{ erg}\) (e.g., Humphreys & Davidson 1994; Smith 2008). Moreover, Smith (2008) argues that roughly half of this kinetic energy is in very fast moving material \((>3000 \text{ km s}^{-1})\) that has little mass and lies at larger radii, thereby contributing little to the optical depth. Phrasing the scaling in terms of the peak wavelength, \(M_{ej} \propto \lambda_{peak}^3\) and \(E_{ej} \propto \lambda_{peak}^8\), further emphasizes the problem with this solution. Using a thicker shell exacerbates these problems since it leads to a larger mass-weighted radius.

In order to understand the mid-infrared limits we must first choose which HST star to call the survivor (see Figure 2). Filippenko et al. (1995) propose star 6, with \(B\) and \(V\) magnitudes of \(24.82 \pm 0.25\) and \(24.50 \pm 0.16\) mag. Van Dyk et al. (2002) propose star 11, which they estimate to have an \(I\) magnitude of \(24.3 \pm 0.22, B - I > 1,\) and \(V - I > 1.1\) mag. Chu et al. (2004) propose star 7 from Van Dyk et al. (2002), with \(B, V,\) and \(I\) magnitudes of \(24.04 \pm 0.14, 23.85 \pm 0.14,\) and \(23.83 \pm 0.14\), respectively. Chu et al. (2004) prefer this identification because (1) it appears to be spatially coincident with the radio source, although this has been challenged by Van Dyk et al. (2005), (2) it appears to be the only \(H\alpha\) source, and (3) its \(H\beta\) line has broad wings (at least \(\pm 550 \text{ km s}^{-1}\), limited by the noise in the spectrum). It does not, however, have the forbidden lines \([O\ I] \lambda 6300, [O\ III] \lambda 4959/5007\) expected from a remnant, suggesting the \(H\alpha\) emission is stellar and associated with an LBV. It is also too blue to be well modeled as an extinguished (hot) star, as noted by Chu et al. (2004). Of the Van Dyk et al. (2002) candidates closest to the preferred positions, 5 and 9 also have the wrong spectral slopes, while 6 and 11 are easily fit. Star 8, which has not been proposed as a candidate because it is too distant, is the only nearby source with significant dust emission (see Figures 3 and 4).

In practice, it matters little which star we use for the survivor. They are all faint compared to the progenitor star and so must be heavily extincted in the optical. Once most of the optical/UV flux must be absorbed, it matters little for the expected mid-IR luminosities whether it is 90% or 99%. Similarly, the spectral shape of the candidate matters little, since the optical depth is principally determined by the magnitude difference between the survivor and the progenitor rather than the color. Thus, for simplicity we will simply give the survivor the typical magnitude of the candidates, \(V = 24\) mag, and ignore the colors.

We have two possible choices for the intrinsic properties of the star. First, we can simply normalize it using the pre-transient luminosities. Alternatively, we can follow Goodrich et al. (1989) and assume that the star was in an S Doradus phase just before the transient and has now returned to its hotter, but similar luminosity quiescent state. If we set the stellar temperature to \(T_* = 7500\ K\) and normalize it by the Utrobin (1987) magnitudes, we get a luminosity of \(L_* \simeq 10^{5.9} L_\odot\). This is higher than the Goodrich et al. (1989) proposal of \(10^{6.4} L_\odot\), but matches their proposed S Doradus outburst temperature and agrees tolerably well with the \(B - V\) color of Utrobin (1987). Both raising and lowering the assumed temperature increases the luminosity because for \(T_* = 7500\ K\) the peak of the SED lies near the normalizing photometric bands. In fact, with any significant change in the temperature or the addition of significant foreground extinction, the luminosity becomes impossibly large (\(L_* > 10^7 L_\odot\)).

Figure 5 shows the resulting models. Dust optical depths of \(\tau_V = 7\) and 11.5 for graphitic and silicate dusts lead to enough extinction to make the optical flux consistent with a \(V = 24\) mag flux for the surviving star. Choosing inner edge dust temperatures of \(T_d = 500\) and 300 K corresponds to putting the inner edge of the dusty shell at \(R \simeq 1.3 \times 10^{17} \text{ cm}\). The outer edge dust temperatures are roughly 140 K. Using a thin shell, with \(R_{out} = 1.2 R_n\) instead of \(2 R_n\) leads to no significant changes. It is immediately apparent that the predicted mid-IR emission is grossly discrepant with the constraints even when we compare the model to the integrated emission from the region (defined here by the 2\(^{4}\) IRAC fluxes and the MIPS aperture fluxes) without any division of the emission over the multiple sources within it (see Figure 4). The cool stellar temperature exacerbates the problem because much of the near-IR emission is little affected by extinction.

The alternate hypothesis, that the star has reverted to a quiescent hot state (Goodrich et al. 1989), changes things little. Here we assume that the surviving star has now left its S Doradus phase, and again has a high photospheric temperature with a quiescent magnitude that is 4 magn fainter than before the eruption, \(B \simeq 22\) mag. For blackbodies with \(T_\ast = 30,000\ K\) and \(40,000\ K\), this implies luminosities of \(L_* \simeq 10^{6.2} L_\odot\) and \(L_* \simeq 10^{6.4} L_\odot\) that are significantly below that implied by the pre-eruption luminosities, as also noted by Humphreys et al. (1999). Figure 6 presents the \(T_* = 30,000\ K\) models. The visual optical depths are now much smaller (\(\tau_V = 2.5\) and 4.5 for graphitic and silicate dusts) because most of the flux is in the UV where the dust opacities are higher. Choosing inner edge dust temperatures of \(T_d = 400\) and 300 K corresponds to putting the inner edge for the dusty shell at roughly \(R \simeq 1.5 \times 10^{17}\) cm. The outer edge dust temperatures are roughly 100 K. Again, using
a thin shell leads to no significant changes. The discrepancies are smaller here, partly because the stellar luminosity is a factor of five lower than in the models of Figure 5, and partly because the star has little near-IR luminosity compared to the cooler progenitor model. Nonetheless, the predicted mid-IR fluxes are still much higher than allowed by the observations. Raising the stellar temperature to $T_\star = 40,000 \, K$ in order to better match the pre-transient luminosity or the Goodrich et al. (1989) model makes the problem worse by a factor of two.

In the end, the two most important variables are the intrinsic luminosity and the radius of the dust shell, or equivalently the ejection velocity of the material. We can explore these models by normalizing our DUSTY models to fit the generic $V$-band optical depths are again chosen to match the luminosity corresponding to our generic $V = 24$ mag extincted, surviving star (filled pentagon), and the inner shell radius is set to be close to $10^{17}$ cm.

(A color version of this figure is available in the online journal.)

Figure 5. Models normalized by the pre-outburst magnitudes of Utrobin (1987). The predicted SEDs for graphic (silicate) dust shown by the heavy solid (dashed) curves lie far above the total mid-IR emission (filled squares) from the SN 1961V region let alone that of any sub-component (see Figure 4). In this case, the progenitor model (light solid curve) is a $T_\star = 7500 \, K$ blackbody normalized to match the pre-outburst magnitudes (open squares) from Utrobin (1987). The progenitor luminosity is $L_\star = 10^{6.9} \, L_\odot$ and it would increase, leading to larger discrepancies, if we used a higher or lower stellar temperature or added any additional foreground extinction. The $V$-band optical depths are chosen to match the luminosity corresponding to our generic $V = 24$ mag extincted, surviving star (filled pentagon), and the inner shell radius is set to be close to $10^{17}$ cm.

(A color version of this figure is available in the online journal.)

Figure 6. Models following the Goodrich et al. (1989) scenario. The predicted SEDs for graphic (silicate) dust shown by the heavy solid (dashed) curves still lie well above the total mid-IR emission (filled squares) from the SN 1961V region let alone that of any sub-component (see Figure 4). In this case, the progenitor model (light solid curve) is a $T_\star = 30,000 \, K$ blackbody normalized to match the Goodrich et al. (1989) normalizing magnitude of $B = 22$ mag. leading to a stellar luminosity of $L_\star = 10^{6.2} \, L_\odot$ which is somewhat low. The $V$-band optical depths are again chosen to match the luminosity corresponding to our generic $V = 24$ mag extincted, surviving star (filled pentagon), and the inner shell radius is set to be close to $10^{17}$ cm. For $T_\star = 40,000 \, K$, $L_\star$ would double and be closer to matching the luminosity in Figure 5, which would also double the mid-IR discrepancy.

(A color version of this figure is available in the online journal.)
of high enough quality to make the test, we note that the optical variability should be significant given the parameters of our models. As the optical depth drops, the source should become steadily brighter, as is observed for η Carinae (e.g., Humphreys & Davidson 1994; Humphreys et al. 1999). If we normalize the optical depth to τ1 and time t1, the optical depth scales as \( \tau = \tau_1 (t/t_1)^2 \) (Equation (3)), although the expected magnitude does not simply scale with \( \tau \) because it includes both scattering and absorption. If we take \( \tau_V = 4.5 \) from the silicate models for a hot star, then at \( V = 24.0 \) mag progenitor in 2004, then it should have been 25.7 mag in 1995, and should be 23.4 mag in 2010, 23.1 mag in 2015, and 22.9 mag in 2020. In the cool star models the evolution is even more dramatic because of the higher optical depths. As Chu et al. (2004) noted, there is no sign of optical variability in the published data.

However, it is important to note that η Carinae went through a phase from \( \sim 1900 \) to \( \sim 1940 \) where its optical flux was roughly constant (e.g., Humphreys & Davidson 1994). We do not believe this can be explained by changing the basic scaling of the optical depth with radius. The physics of dust formation demands that the dust form as soon as it is feasible to do so because nucleation of high density with radius. The physics of dust formation demands that the dust form as soon as it is feasible to do so because nucleation depends exponentially on temperature and particle growth is a phase from \( \tau_V \) to \( \text{the plateau phase of the collisional process that proceeds most rapidly at higher densities} \). The vertical lines indicate the minimum \( \tau_{V, \text{min}} = \tau_1 (t/t_1)^2 \) (Equation (3)), although the expected magnitude does not simply scale with \( \tau \) because it includes both scattering and absorption. If we take \( \tau_V = 4.5 \) from the silicate models for a hot star, then at \( V = 24.0 \) mag progenitor in 2004, then it should have been 25.7 mag in 1995, and should be 23.4 mag in 2010, 23.1 mag in 2015, and 22.9 mag in 2020. In the cool star models the evolution is even more dramatic because of the higher optical depths. As Chu et al. (2004) noted, there is no sign of optical variability in the published data.

However, it is important to note that η Carinae went through a phase from \( \sim 1900 \) to \( \sim 1940 \) where its optical flux was roughly constant (e.g., Humphreys & Davidson 1994). We do not believe this can be explained by changing the basic scaling of the optical depth with radius. The physics of dust formation demands that the dust form as soon as it is feasible to do so because nucleation depends exponentially on temperature and particle growth is a collisional process that proceeds most rapidly at higher densities (see Salpeter 1977), and the plateau phase of η Carinae is much too late to correspond to the period of dust formation. There is an effect at high optical depths \( \tau_V \gtrsim 10 \) that the effective opacity evolves more slowly than the mean opacity because the optical emission is dominated by “leaks” through lower opacity paths in the shell. While this can help to slow the optical flux changes in the case of η Carinae, it cannot produce a long-lived plateau and is ineffective at the low optical depths implied by the fluxes of the candidate surviving stars in SN 1961V.

One can, however, produce a plateau by balancing the dropping optical depth against a dropping luminosity or an increasing stellar temperature, as we discuss further in Kochanek et al. (2011, in preparation). In particular, if η Carinae evolved from a cool 7000 K photosphere after the eruption to a very hot 30,000 K photosphere in the early 1900s, then the evolving bolometric correction can temporarily balance the change in the optical depth and produce a fairly long-lived plateau. Doing so requires fine tuning because the evolution in temperature or luminosity has to be matched to both the observational band and the evolution of the dust opacity. Thus, for the same evolution in stellar properties as η Carinae, SN 1961V would show a very different light curve. We cannot, however, rule out such a conspiracy for avoiding optical variability given the presently available data.

4. SN 1969L AND SN 2007GR

Since we were analyzing the Spitzer data already, we measured the fluxes associated with the other two SNe in NGC 1058, SN 1969L, and SN 2007gr, reporting their fluxes in Tables 2 and 3 and presenting their SEDs in Figure 8. SN 1969L lies outside the 70 \( \mu \)m image, and the image was taken before SN 2007gr, so we have no information on their 70 \( \mu \)m fluxes. We detected no flux above background at the location of SN 1969L (Ciatti et al. 1971), at limits on \( \lambda L_\lambda \) of \( 10^{4.9} L_\odot \). Here we used the 3σ upper bounds from the 3.6 \( \mu \)m IRAC aperture and the normal 24 \( \mu \)m aperture. The observations of Type Ic SN 2007gr (Crockett et al. 2008; Valenti et al. 2008) were taken 17 (IRAC) and 31 (MIPS) days after the R-band peak. The mid-IR luminosities are comparable to what was expected for SN 1961V, with luminosities \( \lambda L_\lambda \) of \( 10^{7.0}, 10^{6.8}, 10^{6.5}, 10^{6.4}, \) and \( 10^{6.1} \) for the 3.6, 4.5, 5.8, 8.0, and 24 \( \mu \)m bands, respectively. The SED, as shown in Figure 8, is falling rapidly in the mid-IR, indicating
that the emission is not dominated by a cool dust echo. We estimated $R$-band magnitudes at the two epochs of 13.6 and 14.3 mag based on the light curve in Valenti et al. (2008). The combined optical and mid-IR SED is well fit as a 5000 K blackbody with a luminosity of $10^{5.4} L_\odot$. If we look at the wavelength differenced 4.5 $\mu$m image from before the SN, there does appear to be excess emission, consistent with the presence of the stars having $K$-band excesses in Crockett et al. (2008), but with the resolution of Spitzer and the presence of bright stars just north and south of the site, we cannot say more.

5. DISCUSSION

The basic conundrum is simple. All possible surviving stars are far fainter than the progenitor in the optical. This requires significant visual optical depths so that most of the surviving star’s luminosity is re-radiated in the mid-IR. However, this opacity must be supplied by the material ejected during the transient, and dusty shells ejected at the low velocities of the LBV hypothesis and irradiated by a surviving star lead to mid-IR luminosities in gross conflict with the observational limits. The discrepancy is not a subtle problem, but a disagreement of an order of magnitude or more. The limits could be evaded by pushing the shell so far outward in radius that the dust temperature is too low to have significant emission in the 3.6–24 $\mu$m range, but this solution requires shell masses, velocities, and energies that are extreme even for a true SN. The simplest solution to these problems is that SN 1961V was in fact an SN and there is no surviving star.

To escape the conclusion that SN 1961V was an SN requires that an assumption about the properties of the star or its surrounding dust is greatly in error. We can enumerate three possibilities for changes in the stellar properties: (1) the system was (bolometrically) super-luminous for ~3 decades prior to the transient; (2) the surviving star has been (bolometrically) sub-luminous for the ~5 decades after the transient; and (3) there is no dust and the star now has a very high photospheric temperature, $T_\ast \sim 70,000$ to 100,000 K, so that the faintness of the survivor is entirely due to bolometric corrections. In cases (1) and (2), the change in bolometric luminosity must be an order of magnitude or more. In case (3), such a radical increase in photospheric temperature would have been accompanied by significant mass loss which would be hard to reconcile with the requirement for no dust. Deeper ultraviolet observations than the available Galaxy Evolution Explorer (GALEX) data would constrain this possibility. The remaining possibility is that the dust covering fraction is very small, less than 10%, with our line of sight coincidentally passing through one of the optically thick patches. The mid-IR emission is then reduced by the covering fraction. In this scenario we should still see the steady optical brightness created by an expanding shell modulo the caveat that this evolution can be modified by any simultaneous evolution of the luminosity or temperature of the surviving star. None of these possibilities seems terribly attractive or plausible.

If SN 1961V was an SN, then it becomes one of the rare SNe with observations of its progenitor star, and the only one with a relatively detailed pre-explosion light curve (see Smartt 2009). We know it was very luminous, $L_\ast \sim 10^{5.5} L_\odot$, and likely hot in quiescence following the arguments of Goodrich et al. (1989). Based on the emission line ratios reported by Goodrich et al. (1989) for the Western H II region (the Eastern H II region overlaps the region with SN 1961V and shows evidence for contamination by an SN remnant), we estimate an oxygen abundance of approximately 8.3 following Kewley & Ellison (2008) or approximately $\sim 1/3$ solar and similar to the metallicity of the LMC. This local measurement is a little lower than estimates of $\sim 1/2$ solar from the metallicity gradient measurements by Ferguson et al. (1998). If we select stars at the end points of the Padua (Marigo et al. 2008) isochrones with $10^6$, $L_\odot < L_\ast < 10^{6.5}$ and $20,000$ K $< T_\ast < 40,000$ K, they correspond to very massive stars, with $M_{\text{ZAMS}} > 80 M_\odot$ for all metallicities from LMC to solar.

These properties are very similar to those of the only other high-mass progenitor to be identified, that of SN 2005gj (Gal-Yam et al. 2007; Gal-Yam & Leonard 2009). For their measurements and parameters (a progenitor with $V = 20.04 \pm 0.15$ mag at 66 Mpc with $E(B - V) \sim 0.07$), this progenitor had a luminosity similar to that of SN 1961V, with $L_\ast \sim 10^{6.7} L_\odot$ for $T_\ast = 20,000$ K. Like SN 1961V it was a Type II, and it had a comparable peak luminosity, near $M_V \sim -17$ mag. Gal-Yam et al. (2007) and Gal-Yam & Leonard (2009) propose that the spectral properties of SN 2005gj are best explained by heavy mass loss or mass ejections closely correlated with the SN. In fact, there is growing evidence that pre-SN bursts of mass loss, while not common, are also not rare. The most remarkable case is the eruption observed two years prior to the peculiar Type Ib SN 2006jc (Pastorello et al. 2007), but the light curves of other SN show strong evidence for mass ejection episodes shortly before the SN (e.g., SN 2006gy, SN 2005ap, SN 2006ft, SN 2007va, see, e.g., Smith 2008; Kozlowski et al. 2010). The case of SN 2006jc may be particularly apt since the spectral evidence for excess helium (Branch & Greenstein 1971) suggests that SN 1961V was close to being a Type Ib rather than a Type IIn pec.

In this context, the complexities of the post-peak light curve are created by variations in the pre-peak mass-loss rate, and these variations may be signaled by the pre-peak variability. There is certainly no problem with the energetics of this scenario. The source of the luminosity is the shock heating of the CSM,

$$L_S = \frac{v_f^2}{2v_w} \epsilon \dot{M} \sim 10^{7.7} \left( \frac{\dot{M}}{10^{-2} M_\odot \text{yr}^{-1}} \right) \left( \frac{v_t}{4000 \text{ km s}^{-1}} \right)^3 \times \left( \frac{100 \text{ km s}^{-1}}{v_w} \right)^{\epsilon} \left( \frac{0.1}{L_\odot} \right),$$

(7)

where $\dot{M}$ is the mass-loss rate, $v_w$ is the wind velocity, $v_t$ is the shock velocity, and $\epsilon < 1$ is the radiative efficiency (e.g., Chugai & Danziger 1994). Alternatively, we can invert the relation

$$\dot{M} = \frac{2L_S v_w}{\epsilon v_f^2} \sim 10^{-3.7} \left( \frac{L_S}{10^6 L_\odot} \right) \left( \frac{4000 \text{ km s}^{-1}}{v_s} \right)^3 \times \left( \frac{v_w}{0.1 L_\odot \text{yr}^{-1}} \right),$$

(8)

to give the required mass-loss rate in terms of the shock luminosity. Figure 9 shows two possible histories of the mass loss based on Equation (8) and setting $L_S = \lambda L_\ast$ based on the light curve in Figure 1. The solution with very large $M$ is designed to produce the first post-peak plateau using mass loss from the pre-peak eruption. It uses a low shock velocity, $v_s = 4000$ km s$^{-1}$, a low efficiency, $\epsilon = 0.1$ and a fast wind $v_w = 500$ km s$^{-1}$ for the first plateau and a slower wind $v_w = 100$ km s$^{-1}$ for the second. The second, lower mass-loss model assumes there is no relation between the first plateau and the pre-peak eruption. It simply adopts the parameters Smith...
velocity is doubled (2) the upper profile is shifted if the efficiency is increased ($\epsilon$)

This solution uses a low shock speed, $v_s = 4000$ km s$^{-1}$, and wind speed of $v_w = 500$ km s$^{-1}$ for the first plateau, dropping to $v_w = 100$ km s$^{-1}$ for the second plateau, and an efficiency $\epsilon = 0.1$. The lower, low mass-loss solution assumes no correspondence between the pre-peak and post-peak light curve features and simply uses the Smith et al. (2009) parameters for SN 2005ip of $v_s = 10,000$ km s$^{-1}$, $v_w = 120$ km s$^{-1}$, and $\epsilon = 0.5$. The arrows indicate how the upper profile is shifted if the efficiency is increased ($\epsilon = 1$), if the shock velocity is doubled ($\epsilon v_s$) or if the wind velocity is reduced by an order of magnitude ($v_w/10$).

The mass-loss rates in the first model are $\dot{M} \simeq 10^{-2} M_\odot$ yr$^{-1}$ for the first plateau and $\dot{M} \simeq 10^{-3} M_\odot$ yr$^{-1}$ for the second. These are relatively small compared to the mass-loss rates of $\eta$ Carinae in its Great Eruption and comparable to its present-day mass-loss rate (Humphreys & Davidson 1994). The solution is driven to high $\dot{M}$ because it tries to make the timing of the first post-peak plateau match that of the pre-peak transient, and even here we have been generous and assumed we could make the transition around 1955 by taking advantage of the monitoring gap in that period. This then forces a relationship between the shock velocity and the wind velocity that $\Delta v_{\text{shock}} = \Delta v_{\text{wind}}$, where $\Delta v_{\text{pre}}$ and $\Delta v_{\text{post}}$ are the durations of the pre-peak and post-peak phases. To minimize the required $\dot{M} \propto v_s^{-2}(v_s/v_w)$ we want the highest possible shock velocity with the greatest possible ratio to the wind velocity. If the timing model that tries to produce the first post-peak plateau with the pre-peak eruption.

The other option is that any mass loss from the eruption was closer to the star, and shock luminosity contributions from the material were hidden by the far more luminous emission from the peak of the SN. Without the timing constraints between the eruption and the first plateau, the higher shock velocity and lower wind velocity of the SN 2005ip model, along with its higher estimate for the radiative efficiency, then produce the plateaus with far lower mass-loss rates. Here the mass-loss rates need only be $\dot{M} \simeq 5 \times 10^{-5} M_\odot$ yr$^{-1}$ and $\dot{M} \simeq 10^{-5} M_\odot$ yr$^{-1}$, respectively. This is more typical of the average mass-loss rates of such massive stars (Humphreys & Davidson 1994). The first plateau corresponds to a higher mean mass-loss rate starting around 1900, above an earlier increase that lasted several centuries. This scenario may be more plausible than the first.

Not only was the progenitor of SN 1961V massive, $M_{\text{ZAMS}} \gtrsim 80 M_\odot$, but it must also have been relatively massive at death. While appearing to be rich in helium (Branch & Greenstein 1971), it was still a Type II SN, rather than a Type Ib or Ic. We found no detailed pre-SN models for this mass and metallicity range, but it is in the regime that Heger et al. (2003) estimate would be weak Type Ib/c fall-back SNe leading to black hole formation. The solar metallicity models in Woosley et al. (2002) have already lost much of their helium to mass loss. For their low-metallicity models ($10^{-4}$ solar), the star would need to be more massive at death than $M \simeq 30 M_\odot$ in order to retain any hydrogen. If it was a fall-back SN forming a black hole (BH), SN 1961V was not notably sub-luminous. Alternatively, some massive stars may still form neutron stars (NSs), as suggested by the existence of a magnetar in Westerlund 1. The progenitor of this NS seems to require a >40 $M_\odot$ progenitor given the other massive stars in the cluster (Muno et al. 2006), unless it can be explained by binary evolution and mass transfer (Belczynski & Taam 2008). Since it takes virtually no mass to power accretion onto a $\sim 10 M_\odot$ black hole at the Eddington limit compared to the ejected mass, we might expect the newly formed BH to accrete at the Eddington limit for an extended period of time. However, Perna et al. (2008) found no X-ray emission from the site to a limit of $L_X < 6 \times 10^{37}$ erg s$^{-1}$ (2–10 keV) in 2000 March, corresponding to a limit of order 5% of Eddington.

Finally, the existence of other Type IIn SNe requiring major mass-loss events shortly before collapse changes our prior on the likelihood of such correlations for SN 1961V. Rather than being bizarre, it is simply the closest example, one which is so close that we could see the pre-SN activity. SN 1961V, SN 2005gl, and their relatives are all cases where the correlated mass loss is large and dramatic. We usually assume that stars are evolving quasi-statically in their last phases, with no indicators of imminent death, yet this clearly does not hold for this class of objects. It is an interesting question whether this phenomenon is limited to a special class of SN, as proposed by Gal-Yam et al. (2007), or that we presently only notice the most dramatic examples of a more ubiquitous phenomenon. In either case, it appears that studies of SN progenitors should evolve from simple attempts to obtain a single snapshot of the star to monitoring their behavior over their final years.

We thank John Beacom, Jos ´e Prieto, and Todd Thompson for discussions and comments, Rebecca Stoll for estimating the local gas phase metallicity, and Robert Soria and Rosalba Perna for providing a softer energy band X-ray flux limit.

---

\[ \text{Figure 9. Possible mass-loss histories. The upper, high mass-loss solution is a} \]
\[ \text{model that tries to produce the first post-peak plateau with the pre-peak eruption.} \]
\[ \text{This solution uses a low shock speed,} \quad v_s = 4000 \text{ km s}^{-1} \quad \text{and wind speed of} \]
\[ v_w = 500 \text{ km s}^{-1} \quad \text{for the first plateau, dropping to} \quad v_w = 100 \text{ km s}^{-1} \quad \text{for the} \]
\[ \text{second plateau, and an efficiency} \quad \epsilon = 0.1. \quad \text{The lower, low mass-loss solution} \]
\[ \text{assumes no correspondence between the pre-peak and post-peak light curve} \]
\[ \text{features and simply uses the Smith et al. (2009) parameters for SN 2005ip of} \]
\[ v_s = 10,000 \text{ km s}^{-1} \quad v_w = 120 \text{ km s}^{-1} \quad \text{and} \quad \epsilon = 0.5. \]
\[ \text{The arrows indicate how the upper profile is shifted if the efficiency is increased} \]
\[ \text{($\epsilon = 1$), if the shock velocity is doubled ($\epsilon v_s$) or if the wind velocity is reduced} \]
\[ \text{by an order of magnitude ($v_w/10$).} \]

---

\[ \text{With a similar limit of} \quad <2 \times 10^{37} \text{ erg s}^{-1} \quad \text{for the softer 0.3–8 keV band} \]
\[ \text{(R. Soria & R. Perna 2010, private communication).} \]
REFERENCES

Alard, C. 2000, A&AS, 144, 363
Alard, C., & Lupton, R. H. 1998, ApJ, 503, 325
Aretxaga, I., Benetti, S., Terlevich, R. J., Fabian, A. C., Cappellaro, E., Turatto, M., & della Valle, M. 1999, MNRAS, 309, 343
Barbon, R., Benetti, S., Cappellaro, E., Patat, F., Turatto, M., & Iijima, T. 1995, A&AS, 110, 513
Belczynski, K., & Taam, R. E. 2008, ApJ, 685, 400
Branch, D., & Cowan, J. J. 1985, ApJ, 297, L33
Bertola, F. 1964, Ann. Astrophys., 27, 319
Bertola, F. 1963, Contrib. Oss. Astrofis. Univ. Padova Asiago, 142, 3
Bertola, F. 1965, Contrib. Oss. Astrofis. Univ. Padova Asiago, 171, 3
Bertola, F. 1967, IBVS, 196, 1
Bertola, F., & Arp, H. 1970, PASP, 82, 894
Branch, D., & Cowan, J. J. 1985, ApJ, 297, L33
Branch, D., & Greenstein, J. L. 1971, ApJ, 167, 89
Chugai, N. N., & Danziger, I. J. 1994, MNRAS, 268, 173
Cifuentes, S., Casertano, S., & Paczyński, B. 1972, ApSoS, 13, 29
Cowan, J. J., Henry, R. B. C., & Branch, D. 1988, ApJ, 329, 116
Crockett, R. M., et al. 2008, ApJ, 672, L92
Daggett, J. B., & Branch, D. 1985, AJ, 90, 2303
Draicer, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Eck, C. R., Cowan, J. J., & Branch, D. 2002, ApJ, 573, 306
Elitzur, M., & Ivezic, Z. 2001, MNRAS, 327, 403
Fazio, G. G., et al. 2004, ApJS, 154, 10
Ferguson, A. M. N., Gallagher, J. S., & Wyse, R. F. G. 1998, AJ, 116, 673
Fesen, R. A. 1985, ApJ, 297, L29
Filippenko, A. V. 1997, ARA&A, 35, 309
Filippenko, A. V., Barth, A. J., Bower, G. C., Ho, L. C., Strickfellow, G. S., Goodrich, R. W., & Porter, A. C. 1995, AJ, 110, 2261
Gal-Yam, A., & Leonard, D. C. 2009, Nature, 458, 865
Gal-Yam, A., et al. 2007, ApJ, 656, 372
Goodrich, R. W., Stringfellow, G. S., Penrod, G. D., & Filippenko, A. V. 1989, ApJ, 342, 908
Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288
Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025
Humphreys, R. M., Davidson, K., & Smith, N. 1999, PASP, 111, 1124
Kochanek, C. S., & Szczygieł, D. M., Stanek, K. Z., Thompson, T. A., & Beacom, J. F. 2010, ApJ, 715, 1094
Klemola, A. R. 1986, PASP, 98, 464
Kochanek, C. S. 2009, ApJ, 707, 1578
Kozlowski, S., et al. 2010, ApJ, 722, 1624
Li, W., Filippenko, A. V., Van Dyk, S. D., Hu, J., Qiu, Y., Modjaz, M., & Leonard, D. C. 2002, PASP, 114, 403
Li, W., et al. 2011, MNRAS, 412, 1441
Marigo, P., Girardi, L., Bressan, A., Groenewegen, M. A. T., Silva, L., & Granato, G. L. 2008, A&A, 482, 883
Muno, M. P., et al. 2006, ApJ, 636, L41
Pastorello, A., et al. 2007, Nature, 447, 829
Pastorello, A., et al. 2010, MNRAS, 408, 181
Perma, R., Soria, R., Pooley, D., & Stella, L. 2008, MNRAS, 384, 1638
Prieto, J. L., Szczygieł, D. M., Kochanek, C. S., Stanek, K. Z., Thompson, T. A., Beacom, J. F., Garnavich, P. M., & Woodward, C. E. 2011, arXiv:1007.0011
Richmond, M. W., Treffers, R. R., Filippenko, A. V., & Paik, Y. 1996, AJ, 112, 732
Rieke, G. H., et al. 2004, ApJS, 154, 25
Rupen, M. P., van Gorkom, J. H., Knapp, G. R., Gunn, J. E., & Schneider, D. P. 1987, AJ, 94, 61
Ryder, S., Staveley-Smith, L., Dopita, M., Petre, R., Colbert, E., Malin, D., & Schlegel, E. 1993, ApJ, 416, 167
Salpeter, E. E. 1977, ARA&A, 15, 267
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schlegel, E. M. 1990, MNRAS, 244, 269
Semenov, D., Henning, T., Helling, C., Igner, M., & Sedlmayr, E. 2003, A&A, 410, 611
Silbermann, N. A., et al. 1996, ApJ, 470, 1
Smartt, S. J. 2009, ARA&A, 47, 63
Smith, N. 2008, Nature, 455, 201
Smith, N., Chornock, R., Li, W., Ganeshalingam, M., Silverman, J. M., Foley, R. J., Filippenko, A. V., & Barth, A. J. 2008, ApJ, 686, 467
Smith, N., Humphreys, R. M., & Gehrz, R. D. 2001, PASP, 113, 692
Smith, N., & Owocski, S. P. 2006, ApJ, 645, L45
Smith, N., et al. 2009, ApJ, 695, 1334
Smith, N., et al. 2010, MNRAS, submitted
Stockdale, C. J., Rupen, M. P., Cowan, J. J., Chu, Y.-H., & Jones, S. S. 2001, AJ, 122, 283
Utrobin, V. P. 1987, Sov. Astron. Lett., 13, 50
Valenti, S., et al. 2008, ApJ, 673, L155
van Dyk, S. D. 2005, in ASP Conf. Ser. 332, The Fate of the Most Massive Stars, ed. R. Humphreys & K. Z. Stanek (San Francisco, CA: ASP), 47
Van Dyk, S. D., Filippenko, A. V., Chornock, R., Li, W., & Challis, P. M. 2005, PASP, 117, 553
Van Dyk, S. D., Filippenko, A. V., & Li, W. 2002, PASP, 114, 700
Van Dyk, S. D., Peng, C. Y., Barth, A. J., & Filippenko, A. V. 1999, AJ, 118, 2331
Wagner, R. M., et al. 2004, PASP, 116, 326
Way, S. E., Heger, A., & Weaver, T. A. 2002, Rev. Mod. Phys., 74, 1015
Wright, E. L. 1980, ApJ, 242, L23
Zhang, T., Wang, X., Zhou, X., Li, W., Ma, J., Jiang, Z., & Li, Z. 2004, AJ, 128, 1857
Zwicky, F. 1964, ApJ, 139, 514

C.S.K., D.M.S., and K.Z.S. are supported by NSF grant AST-0908816. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA, and in part on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Institute. STScI is operated by the association of Universities for Research in Astronomy, Inc. under the NASA contract NAS 5-26555. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Facilities: Spitzer, HST