Luminous blue variable eruptions and related transients: diversity of progenitors and outburst properties

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ABSTRACT
We present new light curves and optical spectra for a number of extragalactic optical transients or ‘supernova impostors’ related to giant eruptions of luminous blue variables (LBVs), and we provide a comparative discussion of LBV-like giant eruptions known thus far. New data include photometry and spectroscopy of supernovae (SNe) 1999bw, 2000ch, 2001ac, 2002bu, 2006bv and 2010dn. SN 2010dn appears to be a carbon copy of SN 2008S and NGC 300-OT, whereas SN 2002bu shows spectral evolution from a normal LBV at early times to a twin of these cooler transients at late times. SN 2008S, NGC 300-OT and SN 2010dn appear to be special cases of a broader eruptive phenomenon where the progenitor star was enshrouded by dust, perhaps from a previous unseen eruptive episode. Evidence suggests that their progenitors have initial masses in the range 10–20 M⊙, extending the range of masses susceptible to the violent eruptive phenomenon below the canonical LBV mass range. Examining the full sample, SN impostors are characterized by strong photometric variability on a range of time-scales from a day to decades, potentially suffering multiple eruptions of the same source. The upper end of the luminosity distribution overlaps with the least-luminous core-collapse SNe, but in most cases a distinction can be made based on spectra. The low end of the luminosity distribution is far less well defined, and a distinction between LBV giant eruptions, S Doradus phases of LBVs, novae and possible eruptions of intermediate-mass stars is not entirely clear. We discuss observational clues concerning stellar winds or shocks as the relevant mass-loss mechanism, and we evaluate possible ideas for the physical mechanisms of outbursts, but there is still a great need for theoretical work on this problem. Although known examples of these eruptions are sufficient to illustrate their remarkably wide diversity in the peak absolute magnitude, duration, progenitor stars, outburst spectra and other observable properties, their statistical distribution is an area that will benefit greatly from current and upcoming transient surveys. Based on the distribution of these eruptive properties, we propose that the prototypical object SN 1961V was not a member of this class of impostors after all, but was instead a true core-collapse Type IIn SN that was preceded by a giant LBV eruption.

Key words: instabilities – stars: evolution – stars: massive – stars: mass-loss – supernovae: general – stars: winds, outflows.

1 INTRODUCTION
This paper investigates observations of transient phenomena known variously as luminous blue variable (LBV) eruptions, supernova (SN) impostors or other optical transients usually associated with massive stars. These are thought to be non-terminal eruptions or explosions (i.e. not core collapse) related to the extreme brightening events observed in LBVs, such as η Carinae (η Car), although the physical mechanism of the outbursts is not yet known. The naming convention is rather haphazard, with some earning official SN designations – only to be recognized later as ‘impostors’ – while others deemed unworthy are demoted to generic optical transients.

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at the time of discovery.1 When designated as SNe, their spectra are classified as Type II (Schlegel 1990; see Filippenko 1997 for a review) due to the strong, relatively narrow H I emission lines that arise from their sluggish winds or ejecta, typically moving at \( \lesssim 1000 \text{ km s}^{-1} \).

Only two of these events have been witnessed in our own Milky Way (MW) Galaxy,2 both being historical naked-eye transients: P Cygni erupted in AD 1600 and η Car suffered its so-called Great Eruption in the mid-19th century. While small in number, these nearby events have had an enormous influence on our understanding of the phenomenon, since their physical parameters are reasonably well constrained and we can verify that the stars survived the eruptive events. They are the only two outbursts where we can directly measure the total ejected mass; analysis of their spatially resolved circumstellar shells implies more than 10 M⊙ in the case of η Car (Smith et al. 2003b) and only about 0.1 M⊙ for P Cygni (Smith & Hartigan 2006). The radiated and kinetic energy in these events also differed by more than two orders of magnitude, so from just these two events we can already see a wide diversity among the eruptions of LBVs – a major theme in this paper.

Additional examples from nearby external galaxies are also known. SN 1954J was the eruption of the bright blue irregular variable V12 in NGC 2403 (Tammann & Sandage 1968; Smith, Humphreys & Gehrz 2001; Van Dyk et al. 2005), and the famously weird object SN 1961V was originally categorized as a Type V event (Zwicky 1964), but was later thought to be an extreme version of a non-terminal eruption a la η Car (Goodrich et al. 1989; Filippenko et al. 1995; see also Shklovsky 1968). Together with P Cygni and η Car, these four historical LBV giant eruptions have come to represent the class of SN impostors (Humphreys, Davidson & Smith 1999; Van Dyk 2005).3 The eclipsing binary HD 5980 [the most luminous star in the Small Magellanic Cloud (SMC)] and V1 in NGC 2366 both suffered eruptions in the mid-1990s, and over a dozen additional examples have been discovered in the past decade during the course of various SN searches. A list of these events is provided later in this paper.

LBVs are thought to be massive stars that are unstable because they have reached a point in their evolution where they are dangerously close to the classical Eddington limit, partly due to the core evolution and partly due to the mass-loss in preceding phases (see e.g. Smith & Conti 2008). It was suggested long ago that cool temperatures in the stellar envelopes may lead to an opacity-modified Eddington limit that may play a role in initiating the outbursts (Appenzeller 1986; Lamers & Fitzpatrick 1988), but further progress on the physical mechanism causing LBV eruptions has been slow to enter the referred literature. Most theoretical work on LBV eruptions so far has focused on the physics of driving powerful winds in quasi-steady state when a star exceeds the Eddington limit (e.g. Shaviv 2000; Owocki, Gayley & Shaviv 2004; Owocki & van Marle 2007; van Marle, Owocki & Shaviv 2008, 2009). With the high mass-loss rates required for LBV eruptions, the material must be optically thick and therefore continuum-driven or hydrodynamically launched, rather than line-driven (Smith & Owocki 2006; van Marle et al. 2008). For this reason, these super-Eddington (SE) continuum-driven winds are of interest as a potential mode of mass-loss at low metallicity (Smith & Owocki 2006). Although the underlying mechanism behind the increased luminosity remains unknown, the massive shells seen around many LBVs with nebular masses of a few to 20 M⊙, combined with the fact that these episodes appear to recur, argue that the episodic ejection of the H envelope in LBV eruptions is a dominant mode of mass-loss for massive stars (Smith & Owocki 2006). The traditional explanation for LBV eruption light curves in historical examples (e.g. Humphreys & Davidson 1994; Humphreys et al. 1999) has been that a massive star increases its bolometric luminosity output and then reaches or exceeds the classical Eddington limit; this initiates catastrophic mass-loss. Dust condensation in the ejected shell eventually obscures the star and causes the object to fade at visual wavelengths, although how dust forms in these outflows is not understood. Humphreys et al. (1999) suggested that these ‘giant eruptions’ differ from the more typical ‘S Doradus (S Dor) variability’ exhibited by LBVs in that their bolometric luminosity increases, whereas the visual brightening in a normal S Dor episode is thought to be a change in the bolometric correction at constant luminosity. The traditional view has been that LBVs should be relatively cool in their bright phases, exhibiting spectra similar to those of F-type supergiants (Humphreys & Davidson 1994). Modern observations are revealing that these and other characterizations of LBV eruptions, which are based on few examples, are not necessarily true for the class, and so our understanding of these events is still developing as we discover additional examples.

A qualitative shift in interpreting LBV giant eruptions came with the recent recognition that strong shock waves may also play a role in some of the outbursts. This became apparent following the discovery of very fast ejecta surrounding η Car (Smith 2008), but it had been suspected earlier based on the rough equipartition in the kinetic and radiated energy budgets of its 19th century giant eruption (Smith et al. 2003b). Smith (2008) suggested that we may expect to see X-rays or radio emission from some LBV eruptions and that this evidence for a shock would not necessarily implicate a core-collapse event. Since then, Dessart, Livne & Waldman (2010) have explored weak explosions as a possible mechanism for some SN impostor events, and additional observational evidence for an explosive component in LBV eruptions is accumulating. In particular, Smith et al. (2010a) proposed that the fast (\( \sim 5000 \text{ km s}^{-1} \)) ejecta seen in absorption in SN 2009ip may result from an explosion similar to that inferred for η Car and that shock excitation may be important in explaining some of the diversity among spectral properties of LBV eruptions (see also Foley et al. 2011). Preliminary reports of a high X-ray luminosity in the very recent LBV eruption SN 2010da (Immler, Brown & Russell 2010) may also suggest the influence of a shock, but this new object is still being studied.

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1 While none of these names is ideal, we tentatively prefer ‘LBV-like eruptions’, since it is based on an observationally established class of objects, while we remain cognizant of the possibility that LBV-like outbursts might also occur in cool (i.e. not blue) stars, like red supergiants (RSGs), or stars that are not necessarily the most massive. This paper attempts to provide a comparative study of the light curves and spectra for known examples of this class. One must also be careful to distinguish between ‘LBVs’ – which refers to a particular class of variable stars, not all of which have been observed to suffer a giant eruption such as that of η Car – and ‘LBV-like eruptions’, which refers to the temporary brightening event that resembles the giant eruptions observed in LBVs like η Car.

2 If V838 Mon is a similar type of event, then it would be the third example in our Galaxy.

3 As we argue in this paper, however, SN 1961V may be a true core-collapse Type II SN event. One day before the submission of this paper, we learned that C. Kochanek (2010, private communication) and collaborators simultaneously reached a similar conclusion about SN 1961V based on the absence of an expected mid-infrared (mid-IR) counterpart.
at the time of writing (see below). The influence of both shocks and SE winds on observations of LBV eruptions was discussed in detail by Smith et al. (2010a). Although shocks may play a role in a few cases, strong SE winds must operate in many of the LBV-like eruptions.

Another key development in our interpretation of these eruptions is that their progenitors may be substantially more diverse than previously recognized. SN 2008S and the 2008 optical transient in NGC 300 (hereinafter N300-OT) were similar in their observed properties to other SN impostors, but Prieto and collaborators (Prieto 2008; Prieto et al. 2008a; Thompson et al. 2009) discovered that their progenitors were faint and heavily obscured. While only upper limits were available for visual wavelengths, archival Spitzer data suggested IR luminosities of \( \lesssim 10^{4.5} \, L_\odot \) before the eruptions. If the progenitor stars were cool, their observed IR luminosities could be consistent with initial masses as low as 8–10 \( M_\odot \), suggesting the intriguing possibility that these eruptions might be associated with weak electron-capture SNe in extreme asymptotic giant branch (AGB) stars (Botticella et al. 2009; Thompson et al. 2009) or that they may be associated with obscured OH/IR stars (see also Khan et al. 2010a). On the other hand, if they were heavily obscured supergiant stars, their IR luminosities would imply initial masses of 10–20 \( M_\odot \) (Berger et al. 2009; Bond et al. 2009; Smith et al. 2009a, 2010a). Smith et al. (2010a) discussed this debate in detail, showing that the IR luminosity of N300-OT, for example, was quite similar to the progenitor luminosity of V12/SN 1954J. For the nearby case of N300-OT, at least, studies of the surrounding stellar population favour an initial mass of 12–25 \( M_\odot \) (Gogarten et al. 2009), apparently ruling out the low-mass option. In any case, the progenitors of SN 2008S and N300-OT were probably less massive than classical LBVs, which were thought to extend down to initial masses of only 20–25 \( M_\odot \) (Smith, Vink & de Koter 2004).

Initial masses below \( \sim 20 \, M_\odot \) for some of these events have rather profound implications for the larger class of LBV-like eruptions, because stars of this mass are not expected to approach or exceed the classical Eddington limit during the normal course of their post-main-sequence evolution. Together with the evidence for explosive shock waves described above, this seems to favour a deep-seated energy injection, rather than a runaway near-Eddington instability in the outer envelope. Furthermore, if being dangerously near the Eddington limit is not a necessary precondition for these eruptions after all, then the same (or a related) mechanism that drives giant eruptions of luminous stars, like \( \eta \) Car, might also operate in lower mass stars, perhaps even below 8 \( M_\odot \). In this context, relieved of the notion that LBV-like eruptions are exclusive to the most massive stars, it is prudent to explore the diversity in this class of non-terminal stellar eruptions. As the astronomical community embarks upon an era of more intensive transient studies, additional examples should illuminate and quantify the statistical distribution across this diverse range of properties.

In this paper, we collect examples of LBV-like giant eruptions known thus far, examining their light curves, spectra and several derived properties. In Section 2, we present some unpublished data on previous SN impostors as well as on some recent examples. In Section 3, we compile a list of known events and present their light curves and spectra, and we provide a detailed comparative discussion of their various observational properties. We explore the diversity of the sample and its implications for the physics behind these eruptions in Section 4. We also briefly discuss the overlap with transients that may be related but have not been considered as LBV eruptions so far, and we consider which objects should belong to the class.

### 2 NEW OBSERVATIONS

For new observational material on SN impostors, our data were collected as part of the Lick Observatory Supernova Search (LOSS; Filippenko et al. 2001; Filippenko 2003; Leaman et al. 2011; Filippenko, Li & Treffers, in preparation). Most of our photometry comes from the 0.76-m Katzman Automatic Imaging Telescope (KAIT) at the Lick Observatory, while our new spectra were obtained using the Kast spectrograph (Miller & Stone 1993) on the 3-m Shane reflector at Lick, or at the 10-m Keck telescopes with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995), or the Deep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003). During most of the spectroscopic observations, the slit was aligned along the parallactic angle to reduce differential light losses (Filippenko 1982). Details concerning the new data are given in subsequent sections. UT dates are used throughout this paper.

#### 2.1 New photometry

Optical photometry of the SN impostors was generally obtained with KAIT. Several objects were followed in multiple passbands (\( BVRI \)) soon after discovery. For some other objects, no dedicated follow-up campaign was initiated, but their host galaxies were monitored without using a filter during the course of our SN search, so we have unfiltered data of the eruptions as a byproduct. For the objects with \( BVRI \) photometry, we obtained calibrations of the fields by observing them together with several Landolt (1992) standard stars at various airmasses during photometric nights. Deep template images of the fields after the objects have faded beyond detection have also been obtained. These template images and calibrations were used in the KAIT photometry pipeline (Ganeshalingam et al. 2010) to perform image subtraction and calibration to the standard photometry system.

For the objects having only unfiltered data, we consider the derived magnitudes as being close to the \( R \) band (Li et al. 2003). Template images are constructed for each field by choosing the best monitoring data and then stacking them. For photometric calibration, we use the \( R \) magnitudes for the stars in the SN fields in the USNO B1 catalogue (Monet et al. 2003). Although the accuracy of this calibration is only \( \pm 0.2–0.3 \, m \) for an individual star, there are usually more than 10 stars available in each field, so the uncertainty due to calibration is \( \sim 0.1 \, m \). The data are then reduced in a manner similar to the KAIT photometry pipeline. The final photometry of the objects is listed in Tables 1–5 and the apparent light curves are shown in Fig. 1. We comment on each individual object below.

**SN 1999bw.** Unfortunately, SN 1999bw was not extensively observed by KAIT and the luminosity appears relatively constant over the \( \sim 10 \, d \) when it was observed. The apparent \( B - V \) colour at the time of the discovery is \( \sim 0.8 \, m \), suggesting either that the eruption was redder than a normal LBV or that it suffered significant circumstellar reddening.

#### Table 1. New photometry of SN 1999bw.

<table>
<thead>
<tr>
<th>JD</th>
<th>( B , m )</th>
<th>( V , m )</th>
<th>( R , m )</th>
<th>( I , m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>245 1289.69</td>
<td>19.27 \pm 0.14</td>
<td>18.45 \pm 0.06</td>
<td>17.99 \pm 0.07</td>
<td>17.60 \pm 0.10</td>
</tr>
<tr>
<td>245 1291.70</td>
<td>–</td>
<td>18.36 \pm 0.05</td>
<td>17.98 \pm 0.08</td>
<td>17.67 \pm 0.06</td>
</tr>
<tr>
<td>245 1292.69</td>
<td>–</td>
<td>18.39 \pm 0.14</td>
<td>17.87 \pm 0.12</td>
<td>17.69 \pm 0.13</td>
</tr>
<tr>
<td>245 1295.72</td>
<td>–</td>
<td>18.37 \pm 0.10</td>
<td>–</td>
<td>17.83 \pm 0.30</td>
</tr>
<tr>
<td>245 1298.72</td>
<td>–</td>
<td>18.33 \pm 0.08</td>
<td>17.82 \pm 0.08</td>
<td>17.72 \pm 0.11</td>
</tr>
</tbody>
</table>
it had faded by ~3 mag. The light curve of SN 2002bu shows an initial 10–20 d rounded peak, followed by a ‘hump’ (i.e. almost a plateau) with a subsequent slower rate of decline; qualitatively, this decline with a change in the decay rate resembles that of SN 1997bs (Van Dyk et al. 2000). The apparent colour reddens with time, from $B - V \approx 0.45$ mag at peak to ~0.8 mag at late times (Fig. 1), similar to the colour evolution of SN 2008S (Smith et al. 2009a). The colour evolution is substantially different from that of a normal Type II-P SN, never getting as red as Type II-P SNe and apparently becoming slightly blue again as the object fades. 

**SN 2003gm.** We obtained only two unfiltered KAIT measurements of SN 2003gm, including the discovery and one image 6 d later. Both were at 17.0 ± 0.1 mag; the limited light curve is not shown.

**SN 2006bv.** We obtained three unfiltered measurements of SN 2006bv with KAIT, as listed in Table 4 and shown in Fig. 1, where it has been shifted by ~2 mag for clarity of display. The peak occurred a few to 20 d after discovery. Unfortunately, no late-time measurements are available and we were not able to secure spectra of the eruption.

**U2773-OT.** We presented KAIT unfiltered photometry of this 2009 transient in UGC 2773 (hereinafter U2773-OT) in Smith et al. (2010a), but the transient has remained bright and even continued its slow rise in the years since then. Table 5 gives additional unfiltered KAIT photometry of this source, continuing after the last data point in the previous paper. See Smith et al. (2010a) for further details.

**SN 2010dn.** We obtained limited $BVRi$ photometry of SN 2010dn with KAIT and the 1.0-m Nickel telescope at Lick Observatory, as listed in Table 6 and plotted in Fig. 1(a). The rate of fading resembles that of other SN impostors during the observed time-interval, and the $B - V$ colour of ~0.5 mag is similar to that of SN 2002bu at early times (Fig. 1b).

### 2.2 Previously unpublished spectra

Table 7 gives a log of our new spectroscopic observations. All optical spectra were reduced using standard techniques (e.g. Foley et al. 2003). Routine CCD processing and spectrum extraction were completed with IRAF (Image Reduction and Analysis Facility), and the data were extracted with the optimal algorithm of Horne (1986). We obtained the wavelength scale from low-order
Table 6. New photometry of SN 2010dn.

<table>
<thead>
<tr>
<th>JD</th>
<th>B mag</th>
<th>V mag</th>
<th>R mag</th>
<th>I mag</th>
</tr>
</thead>
<tbody>
<tr>
<td>2455352.70</td>
<td>17.94 ± 0.03</td>
<td>17.52 ± 0.03</td>
<td>17.17 ± 0.02</td>
<td>16.84 ± 0.03</td>
</tr>
<tr>
<td>2455354.69</td>
<td>17.98 ± 0.04</td>
<td>17.51 ± 0.04</td>
<td>17.16 ± 0.02</td>
<td>16.88 ± 0.04</td>
</tr>
<tr>
<td>2455356.72</td>
<td>18.24 ± 0.21</td>
<td>17.53 ± 0.12</td>
<td>17.14 ± 0.06</td>
<td>16.79 ± 0.05</td>
</tr>
<tr>
<td>2455358.69</td>
<td>17.95 ± 0.08</td>
<td>17.61 ± 0.05</td>
<td>17.25 ± 0.03</td>
<td>16.92 ± 0.06</td>
</tr>
<tr>
<td>2455360.70</td>
<td>18.07 ± 0.04</td>
<td>17.71 ± 0.04</td>
<td>17.32 ± 0.02</td>
<td>16.97 ± 0.03</td>
</tr>
<tr>
<td>2455370.73</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2455374.71</td>
<td>18.66 ± 0.07</td>
<td>18.03 ± 0.04</td>
<td>17.56 ± 0.03</td>
<td>—</td>
</tr>
</tbody>
</table>

rather noisy. It shows strong, relatively narrow Balmer emission lines characteristic of LBVs. The Hα line has a Lorentzian shape with the full width at half-maximum (FWHM) ≈ 630 km s⁻¹, but broad wings extend to roughly ±3000 km s⁻¹ in our data. This could be due to electron scattering, but it may also suggest that some of the mass is moving rather fast, similar to SN 2009ip (Smith et al. 2010a) and η Car (Smith 2008). No P Cygni absorption is seen at this low resolution in Hα. Aside from Hβ, no other emission features are seen in this wavelength range, but Na i D absorption is present.

SN 2000ch. The light curve and spectra of SN 2000ch were already discussed in detail by Wagner et al. (2004). However, we obtained an additional high signal-to-noise ratio (S/N), late-time spectrum after that paper was published. The new spectrum of SN 2000ch in Fig. 2 was obtained ~4 yr after the discovery, on 2004 April 26, using the Lick 3-m reflector. Even at this late time, the spectrum still shows relatively broad (FWHM ≈ 1500 km s⁻¹), strong Balmer emission lines as well as prominent triplet He i lines and even He II λ4686. O i λ8446 is also visible. The Balmer lines have strengthened relative to the continuum, with about twice the equivalent width (EW) compared to day 28. In the 2004 spectrum, we can now see clear P Cygni absorption features in the higher order Balmer lines.

This new, late-time spectrum is now quite valuable, because Pastorello et al. (2010) recently reported the discovery of multiple subsequent eruptions of the same star that produced SN 2000ch, but much later in 2008 and 2009. According to their photometry, our 2004 spectrum showing a very strong Hα line with an emission EW of 461 Å was obtained at relative quiescence, about halfway between the 2000 and 2008 eruptions. It suggests that the wind speed during quiescence is similar to that during the eruptive states. Most of the same spectral features (e.g. He i emission lines) are also seen in spectra of the subsequent outbursts, although the He i and He II lines appear to weaken at some epochs during outburst phases (Pastorello et al. 2010).

SN 2001ac. The visual spectrum of SN 2001ac has a blue continuum and narrow Balmer emission lines typical of LBVs. The spectra are rather noisy, so we cannot comment on many details. One interesting aspect is that over a relatively short time-period of about a week, between days 9 and 17, the prominent and broad emission feature near 5800 Å disappears. This could be a blueshifted emission line of He i λ5876 from some hot and fast ejecta seen at early times, but this is speculative with such a noisy spectrum. After this broad emission fades, the spectrum closely resembles that of SN 1999bw. As in many LBVs, the Hα line in SN 2001ac exhibits a composite profile, with a narrow core that can be approximated with a Gaussian FWHM ≈ 287 km s⁻¹ on day 9, but also with a broader base that can be fitted with a Gaussian with FWHM ≈ 1505 km s⁻¹ and extending to roughly ±1500 km s⁻¹ at the continuum level. The emission-line EW on day 9 is 46 Å. The day 17 Hα...
Table 7. New spectroscopy of SN impostors.

<table>
<thead>
<tr>
<th>Transient</th>
<th>UT date</th>
<th>Day</th>
<th>Telescope/instrument</th>
<th>Range (Å)</th>
<th>λ/Δλ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 1999bw</td>
<td>1999 April 24</td>
<td>4</td>
<td>Lick/Kast</td>
<td>4300–7000</td>
<td>700</td>
</tr>
<tr>
<td>SN 2000ch</td>
<td>2004 April 26</td>
<td>1456</td>
<td>Keck/LRIS</td>
<td>3300–9400</td>
<td>1000</td>
</tr>
<tr>
<td>SN 2001ac</td>
<td>2001 March 21</td>
<td>9</td>
<td>Lick/Kast</td>
<td>3300–7830</td>
<td>700</td>
</tr>
<tr>
<td>SN 2001ac</td>
<td>2001 March 29</td>
<td>17</td>
<td>Keck/LRIS</td>
<td>4350–6860</td>
<td>1000</td>
</tr>
<tr>
<td>SN 2002bu</td>
<td>2002 April 8</td>
<td>11</td>
<td>Lick/Kast</td>
<td>3300–10400</td>
<td>700</td>
</tr>
<tr>
<td>SN 2002bu</td>
<td>2002 April 20</td>
<td>23</td>
<td>Lick/Kast</td>
<td>3300–10400</td>
<td>700</td>
</tr>
<tr>
<td>SN 2002bu</td>
<td>2002 May 7</td>
<td>40</td>
<td>Lick/Kast</td>
<td>3300–10400</td>
<td>700</td>
</tr>
<tr>
<td>SN 2002bu</td>
<td>2002 June 8</td>
<td>72</td>
<td>Lick/Kast</td>
<td>3100–10400</td>
<td>700</td>
</tr>
<tr>
<td>SN 2002bu</td>
<td>2002 June 17</td>
<td>81</td>
<td>Lick/Kast</td>
<td>3100–10400</td>
<td>700</td>
</tr>
<tr>
<td>SN 2010dn</td>
<td>2010 June 8</td>
<td>9</td>
<td>Lick/Kast</td>
<td>3430–10260</td>
<td>700</td>
</tr>
<tr>
<td>SN 2010dn</td>
<td>2010 June 11</td>
<td>12</td>
<td>Keck/DEIMOS</td>
<td>6101–7410</td>
<td>4400</td>
</tr>
<tr>
<td>SN 2010dn</td>
<td>2010 June 18</td>
<td>19</td>
<td>Lick/Kast</td>
<td>3510–9920</td>
<td>700</td>
</tr>
<tr>
<td>SN 2010dn</td>
<td>2010 November</td>
<td>159</td>
<td>Keck/LRIS</td>
<td>3662–7634</td>
<td>1000</td>
</tr>
</tbody>
</table>

Figure 2. Optical spectra of SN impostors obtained with the Lick 3-m reflector (see Table 7); in each case, the number of days after discovery of the transient is given. The day 28 spectrum of SN 2000ch was published by Wagner et al. (2004), but the others were previously unpublished. SN 1999bw on day 4 is a fairly noisy spectrum dominated by Balmer lines. The late-time spectrum of SN 2000ch obtained about 4 yr after discovery shows changes from the earlier spectrum and covers a wider wavelength range. The two spectra of SN 2001ac on days 9 and 17 show interesting evolution over a short time; the broad He I λ 5876 line disappears and the Balmer lines fade.
Figure 3. Previously unpublished Lick 3-m Shane spectra of SN 2002bu on days 11, 23, 40, 72 and 81. The continuum reddens with time and the Balmer emission-line EWs become stronger as the continuum fades. The FWHM in km s\(^{-1}\) (plus either ‘G’ for Gaussian or ‘L’ for Lorentzian) and the EW in Å of H\(\alpha\) are listed next to the emission line for each epoch. (In this paper, for simplicity, we list emission-line EWs as positive numbers, contrary to the normal convention; no absorption-line EWs were measured.) The spectrum transitions from a ‘hot’ LBV at early times to a ‘cool’ LBV at late times, with the red [Ca II] doublet and the IR Ca II triplet strengthening, while Ca II H&K go from absorption to emission. The blue tracing at the bottom is the day 11 spectrum plotted over the last day 81 spectrum to emphasize the changes in the continuum shape and line intensities. The orange curves show blackbodies. All epochs have been dereddened by the same value of \(E(B-V) = 0.012\) mag (i.e. correcting for Galactic reddening, but not any additional reddening that may be local, so the blackbody temperatures shown are lower limits).

The most remarkable aspect of the spectrum of SN 2002bu is its evolution over time. As the transient fades during the first ~80 d, the continuum becomes substantially redder, while emission lines from the [Ca II] doublet and the Ca II IR triplet strengthen relative to the continuum. Ca II H&K transition from strong absorption features at early times to narrow emission features at late times, and a more complex absorption spectrum is evident in the last two epochs on days 72 and 81. Additionally, the H\(\alpha\) line (Fig. 4) shows a change from a Lorentzian profile for the first three epochs, similar to SN 2009ip (Smith et al. 2010a), to a more Gaussian profile with an asymmetric shape. The red wing of H\(\alpha\) appears to weaken at late times, perhaps indicating the blueshift of lines that results when new dust forms and blocks emission from receding parts of the ejecta or the circumstellar medium (CSM) interaction region, as seen in some Type IIn SNe (see e.g. Smith et al. 2009b). Given the dusty shells resolved around Galactic LBVs, like \(\eta\) Car, dust formation in an eruptive event would not be surprising, although direct evidence for it has been scant so far.

In the last spectrum on day 81, the continuum cannot be fitted with a single blackbody. At \(\lambda < 7000\) Å it appears to be well fitted by a 5500-K blackbody, but in this case the excess emission at longer wavelengths is significant.
wavelengths implies an IR excess, perhaps due to emission from hot dust. The IR excess could be caused by newly formed dust or an IR echo (or both; Smith et al. 2009b; Fox et al. 2010), but formation of new dust is consistent with the Hα line-profile evolution. Interestingly, we note that Thompson et al. (2009) reported the detection of a mid-IR source in archival Spitzer images at the approximate position of SN 2002bu. From the limited Infrared Array Camera (IRAC) and Multi-band Imaging Photometer for Spitzer (MIPS) data obtained 2 and 6 yr after the outburst, respectively, Thompson et al. (2009) could not confirm that it was indeed a detection of SN 2002bu at late phases. Taken together with our spectral evidence for dust formation, however, this mid-IR source seems at least consistent with the hypothesis that substantial dust formed in this event.

Overall, the observed spectral changes signify a transition from a spectrum that at early times resembles hot SN impostors with smooth continua and strong Balmer lines, like SN 1997bs and SN 2009ip, to one that at late times looks cooler and develops the strong [Ca ii] lines seen in SN 2008S and NGC 300-OT. Smith et al. (2010a) discussed the dichotomy of these ‘hot’ and ‘cool’ spectra in various LBVs, but here in SN 2002bu we see them both in the same object over time. A transition such as this could be quite common among LBVs, since so far, few SN impostors have good spectral coverage as the objects fade during a major eruption. For example, there is only one spectrum on day 2 available for SN 1997bs (Van Dyk et al. 2000), to which the spectra of SN impostors are often compared. This provides yet another link in observed properties between LBVs and the unusual transients with obscured progenitors, SN 2008S and NGC 300-OT (see Smith et al. 2010a for further discussion of this link). A more inclusive comparison of the spectra of several LBVs is provided later in this paper.

The detailed evolution of the Hα line in SN 2002bu is interesting (Fig. 4). From day 11 to 23 the line becomes slightly narrower and weakens relative to the continuum, showing a Lorentzian profile at both epochs (this change is real, since both observations were obtained with identical observing configurations). The day 40 profile is transitional; it has about the same relative strength as on day 23, but is now somewhat broader and slightly asymmetric, with a developing hump on its blue side. By the last two epochs, substantial changes are apparent; the line now has a more Gaussian profile shape and is broader, with FWHM ≈ 1200 km s\(^{-1}\), and it seems to be more asymmetric or blueshifted. It is intriguing that this progressive blueshift might be evidence for dust formation, as noted above. Hβ also seems to have developed blueshifted P Cygni absorption features at −3500 km s\(^{-1}\) in the last two epochs, similar to SN 2009ip (Smith et al. 2010a; Foley et al. 2011), although these might instead be due to some other absorption feature. Hβ also seems to develop stronger, broad, blueshifted absorption, but it is at a different velocity. Higher resolution spectra of this transient would have been valuable.

SN 2010dn. We illustrate spectra of SN 2010dn in Fig. 5. Moderate-resolution spectra obtained with the Kast spectrograph at Lick Observatory on days 9 and 19 after the discovery are shown in Fig. 5(a), where they are compared with the nearly identical spectrum of SN 2008S from Smith et al. (2009a) that was obtained with the same instrument. Both objects exhibit strong narrow [Ca ii] and Ca ii emission, in addition to the Balmer emission lines. The overall continuum shape and weak spectral features in the blue are also remarkably similar in both objects. In fact, spectroscopically, SN 2010dn is a near twin of both SN 2008S and N300-OT at early times. A 6900-K blackbody function is illustrated in orange for comparison with the blue continuum shape of SN 2010dn on day 9. On days 9 and 19, we measure Hα emission-line EWs of 31.5 and 26.7 Å (±2 Å), respectively, in the Lick spectra.

A late-time spectrum obtained on day 159 with Keck/LRIS is also shown in Fig. 5(a). The Hα emission EW has increased to 615 ± 30 Å at this late epoch, mainly because the continuum has faded. This behaviour is similar to that of SN 2008S and N300-OT as well (Berger et al. 2009; Bond et al. 2009; Smith et al. 2009a). Although Na i D is seen as very weak absorption at early epochs, the late-time LRIS spectrum in Fig. 5(a) shows Na i D as a strong narrow emission feature on day 159 (this is probably not He i λ5876, since He i λ6680 and λ7065 are undetected). A similar transition from Na i D absorption to emission at late times was also seen in the day 270 spectrum of SN 2008S (Smith et al. 2009a).

We obtained a high-resolution spectrum of SN 2010dn on day 12 after discovery using DEIMOS at Keck-II (Fig. 5b); it exhibits Hα and the [Ca ii] doublet. Velocity profiles of Hα and λ7291 are shown in Fig. 6. Most of the Hα flux can be accounted for with a broad Lorentzian profile having FWHM ≈ 860 km s\(^{-1}\), as demonstrated in Fig. 6(a), but there is also excess emission from a narrow component on top of this profile. Qualitatively, the mostly Lorentzian profile with a small contribution from very narrow emission closely resembles that of the Type IIn SN events SN 1998S and SN 2006gy at early times (Chugai 2001; Smith et al. 2010b); this was thought to be indicative of the diffusion of radiation through an opaque circumstellar envelope or slow wind. In the day 12 spectrum taken with DEIMOS, we measure an Hα emission-line EW of 38.6 Å (±2 Å).

Superposed on this intermediate-width Lorentzian profile is a much narrower Hα emission line. The latter component has the same profile as the narrow emission seen in the pair of [Ca ii] lines, illustrated in Fig. 6(b); the [Ca ii] lines show the narrow profile better because they are free from the underlying broad profile. These narrow components have FWHM values of roughly 110–120 km s\(^{-1}\),
but they are asymmetric, with a very steep drop on the blue side of the line. The red wing has a Lorentzian shape that would imply FWHM = 155 km s$^{-1}$ if it were symmetric, so perhaps this is a better indicator of the expansion speed of the emitting circumstellar gas. These narrow [Ca II] profiles are qualitatively identical to those of the same lines in N300-OT, which also showed asymmetric profiles with a Lorentzian red wing and a steep cut-off on the blue side, with very similar widths of 140–190 km s$^{-1}$ at early times (Berger et al. 2009). Similar profiles were seen in other lines such as [O I] $\lambda\lambda 6300, 6364$ in N300-OT as well (Berger et al. 2009), and we see the same profile in the narrow component of H$\alpha$ in SN 2010dn, so we infer that the shape is not the result of some peculiar excitation/ionization effect unique to Ca$^{+}$.

So far, N300-OT and SN 2010dn are the only SN impostors with comparable high-resolution spectra available for these [Ca II] lines, so their nearly identical asymmetric profiles are intriguing. The shape of these asymmetric forbidden lines has not been explained, but suggests either an intrinsically asymmetric distribution of emitting gas oriented the same way in both objects or the dust obscuration of the blue wing with a particular geometry.

### 3 COMPARATIVE RESULTS

#### 3.1 Comments on individual events

Here we briefly list relevant observational material for suspected members of the class of LBV-like eruptions, collected from the literature for the purposes of this discussion (see Table 8). When published analyses exist, we refer to those papers and adopt the same assumptions except where noted. For new observational material, our data were collected as part of LOSS, as noted above. In most cases below, we adopt distance moduli from NED\(^4\) and we take line-of-sight Galactic extinction values of $E(B-V)$ from Schlegel, Finkbeiner & Davis (1998). Two of the transients listed below were discovered recently; we list them here and provide some initial details for completeness, but cannot yet comment on their late-time behaviour since they are still being studied.

**P Cygni.** Although famous for its namesake line-profile shape, P Cygni is also notable as the first known LBV, and for being only

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\(^4\) http://nedwww.ipac.caltech.edu/
The complex light curve of η Car has a long history of discussion that will not be repeated here (see Frew 2004). A very recent study by Smith & Frew (2011) recovered many new historical observations from the 19th century and uncovered some mistakes in earlier works going back to Herschel’s original reports. The new light curve of Smith & Frew (2011) looks substantially different in detail from previously published and often reproduced light curves of η Car (e.g. Innes 1903; see Frew 2004 for a thorough discussion of the historical data), and the Smith & Frew light curve is used here (Figs 7 and 8). The main phase of the Great Eruption began at the close of 1844, when the star brightened to ~14.0 mag, after which the star declined slowly for ~10 yr. Before that, however, the star suffered two shorter duration bursts in 1838 (~13.5 mag) and 1843 (~13.8 mag), each of which lasted only ~100 d. Again, we do not know what the spectrum looked like during the 1840’s eruption, but reports of its red or ‘ruddy’ colour probably indicate strong Hα emission. [Smith & Frew (2011)] estimate $B - V = 1.3 - 1.6$ mag during the eruption.] Following another smaller eruption in ~1890, the star is apparently still slowly recovering from the upheaval of its 19th-century eruptions (e.g. Smith et al. 2003a; Davidson et al. 2005). The 1890 eruption was probably much more luminous than it looked, since the star is thought to have been buried in ~4 mag of visual extinction at that time (Humphreys et al. 1999). The light curve of the 1890 event is also shown in Fig. 7, with a correction for this extinction applied.

Based on the kinematics of the bipolar Homunculus nebula, the polar expansion speed for the bulk of the matter ejected in the major eruption was 650 km s$^{-1}$, dropping to values as low as 40 km s$^{-1}$ at the pinched equatorial waist (Smith 2006). However, deep spectroscopy of the surroundings outside the Homunculus nebula reveals that the 19th-century eruption also ejected a small amount of extremely fast material moving at ~5000 km s$^{-1}$, probably requiring a strong shock wave during the event (Smith 2008). A smaller bipolar nebula called the Little Homunculus is growing inside the larger one (Ishibashi et al. 2003) and its kinematics suggest that it was ejected in the smaller 1890 event (Smith 2005). Both the kinematics of the Little Homunculus and historical spectra obtained during the 1890 event suggest an ejection speed of ~200 km s$^{-1}$ for that event (Whitney 1952; Walborn & Lilley 1977; Smith 2005).

SN 1954J/V12. This LBV outburst in NGC 2403 was well observed photometrically by Tammann & Sandage (1968), although no spectra of the outburst are available. The massive star was clearly an irregular blue variable star (V12) for a decade before the peak of its giant eruption in 1954 and the star apparently survived the event as a faint reddened star (Smith et al. 2001; Van Dyk et al. 2005). A spectrum obtained by Van Dyk et al. (2005) in 2002 November revealed a narrow Hα profile suggesting an expansion speed of ~700 km s$^{-1}$, although the expansion speed during the peak of the eruption is not known since spectra during the event are not available (in the case of η Car, however, it is reassuring that the present-day wind speed is similar to that of the Homunculus nebula; Smith 2006). As with the case of P Cygni, a brief peak in the light curve with a brighter maximum might have been missed due to a relatively long gap in the observations just before the recorded peak (Tammann & Sandage 1968).

SN 1961V. SN 1961V was discovered by Wild (1961). Of all the ‘SN impostors’, this object is one of the most controversial, due to its very high luminosity ($M_V$ at peak was almost ~18 mag) that blurs any clear distinction between real core-collapse Type IIn SNe and LBV-like eruptions, if it is indeed an LBV. Whether a surviving star is detected is key, but this question has advocates on both sides (Goodrich et al. 1989; Filippenko et al. 1995; Van Dyk, Filippenko

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**Figure 6.** Velocity profiles of (a) Hα and (b) [Ca II] λ7291 from the day 12 Keck/DEIMOS spectrum of SN 2010dn. [Ca II] λ7323 can also be seen at the right-hand side. Symmetric Lorentzian profiles with FWHM = 860 and 155 km s$^{-1}$, respectively, are also shown for comparison in orange.

The third variable star discovered – after Tycho’s SN and Mira. (It was of course not referred to as an LBV at the time, but was called a nova.) Despite the excitement it generated at the time, there are only sparse observations of its AD 1600–1665 eruption, with only a handful of surviving reports during the main light-curve peak that lasted ~10 yr (see Fig. 7; from Smith & Frew 2011). These historical observations are valuable for recording the long-time-scale variability of P Cygni, but the sparse sampling suggests that if there had been short-time-scale variation as exhibited by many other LBV eruptions around the peak, then it could easily have been missed. Thus, a brief unobserved peak could have been more luminous than the several-year sustained peak of the eruption, which had an absolute magnitude of roughly −11 (according to Lamers & de Groot 1992). Most of the observations were made with the newly invented telescope and a typical value for their uncertainty is ±0.2–0.3 mag, although the quality of observations may vary considerably from one epoch to another (see Smith & Frew 2011). These are visual (i.e. unfiltered) observations, converted approximately to the modern V band based on the likely colour of LBV outbursts, although this is uncertain and depends on the reddening and the strength of Hα. The spectrum during the outburst was not recorded, of course.

P Cygni also suffered a second major outburst in 1655 (dashed lines in Fig. 7) that reached a peak almost as bright as the first, with an absolute visual magnitude of roughly −10.5 mag. After this second outburst, P Cygni faded and remained faint for several decades, but then brightened suddenly around 1700. It has been relatively tame and brightening only very slowly since then. From modern observations of its shell nebula, we can infer that the dominant expansion speed of the AD 1600 eruption was about 136 km s$^{-1}$ (Smith & Hartigan 2006).
This remarkable Wolf–Rayet (WR) star plus LBV eruption were observed in spectra obtained during the main eruption. (Koenigsberger et al. 1998). The eruption of this star has apparently taken about a decade to settle back to its pre-outburst state; a recent study by Koenigsberger et al. (2010) finds the same spectral evolution as the main peak during the primary outburst that lasted almost 1 yr, the average wind terminal speed of 300 km s$^{-1}$.

A recent review of the spectral and photometric properties of the dwarf irregular galaxy NGC 2366. Its eruption began when it suffered a giant LBV eruption around 1993–94, at which time the dwarf irregular galaxy NGC 2366 within the dwarf irregular galaxy NGC 2366. Its eruption began when the star brightened rapidly in 1994 and it seems to have stayed near maximum light ever since (see Fig. 7). Interestingly, while the visual magnitude remained roughly constant at $M_V \approx –10.2$ mag during this time, the ultraviolet (UV) flux actually brightened and the temperature increased by spectral analysis increased (Petit et al. 2006). As with HD 5980, this once again contradicts the traditional view of pseudo-photospheres in LBV eruptions having an F-type supergiant expected in LBV eruptions. This turns out to be the case for a number of SN impostors, including V1 (Drissen et al. 2001), SN 2000ch and SN 2009ip (Smith et al. 2010a); we will return to these ‘hot’ LBV eruptions later. The wind speed of the erupting component of the binary system was estimated to be 600 km s$^{-1}$ (Koenigsberger et al. 1998).

Table 8. List of SN impostors considered here.

<table>
<thead>
<tr>
<th>Transient</th>
<th>Host galaxy</th>
<th>Date</th>
<th>Mag (peak)</th>
<th>$\alpha$, $\delta$ (J2000)</th>
<th>Discoverer</th>
<th>Reference</th>
</tr>
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<td>P Cygni</td>
<td>MW</td>
<td>1600–55</td>
<td>2.8</td>
<td>(h m s), (° ' '')</td>
<td>Blaau</td>
<td>[1]</td>
</tr>
<tr>
<td>$\upsilon$ Car</td>
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<td>Herschel</td>
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<td>17.4</td>
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<td>Drissen et al.</td>
<td>[6]</td>
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<td>10 19 46.81, +35 11 31.0</td>
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<td>This work</td>
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<td>NGC 3432</td>
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<td>10 52 41.40, +36 40 08.5</td>
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<td>Puckett &amp; Gauthier</td>
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</tr>
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<td>00 54 36.16, –37 28 26.8</td>
<td>Monard</td>
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<td>22 23 08.26, –28 56 52.4</td>
<td>Maza, Pignata et al.</td>
<td>[14]</td>
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<td>10 18 19.89, +41 26 28.8</td>
<td>Itagaki</td>
<td>This work</td>
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Figure 7. Long-time-scale LBV light curves, adapted from Smith et al. (2010a). These are absolute-magnitude light curves of LBV eruptions for cases where information is available over long (i.e. decade) time-scales, including observations before the main eruptions. We show the historical 19th-century Great Eruption of η Car from Smith & Frew (2011; grey), as well as the 1890 outburst corrected for 4 mag of visual extinction (brown). We also include the pair of eruptions of P Cygni in AD 1600 (green diamonds; solid lines) and AD 1655 (green diamonds; dashed line) (see Smith & Frew 2011, and references therein). The eruption of SN 1954J (V12 in NGC 2403; Tammann & Sandage 1968) is indicated as a grey shaded plot. The absolute magnitude of SN 1961V corrected for $A_B = 0.26$ mag is shown with the small filled squares, compiled from the photometry in Zwicky (1964), Bertola (1963, 1965) and Bertola & Arp (1970). The thick orange curve is the LBV eruption of V1 in NGC 2366 (Drissen et al. 2001; Petit et al. 2006), although shifted to an arbitrary date. The magenta curve is for the eruption of HD 5890 in the SMC during 1993–1994 (from Jones & Sterken 1997). We also show the decade-long pre-eruption light curves from the recent transients SN 2009ip (black filled circles) and U2773-OT (blue stars) from Smith et al. (2010a). Unfiltered visual magnitudes are given for η Car and P Cygni, B magnitude for SN 1954J, photographic (approximately $B$-band) for SN 1961V, V magnitudes for V1 and HD 5980, and unfiltered (approximately $R$-band) magnitudes for SN 2009ip and U2773-OT. Although these are different filters, our multiband photometry of SN 2002bu shows that the V- and R-band light curves are almost identical in shape.

SN 1999bw. We discovered SN 1999bw in KAIT images of NGC 3198 taken as part of LOSS on 1999 April 20.2 (Li 1999), and the early-time spectrum revealed that it was similar to SN 1997bs (Filippenko, Li & Modjaz 1999). As noted earlier, Hα in our day 2 spectrum can be approximated by a Lorentzian profile with FWHM $\approx 630$ km s$^{-1}$, with a broader base having a full width near zero intensity of $\sim 3000$ km s$^{-1}$. Sugerman & Meixner (2004) reported the detection of SN 1999bw in archival IR data obtained in 2004 with the Spitzer Space Telescope, but no detailed follow-up study has been performed. A single spectrum of SN 1999bw was published by Matheson (2005). We obtained limited BVRI and unfiltered photometry of SN 2009ip with KAIT, as listed in Table 1. We procured a Lick/Kast spectrum during the initial peak, listed in Table 7 and shown in Fig. 2. We adopt $m - M = 30.42$ mag for the host galaxy NGC 3198, and $E(B - V) = 0.012$ mag. This suggests that SN 1999bw had a peak absolute R magnitude of about $-12.65$, intermediate between those of P Cygni and η Car. Post-outburst upper limits from HST imaging in 2001, 2006 and 2008 show that the source faded by at least 6 mag at very late times (see Appendix A1).

SN 2000ch (LBV1 in NGC 3432). Observations of SN 2000ch were discussed in detail by Wagner et al. (2004; see also Van Dyk ...
Figure 8. Similar to Fig. 7, but zooming in on the time around peak brightness for several eruptive transients. In addition to the light curves repeated from Fig. 7, we add the V-band light curve of SN 1997bs (Van Dyk et al. 2000; brown dotted), the R-band light curves of SN 2000ch (Wagner et al. 2004; green), SN 2002bu (this work; purple dots), SN 2002kg (Van Dyk et al. 2006; blue), N4656-OT (orange line and orange dots; see text), SN 2008S (Smith et al. 2009a; yellow dots) and NGC 300-OT (Bond et al. 2009; red squares and dashed line), and the I-band light curve of SN 2003gm (Maund et al. 2006; green/black dashed line). For comparison with a normal Type II-P event, we also show the R-band light curve of SN 1999em (Leonard et al. 2002; thick grey curve). We include both the 1837 (solid grey curve) and 1843 (dot–dashed darker grey curve) precursor eruptions of η Car (Smith & Frew 2011).

2005), showing that it had a spectrum similar to that of SN 1997bs with a smooth continuum and bright Balmer emission lines. Its light curve was quite different, however, with a sharp rise and dip over a time-scale of ∼5 d, superposed on a relatively constant plateau. The peak absolute R magnitude was −12.8, and the plateau at roughly −10.6 mag may have been either the quiescent state of a very luminous star or a prolonged S Dor-like eruption. The R light curve from Wagner et al. (2004) is shown in Fig. 8. We obtained additional spectra at Lick, as listed in Table 7 and shown in Fig. 2. The spectrum during the outburst (day 28) has a strong Hα emission line with a Lorentzian profile shape and a FWHM of 1400 km s$^{-1}$. The line is somewhat asymmetric, with a blue wing extending to −2500 km s$^{-1}$ and the red wing reaching +4300 km s$^{-1}$. In our late-time spectrum from 2004 discussed above, the Hα linewidth was similar, with FWHM ≈ 1500 km s$^{-1}$.

As this paper was in the final stages of preparation, Pastorello et al. (2010) presented additional data showing that the same LBV star that erupted as SN 2000ch also suffered three additional eruptions in 2008 and 2009. Thus, perhaps this object should be referred to as ‘LBV1’ in NGC 3432, not SN 2000ch. Like the 2000 transient, these later eruptions were erratic and fast variations with peak R-band absolute magnitudes of −12.1 to −12.7. LBV1 showed rapid dips and recovery on time-scales of a few days, similar to SN 2009ip, but repeatedly over several years. These recurring eruptions are not reproduced in Fig. 8, but this interesting object is discussed thoroughly by Pastorello et al. (2010). In Appendix A2, we also present V- and I-band detections of the survivor of SN 2000ch taken with HST in 2008. Pastorello et al. (2010) draw comparisons between LBV1 and the binary HD 5980, suggesting similar binary encounters as a possible mechanism, among others, behind the rapid and erratic variability. The multiple fast peaks and dips are qualitatively similar to the wild pre-1954 variability of SN 1954J/V12. If this comparison is appropriate, then the erratic variability may signify a growing instability, and we should not be surprised if LBV1 culminates with a more major eruption in the next decade or so. In any case, we should keep an eye on this star!

SN 2001ac. We discovered SN 2001ac in KAIT images taken on 2001 March 12.4 and 13.3 (Beckmann & Li 2001) as part of LOSS. A spectrum obtained by Matheson et al. (2001) was similar to those of SNe 1997bs and 1999bw, with a blue continuum and strong Balmer emission lines. No detailed analysis of SN 2001ac has been published; here we present limited BVRI and unfiltered
KAIT photometry (Table 2) and spectra near maximum light (Table 7, Fig. 3). We also present late-time upper limits from HST data taken in 2008 (Appendix A3). We adopt \( m - M = 32.22 \) mag and \( E(B - V) = 0.027 \) mag for the host galaxy NGC 3504, suggesting a peak absolute \( R \) magnitude of roughly \(-14.1\) mag, comparable to that of \( \eta \) Car. As noted earlier, from our spectrum on day 9, the \( H \) emission-line profile has a composite shape that can be fitted with a Gaussian core FWHM of \( 287 \) km s\(^{-1}\) and broader Gaussian wings with FWHM = \( 1505 \) km s\(^{-1}\).

**SN 2002bu.** Located in NGC 4242, SN 2002bu was discovered by Puckett & Gauthier (2002) on 2002 March 28.26. The progenitor was not detected to limit red magnitudes of \( 20.5 - 21.0 \) mag. Preliminary reports of the spectrum indicated that it resembled a Type IIn SN or an LBV, with strong and narrow Balmer emission lines and a flat continuum (Ayani & Kawabata 2002). We obtained extensive BVRI photometry with KAIT (see Table 3), as well as a series of optical spectra at Lick (Table 7, Fig. 3). We adopt \( m - M = 29.71 \) mag and \( E(B - V) = 0.012 \) mag for NGC 4242. This suggests a peak absolute \( R \) magnitude of roughly \(-15\) mag, which places it among the most luminous examples of the known SN impostors. The multicolour light curves and spectral evolution are described in some detail above. From spectra on day 11, \( H \) exhibits a Lorentzian emission profile with FWHM = \( 893 \) km s\(^{-1}\) and scattering wings that extend to \( \pm 2500 \) km s\(^{-1}\). The temporal evolution of the spectrum was discussed above. As noted earlier, Thompson et al. (2009) identified a mid-IR source possibly associated with SN 2002bu in Spitzer data taken 2 and 6 yr after the outburst.

**SN 2002kg/V37.** The progenitor of this transient in the nearby spiral galaxy NGC 2403 (also host to V12/SN 1954J) was first identified by Van Dyk (2005) as Variable 37 from Tammann & Sandage (1968), a bright blue irregular variable like the Hubble–Sandage variables (i.e. a classical LBV). Observations of the increased brightness that was dubbed SN 2002kg have been discussed in detail by Maund et al. (2006) and Van Dyk et al. (2006). Its absolute peak \( V \) magnitude during the outburst\(^5\) was roughly \(-10\) mag, making it one of the least luminous of the recognized SN impostors, and the total brightening compared to its progenitor was only about \( 2\) mag. We show the KAIT \( R \)-band light curve from Van Dyk et al. (2006) in Fig. 8.

Although SN 2002kg is usually discussed along with the other SN impostors that are attributed to giant LBV eruptions like \( \eta \) Car, it seems plausible that SN 2002kg was not really a giant LBV eruption, but rather a normal S Dor phase of a massive LBV star. This is based on its relatively modest increase in brightness that may be consistent with a change only in bolometric correction. The difference between these two is that a giant LBV eruption is defined as an increase in bolometric luminosity, whereas it is thought that the bolometric luminosity remains roughly constant in a normal S Dor phase (see Humphreys et al. 1999). Van Dyk estimated \( M_{\text{bol}} = -9.8 \) mag for the progenitor star, which is consistent with the observed peak absolute visual magnitude. The outburst SN 2002kg was very similar in magnitude to the previous eruptions experienced by V37 around 1920 and 1930 (Tammann & Sandage 1968). Weis & Bomans (2005) also associated SN 2002kg with V37, and claimed that the surviving star was detected again several years after the outburst.

Both Maund et al. (2006) and Van Dyk et al. (2006) presented spectra of SN 2002kg, showing strong Balmer emission lines with a narrow component having widths of \( 330 - 370 \) km s\(^{-1}\) and broader wings having widths of \( 1500 - 1900 \) km s\(^{-1}\), consistent with electron-scattering wings. P Cygni absorption features in Balmer lines also suggest expansion speeds of \( \sim 350 \) km s\(^{-1}\). The spectra revealed strong, narrow [N \( \alpha \)] \( \lambda \lambda 6548, 6583 \) emission, similar to other LBVs and probably indicating the presence of a massive circumstellar nebula.

**SN 2003gm.** This transient source in NGC 5334 was also analysed in detail by Maund et al. (2006). Unfortunately, photometric data are sparse and the available spectra are rather noisy. We show the \( I \)-band light curve from Maund et al. (2006) in Fig. 8 (green/black). There are only three photometric \( I \)-band points, but as noted by Maund et al. (2006), the absolute peak magnitude and the decay rate appear very similar to those of SN 1997bs. The peak \( M_I \) was about \(-13.7\) mag, and the \( M_R \) and \( M_V \) values are probably similar to within \( \pm 0.8 \) mag.

We obtained unfiltered KAIT photometry on days 6 (discovery) and 6, both of which were \( 17.0 \pm 0.1 \) mag. Early-time spectra of SN 2003gm are similar to those of SN 2000ch, with the \( H \) emission line having a rather narrow width of only \( \sim 131 \) km s\(^{-1}\), but with broader wings having a width of \( 1472 \) km s\(^{-1}\) (Maund et al. 2006). Maund et al. estimated the metallicity of the host galaxy as \( 0.7 Z_{\odot} \). As in the case of SN 2002kg, the progenitor star was identified as a luminous star in pre-explosion data, and Maund et al. (2006) estimated \( M_V \approx -7.5 \) mag for the progenitor, indicating that the star brightened by more than \( 5 \) mag during its giant LBV eruption. In 2008, more than 5 yr after the outburst, we detect a reddened source at the position of SN 2003gm in the \( V, R \) and \( I \) bands in images taken with HST (see Appendix A4; Table A1). This indicates \( M_I \approx -6.6 \) mag, providing evidence that the progenitor star may have survived the event. Its red \( V - R \) colour of \( \sim 0.4 \) mag (corrected for Galactic reddening) at that time seems consistent with its amount of fading (compared to the progenitor) being due to dust formation.

**N4656-OT (2005).** This optical transient source in NGC 4656 was discovered by Rich (2005) at an unfiltered magnitude of 18.0 mag on 2005 March 21 and 22 (the transient was also visible in unfiltered images taken a few days earlier at 18.5 and 18.3 mag; Yamaoke 2005). Elias-Rosa et al. (2005) reported that its spectrum had a blue continuum and strongly narrow Balmer emission lines having widths of \( 730 \) km s\(^{-1}\), but with no broad base as seen in normal Type IIn SNe, suggesting that it was an LBV-like event similar to SN 1997bs and not a SN. The spectrum also showed narrow Ca H&K absorption. Our ground-based detection, described in Appendix A5 (obtained on 2005 June 11; day 82), shows that the transient faded by almost 2 mag in \( \sim 3 \) months (see Fig. 8). Unfortunately, we did not obtain additional data on this transient, and no other comprehensive analysis has been published to date. Adopting \( m - M = 28.69 \) mag (\( d = 5.47 \) Mpc; Tully et al. 2009) and \( A_K = 0.035 \) mag (Schlegel et al. 1998), the peak absolute unfiltered (\( \sim R \) band) magnitude is \( -10.73 \) at the time of the discovery. If indeed N4656-OT is a giant LBV eruption, this makes it one of the less-luminous examples, comparable to SN 1954J or HD 5980. The data also seem consistent with a normal S Dor-type outburst of an LBV. No information is available about its progenitor star, however. The post-outburst source was fainter than mag 26 in 2008 (see Appendix A5).

**SN 2006bv.** Occurring in UGC 7848, SN 2006bv was discovered by Sehgal, Gagliano & Puckett (2006) on 2006 April 28.36 with...
a magnitude of 17.8 in unfiltered images. A spectrum obtained 2 d later showed a smooth blue continuum and narrow Balmer emission lines with FWHM = 400 km s\(^{-1}\) (Blondin et al. 2006). Immler & Pooley (2006) presented optical and UV photometry obtained a few days later and an upper limit to the X-ray flux, and concluded that it was fading rapidly. We secured some limited photometric measurements of SN 2006bv (Table 4), but we were unable to obtain spectra, making it difficult for us to confirm from an independent analysis that this is indeed an LBV and not a faint SN. We adopt \(m - M = 33.0\) mag and \(E(B - V) = 0.015\) mag for UGC 7848, suggesting a peak absolute unfiltered \((\sim R)\) magnitude of roughly \(-15.2\) mag. This places SN 2006bv among the most luminous of the SN impostors, comparable to SN 2002bu.

**SN 2006fp.** This object was discovered on 2006 September 17 by Puckett et al. (2006) at an unfiltered magnitude of 17.7, while images obtained the following night had a slightly brighter magnitude of 17.6. The progenitor was not detected a year earlier to a limiting magnitude of 19.6. Spectra obtained by Blondin et al. (2006) revealed a reddened continuum with strong Balmer emission lines having very narrow widths of 300 km s\(^{-1}\), but with a slightly broader base of around 1000 km s\(^{-1}\) (FWHM). The spectrum was most similar to previous SN impostors SN 1999bw and SN 2001ac, and Blondin et al. noted that the peak absolute magnitude corresponding to the discovery magnitude was roughly \(-14\), similar to other luminous LBV giant eruptions. Since the object was reddened, however, the true absolute magnitude at peak was more luminous.

No comprehensive study of this object has been presented, and we did not secure additional photometry or spectroscopy. Adopting \(m - M = 32.0\) mag for UGC 12182, and correcting also for a rather large line-of-sight Galactic extinction \(A_R = 1.168\) mag (Schlegel et al. 1998), implies that the peak unfiltered absolute magnitude \((\sim R)\) was about \(-15.47\). This makes SN 2006fp among the most luminous giant LBV eruptions at its peak.

**SN 2007irs.** Located in UGC 5979, SN 2007sv was discovered by Dudzianowicz (2007) on 2007 December 20.9 at an unfiltered magnitude of 17.4. Low-resolution spectra obtained by Harutyunyan et al. (2007) show a blue continuum and narrow (FWHM < 1000 km s\(^{-1}\)) Balmer emission lines. No comprehensive study of this object has been presented, and we did not obtain additional photometry or spectroscopy. Adopting \(m - M = 31.57\) mag (20.6 Mpc) and a small Galactic reddening of \(A_R = 0.046\) mag, we find that the absolute magnitude of SN 2007sv at discovery was roughly \(-14.2\) mag, comparable to several other luminous giant LBV eruptions.

**SN 2008S.** This optical transient has been discussed extensively in the recent literature, with comprehensive photometric and spectroscopic data sets published by Smith et al. (2009a) and Botticella et al. (2009). The progenitor was very faint at optical wavelengths, but was detected as a bright IR source in pre-discovery archival *Spitzer* data (Prieto 2008; Prieto et al. 2008a; Thompson et al. 2009). Its optical spectrum had bright, narrow [Ca\textsc{ii}], Ca\textsc{i} and Balmer emission lines, very similar to the spectrum of the yellow hypergiant IRC+10420 (Smith et al. 2009a). Its peak \(R\)-band absolute magnitude was \(-13.9\), and the light curve from Smith et al. (2009a) is shown in Fig. 8. Smith et al. (2009a) noted expansion speeds of \(\sim 1000\) km s\(^{-1}\) near the time of peak luminosity, dropping to \(~ 550\) km s\(^{-1}\) after a few months. Note that the broader 3000 km s\(^{-1}\) component mentioned by Botticella et al. (2009) is probably due to electron-scattering wings. Its post-outburst evolution is complicated by dust (e.g. Prieto et al. 2010; Wesson et al. 2010), so it is not yet clear if the star survived the event.

**N300-OT (2008).** This transient was discovered by Monard (2008) and is a near twin of SN 2008S in most ways, including the obscured nature of its progenitor (Prieto 2008; Prieto et al. 2008b; Thompson et al. 2009). Comprehensive analyses of the optical photometry and spectra were presented by Bond et al. (2009) and Berger et al. (2009). Its peak \(M_R\) was \(-13.3\) mag. Berger et al. inferred an expansion speed of \(~ 560\) km s\(^{-1}\) from the widths of emission lines, whereas Bond et al. (2009) suggested a slower speed of \(~ 75\) km s\(^{-1}\) based on the separation of the double peaks in emission lines. To be consistent with expansion speeds inferred from line widths in other objects, we adopt FWHM = 560 km s\(^{-1}\) as the representative expansion speed in the discussion below.

**SN 2009ip.** This SN impostor is the first in modern times to be discovered with precursor LBV-like eruptive variability in the decade leading up to its peak brightness, and its photometry and spectra were first analysed in detail by Smith et al. (2010a). A subsequent analysis of similar spectra by Foley et al. (2011) confirmed the conclusions of Smith et al. (2010a). The unfiltered light curve presented by Smith et al. (2010a) is shown in both Figs 7 and 8. Smith et al. (2010a) inferred expansion speeds of \(~ 600\) km s\(^{-1}\) from H\textalpha{} line widths, but also noted faster material at 3000–5000 km s\(^{-1}\) seen in broad P Cygni absorption features of lines like He\textsc{i}\,\lambda\,5876. This is the first time we have seen conclusive evidence for a second component with such high speeds reminiscent of the blast wave around \(\eta\) Car; in most other LBVs, the presence of broad emission wings can be explained by electron scattering and does not necessarily implicate faster moving ejecta. Days before the submission of this paper, Drake et al. (2010) reported another subsequent outburst of SN 2009ip, apparently satisfying the expectation of Smith et al. (2010a) that ‘we should not be surprised if the eruption continues’.

**U2773-OT (2009).** As for SN 2009ip, Smith et al. (2010a) discovered that U2773-OT was also an LBV that exhibited eruptive variability in the decade leading up to its discovery. Its spectra were different, however, with narrower lines and a redder continuum, more closely resembling that of a cool S Dor phase. A subsequent analysis of similar spectra by Foley et al. (2011) supported these conclusions. We adopt the unfiltered light curve and optical spectra presented by Smith et al. (2010a), although we also update the light curve with new KAIT photometric observations (see Table 5 and Fig. 8). Spectra of this transient indicated expansion speeds of \(~ 350\) km s\(^{-1}\) (Smith et al. 2010a; Foley et al. 2011).

**SN 2010da.** This transient occurred in NGC 300, about 2 yr after the well-studied and obscured optical transient N300-OT discussed above. As with the first N300-OT, SN 2010da was discovered by Monard (2010) on 2010 May 23. A comprehensive study has not yet been published, but based on initial reports (Berger & Chornock 2010; Bond 2010; Brown 2010; Chornock & Berger 2010; Elias-Rosa, Mauerhan & Van Dyk 2010; Immler et al. 2010; Khan et al. 2010b), this object appears consistent with an LBV giant eruption or SN impostor similar to SN 1997bs in some respects. Its progenitor was relatively faint at visual wavelengths but was apparently enshrouded in dust based on the bright IR source at the same position (Khan et al. 2010a,b). Another preliminary analysis by Laskar, Berger & Chornock (2010) found pre-eruption variability analogous to that of U2773-OT and SN 2009ip (Smith et al. 2010a), but detected in the near-IR. At discovery, it had an apparent \(R\) magnitude of roughly \(16.0\) mag (Monard 2010), suggesting an absolute \(R\) magnitude of \(~ 13.5\) mag, similar to other LBV eruptions and almost identical to the 2008 transient in NGC 300. Further detailed study of this object is currently underway by several groups.

**SN 2010dn.** This recent transient was discovered by K. Itagaki (see Nakano 2010b) in the nearby galaxy NGC 3184. The initial
spectrum taken 2 d after discovery showed narrow Balmer emission lines and a blue continuum similar to those of some LBVs, plus visible emission of [Ca ii] and Ca ii (Vinko et al. 2010). We adopt $m - M = 30.4$ mag (a distance of $\sim 12$ Mpc) and $E(B - V) = 0.017$ mag for NGC 3184, although the presence of [Ca ii] emission suggests a dusty circumstellar environment (Prieto et al. 2008; Smith et al. 2009a, 2010a) so the true reddening may be higher. On day 2, SN 2010dn had an unfiltered magnitude of 17.1 (Nakano 2010b), corresponding to a peak absolute magnitude of roughly $-13.3$ mag. This is similar to that of N300-OT in 2008. Its early-time photometric evolution and colour were similar to those of SN 2002bu (Fig. 1).

We presented the first published spectra of SN 2010dn in Figs 5 and 6 (Section 3.1), and we noted that the overall character of the spectra was almost identical to those of SN 2008S and N300-OT, with strong but narrow [Ca ii] lines, intermediate-width emission from the Ca ii IR triplet and Balmer lines, and a similar continuum suggesting a temperature around 7000 K. The behaviour of the spectrum at late times was also similar to that of SN 2008S. In our high-resolution Keck/DEIMOS spectrum on day 11, the Hα line had FWHM $= 900$ km s$^{-1}$, which is similar to that of SN 2008S, but it displayed a mostly Lorentzian line profile, unlike its close cousins. Atop the Lorentzian Hα profile, it also exhibited a weak narrow component, perhaps indicating that it has an additional dense, slow CSM irradiated by the transient. The asymmetric profiles of the [Ca ii] lines are qualitatively identical to those of N300-OT (Berger et al. 2009). According to Berger (2010), the non-detection of the progenitor in archival HST images obtained $\sim 9$ yr before discovery implies a V-band (F555W) absolute magnitude fainter than $-6.3$ (see also Appendix A6). Based on the [Ca ii] emission lines and associations with dusty environments (Prieto et al. 2008; Smith et al. 2009a, 2010a), however, it is possible that the progenitor could potentially be intrinsically more luminous than this.

### 3.2 Light-curve morphology

The light curves of the SN impostors in Figs 7 and 8 exhibit a wide variety in peak luminosity, duration and shape. As we discuss later, light-curve behaviour is not necessarily correlated with their spectral properties, nor does the duration of the event seem to scale with the ejected mass. Some events show extremely complex and rapid rises and dips in absolute magnitude, sometimes multiple times, whereas other events exhibit a simple 10-yr plateau or single 100-d exponential decay. There does not seem to be any simple way in which the light-curve properties scale, probably because there are a number of different physical parameters that can vary in each system: the progenitor mass and luminosity, the ejected mass and velocity, different input radiative and kinetic energy budgets, possible binary encounters, etc. Without knowing the relevant physical mechanisms, it seems difficult to derive clearly meaningful information from the light curves alone, especially without the benefit of photometric observations in multiple filters.

### 3.3 Colour and temperature evolution

Not much is known about the colour evolution of SN impostors, and the question is mired by the possible presence of severe CSM dust and reddening. There is a relatively poor observational record of the UV characteristics during SN impostor outbursts.

It is becoming clear, however, that some long-lived paradigms are certainly wrong. The common wisdom has been that when in eruption, LBVs should always be seen at relatively cool temperatures of no cooler than $\sim 7500$ K with an F-supergiant-like spectrum (e.g. Davidson 1987; Humphreys & Davidson 1994), and that they therefore have small or zero bolometric correction at peak brightness. The reasoning behind this expectation is that LBVs develop opaque winds during their eruptions, with pseudo-photospheres that always tend towards these temperatures because of the opacity in the wind (see Davidson 1987).

This picture does apply to the cool states of normal S Dor episodes of LBVs (Humphreys & Davidson 1994; Smith et al. 2004), but it apparently is not always the case in giant eruptions. Some giant eruption events do indeed fit the bill, of course, with apparent temperatures of $\sim 7000$ K and F-supergiant-like spectra (e.g. U2773-OT, SN 2002bu, SN 2010dn). However, other SN impostors such as SN 2009ip clearly do not fit this expectation. Detailed UV and optical spectroscopy of V1 in NGC 2366 (Petit et al. 2006), for example, showed a much hotter temperature during its eruption, and revealed that the temperature and bolometric luminosity actually increased with time while the optical photometry showed a plateau. Also, SN 2009ip and other events showed hotter temperatures and a spectrum unlike an F-type supergiant.

In this older view, one would expect the coolest temperatures to coincide with peak luminosity when the pseudo-photosphere is the largest and that the effective photosphere would either stay at constant temperature or even get hotter as the eruption subsides, causing the mass-loss rate and opacity to drop. Instead, in some cases where information is available, we see much warmer temperatures of $12 000$ K or more at peak, with the temperature subsequently becoming cooler as the object fades.

Substantial redward evolution with time may be expected from an explosion that suffers adiabatic cooling as the photosphere recedes through ejecta, as in a Type II-P SN. Fig. 1 shows that the redward colour evolution of SN impostors differs from a normal Type II-P SN, never becoming as red. The more subtle drop in the characteristic emitting temperature with time is similar to a Type IIn SN powered by CSM interaction (e.g. Smith et al. 2010b), where the apparent temperature drops with time because the blast wave decelerates as it sweeps up large amounts of mass (van Marle et al. 2010). Dust formation in these events may also cause increased extinction and reddening, and may therefore have a strong influence on the apparent colour with time. Further investigations of the colour evolution of SN impostors, including both UV and IR observations, are sorely needed.

### 3.4 Peak absolute magnitudes

A key parameter for any transient source is its peak absolute visual magnitude. In the case of LBV giant eruptions, this is critical for evaluating the extent to which the star exceeded its own Eddington limit. Unfortunately, we do not have photometry in the same filters for each source, so we must compare $R$ and unfiltered magnitudes (generally about the same as $R$) to $V$ band or unfiltered visual magnitudes for historical sources like η Car and P Cygni. For sources where both $V$ and $R$ are available, the difference is typically not more than a few tenths of a magnitude, and the qualitative shapes of the light curves in different filters are similar (e.g. SN 2002bu; Fig. 1). Absolute peak magnitudes and the corresponding filters are listed in Table 9.

Fig. 9 shows a histogram of peak absolute magnitudes for SN impostors (hatched), compared to the distribution of peak $R$ magnitudes for normal Type II-P, Type II-L (shaded grey) and Type IIn SNe (narrow hatched), taken from the volume-limited KAIT sample (Li et al. 2011). LBV eruptions clearly form a population that is different from normal core-collapse SNe. While the Type
II-P and Type II-L SNe favour peak absolute magnitudes of roughly $-16.5 \pm 1.5$, the LBVs are skewed to lower luminosity, although there is some small overlap in the tails of each distribution. The completeness at the low end of each distribution has not been well defined. Although there is some overlap between bright LBV-like events and faint Type II-P SNe, their spectra are very different (see Smith et al. 2009a). If, however, there is a population of highly subluminous Type IIb SNe that is due to weak core-collapse SNe, these objects would of course be very difficult to distinguish from LBV-like events.

There appears to be one clear outlier among the LBVs in Fig. 9 and that is the well-known event SN 1961V with a peak absolute magnitude of $-17.8$. SN 1961V is an unusual case, and later in this paper we consider the question of whether it is really an LBV eruption or something else – perhaps a genuine Type IIb SN resulting from core collapse, but preceded by an LBV eruption (see below). SN 1961V is well within the range observed for Type IIb SNe (Fig. 9).

Excluding SN 1961V, all of the LBV eruptions span a range of absolute magnitudes from about $-10$ to $-16$. There is some overlap with the low-luminosity tail of the SN II-P distribution; we note that objects like SN 2005cs, SN 2001dc and SN 1999br (see Pastorello et al. 2007a) are included in this sample. As pointed out by Smith et al. (2009a), the colour evolution and spectral properties of these low-luminosity SNe II-P are quite distinct from those of SN impostors. (The highly reddened SN 2002hh is also included in the SN II-P sample of Fig. 9 and its true absolute magnitude is more luminous than its apparent value because of local extinction.)

The distribution of LBV peak magnitudes in Fig. 9 hints that there may be two subgroups – a more luminous class with peak magnitudes clustered around $-14 \pm 1.5$ and a less luminous group with peaks of $-10$ to $-11.5$ mag. Since the SN impostors in this sample were discovered with widely differing search parameters (it includes historical objects in our Galaxy as well as some discoveries by amateur astronomers and by systematic surveys like LOSS), we cannot test the statistical significance of these two luminosity classes. SN impostors are generally less luminous than true SNe, and it is thus likely that their discoveries are highly incomplete in most SN searches. This is particularly true for the highly subluminous group ($-10$ to $-11.5$ mag), so the true luminosity function of the impostors may look quite different from what is displayed in Fig. 9. For example, in a volume-limited sample, there could be more $-10$ to $-11.5$ mag impostors than the more luminous examples. This is an area where future discoveries of SN impostors will be highly beneficial. Is it really two groups or is it a continuous distribution of luminosities? How low does the distribution of SN impostor peak luminosities go? For the purposes of discussion in this paper, we tentatively refer to these as relatively low- and high-luminosity events, while being mindful that there may not be a true physical separation.

In any case, there is a practical problem with identifying eruptive peak magnitudes of roughly $-10$ or fainter, which is that we enter the territory of quiescent absolute bolometric magnitudes for very luminous stars. At the low end of this distribution, incomplete observational data will make it difficult to reliably distinguish genuine LBV giant eruptions (increase in bolometric luminosity) from the more common S Dor type excursions. Recall that in an S Dor excursion, the star is supposed to brighten at visual wavelengths because of a change in the apparent temperature and radius, but not necessarily luminosity; this alters the bolometric correction, so either UV data or detailed atmospheric models become necessary. However, recent studies of S Dor excursions may hint that the traditional view of constant luminosity may need to be modified as well (e.g. Groh et al. 2009), making the situation more murky.

At first glance, it may be tempting to naively group relatively low- and high-luminosity eruptions into different subclasses, but this would be too oversimplified and not necessarily helpful. In several cases, we have well-studied LBVs where the star suffers...
multiple eruptions, qualifying for the low- or high-luminosity category in subsequent eruptions of the same star. Instead, Fig. 9 should be taken as a demonstration of the rather wide diversity of the eruptive phenomenon in general. A theory that attempts to explain the mechanism of the eruptions should strive to reproduce this diversity.

3.5 Characteristic rise and fall time-scales

The rise time-scales are poorly constrained for most SN impostors, because they are generally discovered around the time of peak luminosity due to the relatively small size of telescopes used for most transient searches (larger telescopes are used mainly for follow-up observations). Adequate information about fainter progenitors is therefore rare, limited to cases with good archival data (see e.g. Appendix A). This situation is, of course, improving with time as high-quality archives become more populated with observations, and as transient searches are conducted with larger telescopes.

Discovery near peak implies a rather sudden onset for the brightening of some SN impostors and hence fast rise time-scales comparable to those of SNe. We do see examples, however, of very slow rise times, as in the case of U2773-OT, which rose steadily for at least 5 yr, and is in fact still rising at the time of writing (2011 January). This, as well as precursor eruptions and variability seen in some objects like η Car. V12/SN 1954J and SN 2009ip, points towards a significant ‘preparatory’ phase in SN impostors that is physically meaningful because it signals a growing instability, rather than a sudden event. This echoes the fact that LBV eruptions are apparently sometimes a preparatory phase for the eventual core-collapse

SN (e.g. Foley et al. 2007; Pastorello et al. 2007b; Smith et al. 2007, 2008, 2010b; Gal-Yam & Leonard 2009).

Time-scales for SN impostors to fade from maximum brightness are much better characterized than their rise times. In SNe, the rate of decline provides information about the ejecta mass (i.e. the diffusion time) and energy source (i.e. radioactive decay rates). In SN impostors, the direct meaning of the decline rate is not immediately clear, but characterizing the distribution of relative rates at which SN impostors fade may eventually help distinguish between models.

For comparison among the sample of sources, we define a timescale, \( t_{1.5} \), as the time in days for a transient to fade by \( \sim 1.5 \) mag from its peak. This is either the time beginning at the discovery or at peak visual luminosity, depending on the available information. Some cases require exceptions, such as the brief precursor eruptions of η Car in 1838 and 1843, when observations are incomplete and we are not sure if the source actually faded by a full 1.5 mag. In cases such as this, the value of \( t_{1.5} \) is approximate and represents the time over which the star appeared to be fading back to its quiescent level. The resulting values of \( t_{1.5} \) are listed in Table 9 and a histogram of the values is plotted in Fig. 10. Cases where more than one value of \( t_{1.5} \) is listed in Table 9 correspond to more than one major outburst observed from the same source. Since this is not a complete sample with uniform coverage for each source, the histogram in Fig. 10 is meant to convey the range of time-scales observed, rather than a statistically significant distribution. Fig. 10 does not show the typical time-scales for Type II-P SNe, which are almost always close to 100 d.

SN impostors span a wide range of fading time-scales peaked at durations around 100 d. There are also examples that fade quickly in only a few days and several cases that last for a decade. An important point that distinguishes SN impostors from true SNe is that the fading time-scale does not necessarily tell us anything about the amount of mass ejected. Both η Car and P Cygni had durations of \( \sim 10 \) yr for their major eruptions, but from measurements of their nebulae we know that η Car ejected more than 10 \( M_\odot \) (Smith et al. 2003b), whereas P Cygni ejected only \( \sim 0.1 \) \( M_\odot \) (Smith & Hartigan 2006). Furthermore, η Car also showed two brief events of \( \sim 100 \) d duration, when it is possible that much of the mass may have been ejected (Smith & Frew 2011), and it had another decade-long

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**Figure 9.** Histogram of peak absolute magnitudes (mostly \( R \), but some \( V \); from Table 9) for giant LBV-like eruptions. These are compared to the absolute \( R \) magnitudes of the volume-limited KAIT sample (Li et al. 2011) of 52 normal Type II-P SNe and 10 Type II-L SNe (added together and divided by 2 for display; shaded grey), and of five Type IIn SNe. Note SN 1961V to the lower right-hand side as the only putative LBV that overlaps with Type IIn SNe.

**Figure 10.** Histogram of the logarithm of values of \( t_{1.5} \) listed in Table 9.

SN impostors span a wide range of fading time-scales peaked at durations around 100 d.
outburst in the 1890s when only 0.1–0.2 $M_\odot$ was ejected (Smith 2005). Unfortunately, measuring the ejected mass for extragalactic SN impostors, where circumstellar nebulae are not resolved, is impossible without a detailed understanding of the physical mechanism and the radiative transport involved in the outbursts. The sustained energy source of the decade-long eruptions is therefore unclear, but it is probably not caused by the diffusion from an extremely large mass of ejecta.

The very fast declines correspond to obvious sharp dips in the light curves, in many cases corresponding to drops in magnitude to the quiescent progenitor’s luminosity or even fainter. Notable cases of these sharp dips are SN 2009ip (Smith et al. 2010a), SN 2000ch (or LBV1 in NGC 3432; Wagner et al. 2004; Pastorello et al. 2010) and SN 2002kg (Maund et al. 2006; Van Dyk et al. 2006). The cause of these is unclear, but Smith et al. (2010a) have hypothesized that they may correspond to sudden ejections of massive shells of material, which expand quickly and cool while remaining opaque. After the shell finally becomes optically thin, the emergent luminosity may return to its previous level. This is of course just a working hypothesis; detailed radiative-transfer calculations that include sudden massive shell ejections would be valuable.

Several objects show evidence for multiple peaks or multiple separate eruptions. This is discussed further below, but it is also relevant to mention here that repeated eruptions in the same source can often have different time-scales. The delay time or dormant time between these multiple outbursts may also be highly relevant, perhaps indicating a recovery time-scale or orbital time-scale in the case of binary encounters. Due to incomplete archival information, it is of course very difficult to constrain the possible occurrence of previous eruptions in objects where precursors have not been documented.

### 3.6 Expansion speeds and line profiles

While the ejecta mass is difficult to estimate from observations of SN impostors, their spectra are extremely valuable for providing direct estimates of the expansion speeds during an eruption. Aside from studying the kinematics of spatially resolved circumstellar nebulae in the nearest examples, which may have been decelerated through the interaction with pre-existing CSMs, direct spectra of outbursts are the only way to understand the kinematics of the ejection. The speed of ejection provides important clues to the nature of the star, because in some scenarios one expects the expansion speed to be related to the star’s escape velocity (e.g. RSG stars have very slow winds of $\sim 20$ km s$^{-1}$, LBVs and blue supergiants have speeds of a few hundred km s$^{-1}$, and compact WR stars typically have fast winds of more than 1000 km s$^{-1}$). The observed expansion speed and its change with time through the outburst are also critical for understanding the physics of the eruptive event (explosive blast wave or sustained wind). In addition, knowing the distribution of SN impostor expansion speeds is relevant for understanding the pre-SN evolution of Type IIn SNe, where narrow lines from the pre-shock CSM can be observed.

To assess the distribution of expansion speeds for our sample of SN impostors, we generally took the FWHM of the Hα emission line, either measured directly in our spectra or quoted from the literature, as the primary indicator of the expansion speed for the bulk of the material in the ejecta or wind. However, this was supplemented with other information. For η Car and P Cygni, values of $V_{\text{exp}}$ were inferred from the kinematics of their expanding nebulae (Smith 2005, 2006, 2008; Smith & Hartigan 2006), and even this is incomplete (e.g. we only listed the polar expansion speed of 650 km s$^{-1}$ for the Homunculus nebula, while a latitude-dependent range of speeds is seen down to 40 km s$^{-1}$ at the equator; Smith 2006). Also, in cases such as SN 2009ip, fast speeds of $\sim 5000$ km s$^{-1}$ are seen in absorption only, in He II and Balmer lines (Smith et al. 2010a; Foley et al. 2011). The adopted values of $V_{\text{exp}}$ are listed in Table 9 and the distribution is shown in Fig. 11.

The dominant outflow speeds in SN impostors span a wide range from around 100 km s$^{-1}$ up to somewhat more than 1000 km s$^{-1}$, with a peak in the distribution around 600–800 km s$^{-1}$ (Fig. 11). Note that in Fig. 11 we are aiming for the dominant outflow speed, so we did not include the fast material moving at $\sim 5000$ km s$^{-1}$ around η Car or SN 2009ip, because in both cases this fast material is thought to constitute a very small fraction of the total mass (Smith 2008; Smith et al. 2010a), in contrast to the case of SN 1961V, which showed an Hα FWHM of 3700 km s$^{-1}$ in spectra taken during the peak of the eruption (Zwicky 1964). The observed expansion speed in Hα is one of several ways in which SN 1961V is a clear outlier among the SN impostors; in fact, we argue later that SN 1961V is not a SN impostor at all, but is instead a true core-collapse SN. From Fig. 11, one can see that the expansion speed of SN 1961V is much closer to the range of speeds seen in Type II-P SNe than to that of the SN impostors. It is also worth noting that there is little overlap between speeds in Type II-P SNe and SN impostors; the KAIT sample of Type II-P SNe are shown for comparison, measured from Fe II lines in the middle of the plateau (see Poznanski et al. 2009). True core-collapse Type IIn SNe apparently fill the gap between LBVs and Type II-P SNe, with typical linewidths of 1000–4000 km s$^{-1}$, although these values are not as consistently measured.
Lorentzian wings. In several cases (e.g. SN 2002bu discussed earlier), there is a transition from a Lorentzian line shape at early times to a Gaussian shape in the same object, and such behaviour is also seen in Type II SNe (Smith et al. 2008, 2010b). This diversity is not understood, but is likely related to the changing optical depth of the wind or ejecta, since electron scattering through dense material will produce Lorentzian shapes. Lorentzian profiles are more notable in SN impostors than in core-collapse SNe because the intrinsic linewidth is narrower, making the scattering wings out to a few 1000 km s$^{-1}$ easier to see. Nevertheless, it is clear that we do not see consistent spectral evolution in all objects. While some transients like SN 2002bu evolve from characteristically ‘hot’ to ‘cool’ with time, there are other examples which are cool at early times or examples that remain hot at late times. Thus, the diversity in spectral characteristics shown in Fig. 12 is real and is likely representative of the class.

All of the SN impostors share the common property of strong Balmer-line emission with relatively narrow profiles compared to SNe (this is, in fact, one of the criteria used to classify them as an SN impostor, in addition to their relatively faint absolute magnitudes). Beyond that, there seems to be a wide range of qualitative properties that can be attributed to the characteristic temperature of the emitting photospheres or pseudo-photospheres. Smith et al. (2010a) have discussed the dichotomy of relatively ‘hot’ LBVs like SN 2009ip and relatively ‘cool’ objects like U2773-OT, while both are characteristics of LBVs. In Fig. 12, we have attempted to very roughly organize the spectra, with the hotter objects on the top half and the characteristically cooler objects towards the bottom. The hot objects are characterized by smoother and steeper blue continua, stronger and broader Balmer lines, relatively weak absorption and less complex spectra in general. The cool objects tend to have redder continua, weaker and narrower Balmer lines, strong Ca II and Ca II emission, deeper P Cygni absorption features, and in some cases stronger absorption spectra similar to F-type supergiants (U2773-OT is the best case of this) or to yellow hypergiants like IRC+10420 (see Smith et al. 2009a). As noted earlier, there are intermediate objects and there are some that transition from relatively hot to cool as time passes. We do not see any trend that the hotter objects are necessarily more luminous, although they do tend to have stronger and somewhat broader Balmer lines.

It is interesting that the narrow Ca II emission that was so remarkable in SN 2008S and N300-OT is actually present to varying degrees in many of the SN impostors. Smith et al. (2010a) have discussed the Ca II and Ca II lines in more detail, while Prieto et al. (2009) and Smith et al. (2010a) suggested that these lines may be related to the presence of pre-existing circumstellar dust.

Few of the objects are hot enough to exhibit He II emission lines, which are generally quite weak if present, and often fade quickly with time. HD 5980 is peculiar in this sense, because it has extremely strong He II and He II emission lines (see Fig. 12). In this case, however, we know that the eruptive star in the HD 5980 eclipsing binary system has a very luminous and hot WR companion star, which may strongly influence the observed spectrum during the outburst. SN 2009ip, SN 2000ch and one early epoch of SN 2001ac also show evidence for weaker He II emission.

### 3.8 Correlations in observed properties?

This subsection could be made very brief by simply stating that there are no obvious correlations among various observed properties of SN impostors. We do not, for example, discern any trend between luminosity and expansion speed, since both fast and relatively slow expansion speeds occur among both luminous and relatively faint SN impostors. Although the description of spectral morphology is more qualitative, we also see no trend that SN impostors with characteristically ‘hot’ spectra are more luminous or vice versa. Instead, the main lesson seems to be that LBVs/SN impostors are highly diverse, occupying a range of parameters without obvious correlations.

As an example, consider Fig. 13, which relates the duration of a transient event to its peak luminosity, as is commonly done for transient sources. This is adapted from a similar plot shown by Kulkarni et al. (2007) and others, although here we have expressed the duration in terms of a somewhat different quantity, $t_{1.5}$. Type Ia SNe and novae obey clear relations described elsewhere and core-collapse SNe tend to be fairly localized (except for Type Ibn SNe). However, the eruptions of LBVs or SN impostors essentially fill the entire range of the so-called ‘gap’ in Fig. 13 between SNe and novae, covering time-scales from a day to decades, and ranging over two orders of magnitude in peak luminosity. As noted elsewhere in this paper, we even have cases where the same star suffered multiple eruptions that appear in very different places in Fig. 13 (these cases are connected by the solid or dashed lines). Although there is no obvious ‘main sequence’ along which LBVs reside in Fig. 13, there does seem to be a concentration around $t_{1.5} \approx 50–100$ d and $M(\text{peak}) \approx -14$ mag. This common location for SN impostors includes the well-studied and often-debated events SN 2008S and N300-OT. The transient M85-OT also appears to reside comfortably among the most common types of SN impostors and is not exceptional in this regard.

As a starting point, then, it may be prudent for theoretical efforts to focus on possible physical mechanisms that can lead to $\lesssim 100$ d events with peak luminosities of $2 \times 10^{42}$ erg s$^{-1}$ and then to explore variations in physical parameters that extend this parameter space. The wide observed diversity may be attributed to a huge range in...
possible physical parameters, such as ejected mass, explosion energy, progenitor mass and luminosity, Eddington factor, etc., which can obviously affect quantities like the relevant thermal or diffusion time-scales and the photospheric radius with time during a transient. The few cases where we have detailed estimates of ejected mass and energy already exhibit differences of orders of magnitude.

Some of the observed diversity may also depend strongly on previous recent mass-loss history. For example, the amount of local dust extinction around the progenitor, and by extension the presence of strong [Ca ii] emission lines, IR excess or perhaps absorption lines in the spectrum, may depend on how recently the star suffered a previous outburst that created a dense and dusty CSM. The same progenitor star might look extremely different depending on how much time has elapsed since the last eruption and how much mass was ejected in that event. A hypothetical eruption of $\eta$ Car that is identical to its 1890 event could look very different if it were to occur a few hundred years from now when the Homunculus nebula has largely dispersed. Thus, the observed diversity in spectra and...
the colour of transient events may not necessarily be tied to diverse physical properties of the outbursts themselves. There is no clear reason to expect the previous mass-loss history to be correlated with other observed properties, of course.

To make matters worse, it is well established that the ejected matter in LBV eruptions can be strongly non-spherical, and so the observed properties may depend on the viewing angle. For example, the outflow speed that one would derive from spectra of η Car would be \( \sim 650 \text{ km s}^{-1} \) if it were viewed from a latitude near the pole, but one would infer a much slower outflow speed of 40–100 km s\(^{-1}\) if an observer happened to be looking from a low latitude projected along the equator (see Smith 2006). This may well play a role in some of the diversity in the outflow speed of SN impostors, shown in Fig. 11.

Similarly, the amount of line-of-sight extinction towards a source may be very latitude-dependent if it arises in the local circumstellar environment. If a progenitor star were surrounded by a dusty torus such as those commonly thought to reside around supergiant B[e] stars, for instance, then an observer situated near the equator might deduce that the progenitor was completely obscured and enshrouded. (A cautionary note is that this same observer would then underestimate the star’s bolometric luminosity by a factor of 5–10 if that estimate were based on the measured IR luminosity.) We might expect something like 10 per cent of SN impostors to be viewed from low latitudes, so perhaps a few cases of heavily obscured progenitors is not so surprising, although Thompson et al. (2009) find that the IR colours of B[e] stars do not match those of the SN 2008S and N300-OT progenitors. Again, there is no expectation that the viewing angle will correlate with any other observed property, except perhaps extinction.

4 DISCUSSION

4.1 Progenitor star diversity

One of the most important clues to the nature of SN impostors is the initial mass and evolutionary stage of the progenitor star in its quiescent state before the outburst. Unfortunately, this information is rarely available and hard to obtain, and detection bias for progenitors tends to favour cases where the progenitor star is relatively luminous. An added difficulty is that, in the absence of eclipsing binaries like HD 5980, it is of course always difficult to measure the star’s mass, which depends on evolutionary models, assumed reddening, uncertain bolometric corrections, assumed inclination and the geometry of obscuring material, possible pre-outburst variability and other factors.

It has been well established that the instability we associate with LBVs occupies a large range of initial mass, from the most massive stars that may exist down to about 20–25 M\(_{\odot}\) (Smith et al. 2004). It is therefore not surprising that several of the SN impostors appear to have very luminous progenitor stars within this range (e.g. SN 2009ip, SN 1997bs, η Car, P Cygni, HD 5980). A few examples seem to have progenitor stars around the lower bound of this mass range at \( \sim 20 \text{ M}_\odot \) (U2773–OT, V12/SN 1954J, V1 in NGC 2366, SN 2002kg, SN 2003gm), while there is suggestive evidence that the \( \sim 18–20 \text{ M}_\odot \) progenitor of SN 1987A may have experienced an LBV-like episode in its pre-SN evolution (Smith 2007).

However, the recent discovery of the relatively faint obscured progenitors of objects like SN 2008S and N300-OT was a surprise and seems to extend this range of initial masses well below 20 M\(_{\odot}\). Given the slope of the initial mass function, we may expect to see more of these events in coming years, hopefully with identifiable progenitor stars. An extremely interesting open question raised by SN 2008S and N300-OT is just how low in initial mass may stars experience extreme LBV-like eruptions. Does the eruptive phenomenon extend even below the lower limit for core-collapse SNe at \( \sim 8 \text{ M}_\odot \) and if so, are sudden energetic bursts important for the formation of some planetary nebulae (PNe)? Thompson et al. (2009) have touched upon this issue, but more examples and better constraints in the progenitor stars are needed. This is discussed further below.

The recent recognition that eruptions similar to LBVs may occur in moderately massive stars with initial masses below 20 M\(_{\odot}\) has rather profound consequences. While the ultimate trigger and physical mechanism for LBV giant eruptions remain unknown, it has generally been accepted that the eruptive behaviour is the consequence of these stars approaching or exceeding the classical Eddington limit. If the progenitor stars of SN 2008S and N300-OT really did have initial masses well below 20 M\(_{\odot}\), this is surprising...
and informative, since stars in this mass range should never approach the classical Eddington limit in the normal course of their evolution. The most massive stars with initial masses above 60 M☉ will naturally and unavoidably be driven to a SE state in their post-main-sequence evolution, while stars with initial masses of 25–40 M☉ may approach the Eddington limit in a post-RSG phase, after they have shed significant mass and thereby raised their \( L/M \) ratio. Stars below 20 M☉, however, have relatively tame luminosities and should not exhibit mass-loss rates sufficiently high to bring their \( L/M \) ratios to such dangerous levels. Thus, while more massive stars can easily exceed the Eddington limit temporarily with small adjustments in opacity or stellar structure, lower mass stars require a substantial input of extra energy to bring them to the exceptional peak luminosities observed and to successfully eject large amounts of mass. While \( \eta \) Car was about five times the Eddington luminosity at the peak of its giant eruption, the SN impostors SN 2008S and N300-OT that reached a similar peak luminosity had Eddington factors of more like 40–80 (see Bond et al. 2009; Smith et al. 2009a).

4.2 Pre-outburst variability and multiple eruptions

We have information about the pre-outburst progenitor star for very few of the eruptive transients discussed here. When this information is available, though, it is extremely valuable. Progenitor detections are hard to obtain and multiepoch progenitor detections are even more rare.

Nevertheless, based on improving archival data, the observational case is building that several SN impostors experience a phase of growing instability that can precede the most dramatic brightening (usually associated with the time of discovery) by a few years or decades. A classic example of this is \( \eta \) Car, which showed a slowly increasing visual magnitude for a century before its mid-19th century eruption, but then – more remarkably – exhibited several very brief precursor brightening events before the main extended bright phase of its eruption (see Smith & Frew 2011). V12/SN 1954J is another key historical example, which showed very peculiar and erratic variability for 5–10 yr before its giant eruption (Tammann & Sandage 1968).

More recent examples include SN 2009ip and U2773-OT, which had slow (~5 yr) episodes preceding their eruptions (Smith et al. 2010a). SN 2000ch has shown multiple recurrences of brief brightening episodes (Pastorello et al. 2010) and SN 2009ip has now undergone another eruption ~1 yr after the previously detected one (Drake et al. 2010). HD 5980 exhibited some minor brightening episodes before its major eruption and, of course, P Cygni suffered a second eruption 55 yr after the beginning of its first major eruption (Smith & Frew 2011). At the very least, the presence of multiple recurring outbursts is a strong indication that the stars survive these events and that the underlying physical mechanism is not a terminal event, such as a core-collapse SN, an electron-capture SN or a failed SN. This is further discussed below.

A critical point is that if these stars can experience multiple outbursts on relatively short time-scales, then there is no guarantee that a given transient event is the first one experienced by that star. A given progenitor may be in a state where it is still recovering from a previous recent burst, which may have been an extremely disruptive event, while any dusty CSM surrounding that progenitor may have been ejected in a very recent but undocumented previous eruption.

Thus, one must be cautious when interpreting the significance of a given progenitor’s observed properties – especially if it is based on a single epoch or a brief range of time. This is perhaps an area where much longer temporal baselines from plate archives may be of substantial benefit. The luminosity one infers from an observation of a progenitor is not necessarily the quiescent bolometric luminosity of the star or the normal state of that star, and may therefore cause erroneous estimates of that star’s initial mass. Furthermore, if the progenitor was heavily obscured, one must be careful in making direct comparisons to classes of stars that are always heavily enshrouded, like OH/IR stars or AGB stars, because the obscuring dust may have a very different origin in a recent eruption. Thus, initial masses and evolutionary states derived from progenitor observations must be taken with a grain of salt. Ideally, one would like to combine information about the progenitor with estimates of the ages of surrounding stars, as Gogarten et al. (2009) did for N300-OT. More studies of this type may help advance the field significantly.

4.3 Outburst diversity: explosions or winds?

All massive stars in the local universe have considerable radiation-driven stellar winds, and these winds become a dominant and defining characteristic for evolved supergiants and hypergiants: the strong emission lines that define WR stars, LBVs, blue supergiants and yellow hypergiants are caused by their extended and often partially opaque stellar winds. Given the similarity between the spectra of SN impostors and those of Galactic LBVs and hypergiants, it is natural to conclude that extreme winds are also the key physical mechanism in SN impostors. Detailed modelling of the spectra for a few events, like V1 in NGC 2366 (Petit et al. 2006), has demonstrated this.

However, recent clues also suggest that the hydrodynamic expulsion of the stellar envelope may be at work in some eruptions. This was suspected based on the ratio of kinetic to radiated energy in \( \eta \) Car (Smith et al. 2003b), and the presence of an energetic blast wave was later confirmed by the discovery of extremely fast ejecta surrounding this star (Smith 2008). Similar fast material has now also been seen in SN 2009ip (Smith et al. 2010a; Foley et al. 2011). Thus, these strong blast waves imply that dynamic explosions are an important ingredient in at least some LBV-like eruptions, in addition to extremely strong winds. While the total mass lost in an event may be the same for an extreme but temporary wind as compared to an explosion, the corresponding implication for the underlying physical mechanism is quite important. An explosion implies a severe restructuring of the star on a dynamical time-scale, requiring a deep deposition of energy inside the star, and the radiative transient we see is an after-effect. In the case of a wind, the implication is that the luminosity of the star has increased, and this increase in luminosity causes mass to be lifted from the surface of the star in quasi-steady-state. Given the complex light curves of some SN impostors, it is easy to imagine a hybrid situation where an initial shock heats the envelope, and the resulting increase in radiative luminosity drives a strong wind. Furthermore, one can propose that a range of energy deposition could lead to a large diversity of observed phenomena ranging from enhanced winds to explosions, as explored by Dessart et al. (2010). In other words, it seems possible that the diversity in winds and explosive phenomena might be different manifestations of the same basic energy deposition.

With the possibility of explosive mechanisms for the origin of SN impostors also comes the possibility that their luminosity might be enhanced or even dominated by the interaction of the blast wave with a dense CSM, as in traditional Type IIn SNe, but with lower energy shock waves. This hypothesis has not been explored much in...
4.4 SN 1961V: LBV megaeruption or a true core-collapse Type IIn SN?

In light of the distribution of LBV-like eruption properties, a close re-examination of SN 1961V is warranted, it is the prototype of Fritz Zwicky’s original Type V class of SNe; it has coloured much interpretation of the SN impostors because of noted similarity to η Car, and it is a rare case where the progenitor star was identified in the decades before the event.

Goodrich et al. (1989) first made the case that SN 1961V was not actually a core-collapse SN, but was instead an exaggerated η Car-like outburst; this was based on the detection of intermediate-width (2000 km s$^{-1}$) H$\alpha$ emission at the expected position of the SN in a ground-based spectrum taken 25 yr after the peak of the eruption (see also Shklovsky 1968). Filippenko et al. (1995) tentatively identified a red source seen in early (aberrated) HST images, suggesting that this may be the dusty source predicted by Goodrich et al. (1989). Later imaging studies with the refurbished HST disagreed on which source was coincident with SN 1961V (Van Dyk et al. 2002; Chu et al. 2004). Despite this disagreement about which star is the potential survivor, SN 1961V is usually regarded as a prototype of the SN impostors because it was well studied and was the original ‘Type V’ supernova. It is ironic then that our present comparison finds SN 1961V to be an extreme outlier among the class of SN impostors in every measurable way. This raises the obvious question: was SN 1961V really an impostor?

After considering the distribution of properties among LBVs and Type IIn SNe, the answer seems to be ‘probably not’. The original motivation for linking SN 1961V to η Car was the relatively narrow width of its emission lines compared to those of Type II-P SNe, plus its slow and unusual light-curve evolution. However, these and essentially all of its observed properties are consistent with the class of true Type IIn SNe, where the narrow lines and extra luminosity are thought to arise from core-collapse explosions interacting with dense CSM. The Type IIn class was not yet recognized at the time of the outburst (leading to Zwicky’s suggestion of a new Type V), but there has been much progress in understanding the properties and diversity of Type IIn SNe in recent years.

Based on photographic spectra taken during the peak of the outburst, Zwicky (1964) inferred an expansion speed of 3700 km s$^{-1}$ from the width of H$\alpha$, while Branch & Greenstein (1971) estimated $V_{\text{exp}} \approx 2000$ km s$^{-1}$ based mainly on calculated fits to Fe ii and similar lines in a series of spectra taken at different times during the event. Goodrich et al. (1989) estimated 2100 km s$^{-1}$ from H$\alpha$ in the very late time spectra. Humphreys & Davidson (1994) contended that such narrow lines meant that SN 1961V was ‘definitely’ not an ordinary SN and more closely resembled η Car. However, the conjecture that SN 1961V was not a true SN based on its narrow lines is invalid. Most bona fide Type IIn SNe have linewidths of 1000–4000 km s$^{-1}$ (e.g. Filippenko 1997; Chugai et al. 2004; Smith et al. 2008, 2009b, 2010b); even some of the most luminous known SNe have lines as narrow as 1000 km s$^{-1}$ (Prieto et al. 2007; Smith et al. 2008, 2010b). Consulting Fig. 11, the expansion speed inferred from linewidths in SN 1961V is clearly more consistent with that of normal SNe than with the rest of the LBV eruptions.

The light curve of SN 1961V – while complex and quite unusual – also does not provide a very compelling case that this object was not a true SN. Fig. 14 compares the light curve of SN 1961V to that of a normal Type II-P SN and to those of two well-studied Type IIn SNe: SN 1988Z and SN 2005ip.$^7$ The long decay time for SN 1961V is easily understood by continued CSM interaction at late times; both SN 2005ip and SN 1988Z were more luminous for a longer time. SN 1961V is thus intermediate between these classic Type IIn SNe and a normal Type II-P SN (i.e. at no time is it less luminous than a normal Type II-P SN), making it a somewhat less-extreme version of CSM interaction than SN 2005ip. Many other Type IIn SNe that are regarded as core-collapse SNe are less luminous than SN 1961V. The absolute magnitude of the brightest peak in the light curve of SN 1961V was almost identical to that of SN 2005ip. The rather stark interruptions in its decline (interpreted as late ‘plateaus’ by Humphreys et al. 1999) also find a clear precedent in SN 2005ip, whose light curve declined rapidly until day 160, when it abruptly hit a floor and remained at the same luminosity (or even rose slightly) for years thereafter (Smith et al. 2009b).

Still, the light curve of SN 1961V is admittedly a bit unusual compared to that of most Type IIn SNe. The key seemingly unique property is that it shows an initial luminous plateau at $-16.5$ mag for

\section*{Figure 14.

Same as Fig. 8, but comparing the light curve of SN 1961V to that of a normal Type II-P SN and two examples of well-studied Type IIn SNe. The light curves of SN 1999em (Type II-P), SN 2005ip (Type IIn) and SN 1988Z (Type IIn) are the same as they appear in fig. 1 of Smith et al. (2009b), except that the light curve of SN 2005ip is shifted by $+130$ d for reasons discussed in the text.}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure14.png}
\caption{Same as Fig. 8, but comparing the light curve of SN 1961V to that of a normal Type II-P SN and two examples of well-studied Type IIn SNe: SN 1988Z and SN 2005ip.$^7$ The long decay time for SN 1961V is easily understood by continued CSM interaction at late times; both SN 2005ip and SN 1988Z were more luminous for a longer time. SN 1961V is thus intermediate between these classic Type IIn SNe and a normal Type II-P SN (i.e. at no time is it less luminous than a normal Type II-P SN), making it a somewhat less-extreme version of CSM interaction than SN 2005ip. Many other Type IIn SNe that are regarded as core-collapse SNe are less luminous than SN 1961V. The absolute magnitude of the brightest peak in the light curve of SN 1961V was almost identical to that of SN 2005ip. The rather stark interruptions in its decline (interpreted as late ‘plateaus’ by Humphreys et al. 1999) also find a clear precedent in SN 2005ip, whose light curve declined rapidly until day 160, when it abruptly hit a floor and remained at the same luminosity (or even rose slightly) for years thereafter (Smith et al. 2009b).}
\end{figure}}

\footnote{Here we find that the peak absolute magnitude was almost $-18$ mag. Humphreys & Davidson (1994) chose to adopt the closest of published distances to NGC 1058 ($m - M = 28.6$ mag; 5.3 Mpc), making the peak magnitude $-16.4$, which is still brighter than any other SN impostor and comparable to normal Type II-P SNe. Most estimates, however, favour a larger distance and therefore a higher luminosity for SN 1961V. The expanding photosphere method applied to SN 1969L gives $m - M = 30.13 - 30.25$ mag for NGC 1058 (Schmidt, Kirshner & Eastman 1992; Schmidt et al. 1994), whereas the Hubble-flow distance (assuming $H_0 = 73.0$ km s$^{-1}$ Mpc$^{-1}$) gives $m - M = 29.77$ mag. We therefore adopt $m - M = 30.0$ mag and also correct the light curve for a Galactic extinction value of $A_B = 0.27$ mag (the $B$-band extinction is probably most appropriate for the photographic magnitudes in the light curve), making the peak absolute magnitude roughly $-17.8$, far exceeding that of any other SN impostor.}
~105 d, followed by a second more extreme peak reaching almost -18 mag before declining rapidly thereafter. This can potentially be understood as a superposition of a normal Type II-P SN plateau (like that of SN 1999em) followed by a late-time addition of luminosity from enhanced CSM interaction, as seen in a Type Ibn SN like SN 2005ip. This superposition is shown schematically in Fig. 14 with the light curve of SN 2005ip (Smith et al. 2009b) shifted by +130 d for comparison. The only requirement here, from the CSM-interaction point of view, is that the CSM shell had an inner cavity of lower density than the main shell, so that the time when the blast wave struck the densest part of the CSM shell was delayed by 120–130 d. A delayed turn-on of the CSM interaction luminosity is understandable with a thin dense shell at a large radius (e.g. van Marle et al. 2010). A late turn-on even has clear observational precedent among Type Ibn SNe: an extreme case is the recent Type Ibn SN event SN 2008iy, which started with a luminosity comparable to a Type II-P SN, but continued to rise slowly for ~400 d (Miller et al. 2010).

With a SN blast wave expansion speed of ~4000 km s⁻¹ (adopting Zwicky’s estimated speed from spectra during the event), the shock would have struck the shell after day ~105 when the rise to the bright peak began if the shell had a radius >250 au. This is entirely plausible, given the observed shells around known LBVs and the shells inferred around other Type Ibn SNe. If that LBV shell had initially been ejected at a few hundred km s⁻¹ (also typical of LBVs), then it would imply that the shell had been ejected within ~5 yr before the final SN explosion. Indeed, ≤1 yr prior to the beginning of the main peak, SN 1961V was already in a precursor outburst state with an absolute magnitude of ~14.5 (see Fig. 8), which is quite similar to η Car and other LBV eruptions. This provides a self-consistent picture, where SN 1961V suffered a precursor LBV outburst that was followed within a few years by a true core-collapse Type Ibn SN.

While somewhat complicated, this scenario fits in well with current ideas about Type Ibn SNe, and it is appealing because it no longer requires the progenitor to have been an astoundingly massive star. If the high pre-maximum luminosity is attributed to an LBV-like outburst rather than a quiescent star, and if the peak outburst was a genuine core-collapse SN explosion, then conjectures that the progenitor was incredibly massive (up to 2000 M⊙; Utrobin 1984; Goodrich et al. 1989; Humphreys & Davidson 1994) are clearly erroneous. It also relieves the difficulty of trying to account for the tremendous energy budget of SN 1961V with a non-terminal event.

If this hypothesis is true, then it is the first definitive detection of a precursor LBV outburst prior to a Type Ibn SN, further strengthening the LBV–Type Ibn SN connection. It would also make the progenitor of SN 1961V the most massive SN progenitor yet identified. This builds upon earlier results of the precursor LBV-like outburst before the unusual Type Ibn event SN 2006jc (Foley et al. 2007; Pastorello et al. 2007b), as well as the detected progenitor of the ‘Type Ibn event SN 2005gl that was inferred to be an LBV-like star (Gal-Yam & Leonard 2009). In fact, it remains possible that the progenitor identified as a possible LBV by Gal-Yam & Leonard (2009) could have been in an eruptive state at the time the pre-discovery archival data were obtained, although this is uncertain. A decade before SN 1961V, the progenitor was observed at an absolute magnitude of about ~12.4, similar to the quiescent bolometric luminosity of η Car. Like Goodrich et al. (1989), we infer that this is probably the quiescent bolometric luminosity of the progenitor star, making it comparable to the most luminous stars known. Since the progenitor resided in a giant H II region similar to the Carina nebula, this appears reasonable.

In this continued CSM-interaction context, the undulations in the late-time decay of SN 1961V are also easily explained by hypothesizing that the expanding blast wave overtook a series of additional shells or clumps at larger radii, causing a small and temporary enhancement in the luminosity. SN 1988Z, SN 2005ip and other Type Ibn SNe demonstrate that this is achievable. The luminosity of a Type Ibn SN can turn on or off at any time, depending on the density of material with which the ejecta are colliding. If the CSM environment was dusty, some of this late-time luminosity may also be attributable to a reflected light echo (recall that the SN 1961V historical light curve is in photographic magnitudes, which favour blue wavelengths).

As noted earlier, putative detections of the surviving star of SN 1961V have been controversial, so proof of the Type Ibn SN hypothesis remains elusive based on modern data. Even if a source is detected at the correct position, however, it may still be fuelled by weak CSM interaction at late times, or it may be another star in the crowded star cluster. For example, Li et al. (2002) detected the Type Ibn event SN 1995N many years after the explosion, while SN 1988Z still remains luminous. The conjecture by Chu et al. (2004) that the Hα source identified in their data (object 7) ‘cannot be the SN or its remnant because of the absence of forbidden lines’ is incorrect if the late-time luminosity is powered by CSM interaction rather than by radioactive decay. Stockdale et al. (2001) detected a non-thermal radio continuum source at the position of SN 1961V, and Chu et al. (2004) showed that this radio source is coincident with the only strong Hα emission-line star in the cluster. The radio and narrow Hα emissions are certainly consistent, in principle, with the strong continued CSM interaction that one may expect in the Type Ibn SN hypothesis. Furthermore, the presence of dust inferred from strong IR emission in the late-time data of SN 1961V is also consistent with the Type Ibn SN hypothesis, because a strong IR excess from new dust formation and from an IR echo were both seen in SN 2005ip (Smith et al. 2009b; Fox et al. 2010).

Thus, we find the most straightforward explanation to be that the peak of SN 1961V was probably not a SN impostor after all, but a bona fide Type Ibn SN caused by a core-collapse event. We suggest that the initial peak for the first ~105 d was akin to the plateau of a normal Type II-P SN (this does not exclude the possibility of narrow lines from CSM interaction being present at that time), while the so-called ‘super outburst’ when SN 1961V reached M_H ~ -18 mag and then faded rapidly may have been powered by CSM interaction as in a Type Ibn SN like SN 2005ip. In this scenario, the essential difference between SN 1961V and a conventional Type Ibn SN is that the CSM interaction was delayed, probably because the CSM shell was at a large radius with an interior cavity. In future studies, readers of this paper are therefore advised to disregard the fact that SN 1961V was included in figures comparing the light curves and other properties of LBV-like eruptions, at least to the extent that these plots are taken as indicative of LBVs.

4.5 Other intermediate-luminosity transients

While the distinction between LBV-like eruptions and true core-collapse SNe may be more clear after considering the distribution of LBV-like eruption properties, the bottom end of the LBV distribution remains nebulous. Drawing a clear dividing line between true LBV giant eruptions and ‘normal’ S Dor eruptions is not as easy as previously suggested (e.g. Humphreys & Davidson 1994), since the notion that S Dor eruptions always occur at constant bolometric luminosity has not withstood rigorous analysis (Groh et al. 2009), and the conjecture that these eruptions should always have atmospheres...
with temperatures around 8000 K is also incorrect. For example, it is unclear if the eruptions of HD 5980 and SN 2002kg do indeed qualify as giant LBV eruptions, since we do not know that they experienced a substantial increase in bolometric luminosity, and the total amount of mass and energy lost was not much in excess of the stars’ quiescent output. Of course, defining a transient as a giant LBV eruption or S Dor outburst at the lower end of SN impostor luminosities (see Fig. 13) also requires reliable knowledge of the progenitor’s luminosity — in order to decide if the bolometric luminosity has indeed increased — which is often not available. For SN impostors with relatively high peak luminosities above $-13$ mag, this is not a problem because no stars have a quiescent luminosity this high, and so the bolometric luminosity must have increased substantially.

Furthermore, the bottom end of the luminosity distribution for SN impostors also overlaps with transients that may not be LBV eruptions and might not even be associated with massive stars. Thompson et al. (2009) have proposed a new subclass of transients where the progenitor star was heavily obscured and had relatively low bolometric luminosities, exhibiting [Ca ii] emission in addition to narrow Balmer emission lines. This was inspired largely by the discovery and detailed observations of SN 2008S and N300-OT, discussed extensively above. However, whether these transients constitute an entirely new class of outbursts, or if they instead represent an extension of LBV-like eruptions to lower masses than previously thought (i.e. below 20–25 $M_\odot$), is controversial (see Smith et al. 2010a for a recent summary of the debate; see also Thompson et al. 2009; Smith et al. 2009a; Prieto et al. 2010). The source of the disagreement is that all of the properties attributed to this putative new class of objects are already observed among known LBVs. Obscuring dust shells are certainly common among known LBVs, while we have demonstrated here (Fig. 12) that the presence of [Ca ii] emission is seen in many of the SN impostors to varying degrees, although it had not been emphasized in discussions before 2008, and these lines are seen in hypergiants like IRC+10420 having very strong winds (Smith et al. 2009a).

Recently, Prieto et al. (2009) presented a mid-IR spectrum of N300-OT that contained an emission feature reminiscent of the polycyclic aromatic hydrocarbon (PAH) features seen in some proto-PNe, and they interpreted this as an indication that the progenitor of N300-OT was a carbon-rich super-AGB star. However, the presence of PAH emission features does not necessarily constitute C-rich chemistry. Moreover, prominent PAH features have been seen in the mid-IR spectra of known LBVs such as HD 168625 (e.g. Umana et al. 2010), which has a luminosity corresponding to an initial mass of about 25 $M_\odot$. One cannot rely on the inference of amorphous carbon grains (e.g. Wesson et al. 2010) as necessarily indicative of carbon-rich gas chemistry either, since carbon grains form at much higher temperatures than silicates, and the conditions for rapid dust formation in ejected shells may be very different from the conditions in RSG/AGB winds. The presence of PAH features in a SN impostor spectrum, or the presence of carbon grains, is therefore not necessarily indicative of a carbon-rich AGB-star progenitor.

Alternatively, it is quite possible that the reason the progenitor stars of SN 2008S and N300-OT were obscured (and possibly why they had low luminosities) is because the stars suffered a previous recent outburst that had not been documented. LBVs are known to suffer multiple successive eruptions (see Section 4.2). The most distinguishing property of the SN 2008S and N300-OT progenitors was their relatively low luminosity, implying initial masses below 20 $M_\odot$. Although the observed IR luminosities (which are really minimum luminosities) are consistent with some models for the most extreme super-AGB stars, studies of the star formation history of the N300-OT environment favour a more massive progenitor star of 12–25 $M_\odot$ (Gogarten et al. 2009).

Thus, it is difficult to reliably classify SN 2008S and N300-OT as an entirely new and separate type of transient (note that they reside in the most common location for SN impostors in Fig. 13). Until we actually identify the underlying physical mechanism of the outbursts (see Section 4.6), this difference is rather semantic, depending on whether one prefers to see them as an extension of eruptive phenomena in more massive stars or a different class of eruptions occurring in stars below 20 $M_\odot$. (In either case, they are extremely interesting and may be more common than SN impostors from more massive progenitors simply because of the slope of the initial mass function.) For these reasons, we have included SN 2008S and N300-OT among the other SN impostors, but perhaps the debate will continue for decades until the stars recover from the outbursts and reveal themselves or until they finally explode as core-collapse SNe.

Nevertheless, it appears that some recent transients are pushing the bottom end of the envelope that encompasses LBVs, the strongest evidence of which is their relatively low luminosity progenitors and stellar environments. The physical mechanism of all these outbursts remains elusive. The following transients share some overlap with LBVs, but do bear perceived differences well. We note them in a separate section here because previous authors interpreted them as something other than LBVs.

**V838 Mon.** The best studied of this group of unusual transients is V838 Mon, which erupted at a distance of ~6 kpc in our Galaxy in 2002 and has since produced a spectacular light echo in its circumstellar reflection nebula (Bond et al. 2003; Sparks et al. 2008). The transient had a peak absolute $V$ magnitude of $-9.8$, and studies of its associated cluster of B-type stars imply an age of $<25$ Myr and an initial mass of $>8 M_\odot$ if the transient is an evolved star (Afsar & Bond 2007). The complex, multipeaked $BVI$ light curve from Sparks et al. (2008) is shown in Fig. 15. From this, we determine values of $t_{1.5}$ of roughly 12 and 75 d for the main and secondary peaks, respectively.

Fig. 16 shows a visual spectrum of V838 Mon from our spectral data base (see also Rushton et al. 2005), obtained with Lick/Kast on 2002 February 11, about 5 d after the main $B$- and $V$-band peak in the light curve. This spectrum is representative of the early bright stages of the transient, whereas the spectrum evolved significantly at late times, becoming much redder and displaying deep molecular absorption features (e.g. Bond et al. 2003). We find it quite remarkable that the spectrum of V838 Mon near maximum light is nearly a carbon copy of the visual-wavelength spectrum of U2773-OT, which had a more luminous LBV progenitor star and a much more luminous and longer lasting eruption than V838 Mon. The only substantive difference between the spectra of V838 Mon and U2773-OT is that the narrow absorption lines in U2773-OT are somewhat stronger than in V838 Mon.

**M85-OT.** We discovered M85-OT during the normal course of the LOSS in 2006 January. Kulkarni et al. (2007) presented the first detailed study of this object and drew attention to its faint progenitor star and the transient’s apparent differences compared to novae, SNe and LBVs. Alternatively, Pastorello et al. (2007a)
argued that it could be a very faint core-collapse SN. The absolute \( R \)-band light curve of M85-OT from Kulkarni et al. (2007) is shown in Fig. 15. Kulkarni et al. suggested that the peak luminosity and decay rate of this transient occupied a ‘gap’ between novae and SNe in luminosity, but faster than LBVs. As we have seen in this paper, however, LBV eruptions occupy a larger range of characteristic fading times than previously recognized, from a day to a decade, and the light curve of M85-OT (with a peak absolute magnitude of almost \(-13\) and a decay time of 80–100 d) fits well within the parameter space occupied by known LBV giant eruptions (Fig. 13).

M85-OT also appeared somewhat redder than LBVs, suggesting a temperature of roughly 5000 K (Kulkarni et al. 2007), but this depends on the assumed extinction and reddening. Note that these authors estimated an upper limit to the extinction based on the observed Balmer decrement, assuming that it should follow the standard Case B low-density recombination value. However, Balmer-line ratios in dense winds and ejecta do not always follow these standard recombination values, so the reddening could be higher. Indeed, Prieto et al. (2008b) later showed that M85-OT had a large IR excess, suggesting a very dense and dusty CSM. This means that the apparent temperature of M85-OT may have been warmer than 5000 K and that its peak magnitude was probably more luminous. It also means that the progenitor could have been substantially more luminous than the Kulkarni et al. (2007) upper limit to the progenitor star’s absolute \( g \) magnitude of \(-4.1\) mag. While this would still be fainter than the most luminous LBVs, it approaches the values inferred for N300-OT and SN 2008S.

In Fig. 16, we illustrate the Keck/LRIS spectrum of M85-OT from Kulkarni et al. (2007), corrected for the value of \( E(B - V) = 0.14 \) mag adopted by those authors (black spectrum) as well as for a higher reddening of \( E(B - V) = 0.7 \) mag (grey spectrum). With correction for this higher reddening, the continuum can be approximated by a temperature around 6500 K, except for wavelengths below 4500 Å where line blanketing may be important (this is also the case for fits involving cooler temperatures and lower reddening correction). The point of this comparison is that a larger value for the extinction and reddening is plausible, which could mean that the transient and its progenitor were more luminous; for example, adopting a reddening of 0.7 mag, as shown here, the peak absolute visual magnitude would have been around \(-14.5\).

The spectrum of M85-OT closely resembles that of N300-OT, also shown in Fig. 16 for comparison. Both transients have weak emission from the \( \text{Ca II} \) IR triplet, weak and narrow \( \text{H} \& \text{K} \) absorption, implying that at the times when the spectra were taken, the emitting photospheres probably had similar temperatures. In that case, the higher reddening correction we have shown here would also bring the continuum shapes into better agreement.

After considering the distribution of properties of LBV-like eruptions described in this paper, as well as a comparison between the spectra of M85-OT and N300-OT, it is much less clear based on the properties of the outburst alone that M85-OT is something altogether different from other SN impostors, especially if it is shifted upwards by 0.5–1 mag in Fig. 13 due to a higher reddening value. The strongest case for a different type of source comes from its local environment that implies an initial mass around 7 M\(_{\odot}\) or less (Ofek et al. 2008), which is lower than that of V838 Mon and N300-OT.

**SN 2010U.** Nakano (2010a) discovered SN 2010U in NGC 4212, at an unfiltered magnitude of 16.0, on 2010 February 5.6. The peak unfiltered magnitude was 15.9 and the progenitor was undetected with a limit of 18.0 mag. At a distance of 3.3 Mpc for NGC 4212, the corresponding peak absolute magnitude is roughly \(-11.7\) (not corrected for reddening). A spectrum obtained by Marion, Vinko & Wheeler (2010) 2 d after the discovery showed a blue continuum with strong narrow Balmer emission lines having P Cygni absorption features indicating outflow speeds of \(-900 \text{ km s}^{-1}\), similar to many SN impostors. Humphreys et al. (2010) recently suggested that this source is not an LBV eruption, but is instead a luminous nova. The light curve is shown in Fig. 15 for comparison. It does fade faster than some LBVs like HD 5980 and V12 (shown here), but the rapid fading is comparable to or even slower than that of brief events in SN 2009ip (Smith et al. 2010a) and SN 2000ch (Wagner et al. 2004; Pastorello et al. 2010). Its peak luminosity is closer to that of SN impostors than to novae (Fig. 13).

We obtained one spectrum of SN 2010U on 2010 February 7 using Keck/LRIS, as shown in Fig. 16. This date corresponds to 2 d after the discovery and about 1 d after maximum light (i.e. well before the transient faded significantly). Among our sample of SN impostors, SN 2010U most closely resembles the spectrum of SN 2000ch (also shown in Fig. 16). It is interesting, then, that the fast decay and peak absolute magnitude of SN 2010U are also very similar to those of SN 2000ch, which is a confirmed LBV showing additional multiple eruptions many years later (Pastorello et al. 2010). It would be worthwhile to continue monitoring SN 2010U, to see if it follows suit. Based on the similarity in both light curves and spectra between SN 2010U and SN 2000ch, the claim that SN 2010U is a luminous nova and not an LBV-like eruption becomes less secure; the observed properties of the transient seem as consistent with LBVs as with novae. As noted by Humphreys et al. (2010), however, the upper limits for the progenitor star and its surrounding population seem to argue that it had an initial mass \( \lesssim 5 M_{\odot} \). This provides another case where eruptions that closely resemble LBVs seem to occur in lower mass stars as well.
Figure 16. Spectra from our data base of a few of the intermediate-luminosity transients discussed in Section 4.5, compared to SN impostors shown earlier in Fig. 12. The spectrum of SN 2010U was taken on 2010 February 7 with Keck/LRIS and corresponds to day 2 after discovery. We obtained the spectrum of V838 Mon with the Lick 3-m Kast spectrograph on 2002 February 11, about 5 d after the brightest peak in the B and V light curves (see Fig. 15). The observed flux has been corrected for $E(B - V) = 0.87$ mag, following Munari et al. (2005). The spectrum of M85-OT is the Keck/LRIS spectrum from Kulkarni et al. (2007); here we show it corrected for $E(B - V) = 0.14$ mag (black), as in that paper, as well as what it would look like if corrected for a larger value of $E(B - V) = 0.7$ mag (grey) for comparison. The spectra of SN 2000ch, UGC 2773-OT and N300-OT are the same as in Fig. 12.

M31 RV1. Rich et al. (1989) discovered a luminous red variable star in M31, which rose to a bolometric absolute magnitude of $-9.8$ in 1988 September. In the I band, it then faded about 3 mag in 43 d and had been 5 mag fainter in pre-discovery images. It did not fade nearly as much in the K band after discovery, suggesting that the bolometric luminosity did not necessarily change much and that either dust obscuration increased or the object cooled after the outburst. The nature of this transient is unclear, but it showed the absorption-line spectrum of an M0 supergiant plus narrow Balmer-line emission. IR data are not available before the discovery, so one cannot exclude the possibility that the progenitor was heavily obscured.

Kulkarni et al. (2007) compared M31 RV1 to M85-OT, although the latter source was more luminous and faded more slowly; moreover, M85-OT showed the Ca ii IR triplet and other features in emission, and did not exhibit the TiO and other absorption bands characteristic of a cool M supergiant. In terms of its absolute magnitude and strong evolution to the red as it faded, M31 RV1 was more like V838 Mon than M85-OT, although it is not known to have had a complex multi-peaked light curve like V838 Mon. Recently, Shara et al. (2010) examined archival HST images of M31 RV1 obtained 10 yr after the transient event and suggested that a detected source is consistent with an old nova rather than a merger event, but continued study of the remnant object is needed.

PTF10fqs. This is an apparently red-coloured transient located in the outer parts of a spiral arm of M99, with a peak absolute visual magnitude of about $-11$, expansion speeds of $\sim 800$ km s$^{-1}$ and a spectrum very similar to that of V838 Mon as well as SN impostors SN 2008S and N300-OT (Kasliwal et al. 2010). Overall, the outburst of PTF10fqs appeared extremely similar to other SN impostors on the faint end of the distribution. As with M85-OT, visual upper limits to its progenitor would imply a star less massive than $\sim 8$ $M_\odot$ if there were no local extinction. However, based on the red colour of the transient and the presence of [Ca ii] emission in its spectrum, the progenitor may have been heavily obscured like SN 2008S and N300-OT; unfortunately, upper limits in the mid-IR are well above the IR luminosities for the progenitors of SN 2008S and N300-OT, so a more massive star cannot be ruled out for PTF10fqs.

The initial masses of these objects are uncertain, but at least one can be confident that they are not among the most luminous stars known. Stellar ages for the local environments of both V838 Mon and M85-OT are consistent with initial masses curiously close to the dividing line between core-collapse SNe and massive white dwarfs at around $8 M_\odot$. For PTF10fqs, a more massive star cannot be ruled out because of the uncertainty in the pre-outburst extinction, but it may be in this range as well. The progenitor of SN 2010U was proposed to be somewhat lower at $\sim 5$ $M_\odot$. One obvious possible suggestion for these transients is that they may arise from electron-capture SNe, expected to occur at initial masses around $8$–$10$ $M_\odot$. This possibility was suggested for SN 2008S and N300-OT as well (Botticella et al. 2009; Thompson et al. 2009) and although
mounting evidence argues against this interpretation for these particular sources, it remains feasible for the other objects.

Additional potential explanations include a wide variety of failed core-collapse SNe (e.g. Fryer et al. 2009; Moriya et al. 2010), the explosive birth of a massive white dwarf initiating the PN phase (Thompson et al. 2009), or stellar mergers and other tidal encounters (see below). The possibility that the PN phase might be initiated by a sudden explosive or eruptive event is extremely interesting from the point of view of understanding of the late-time evolution of intermediate-mass stars and the dynamics of PNe, but well beyond the scope of this paper and in need of further theoretical investigation. If true, there is potentially a great deal of synergy between studies of the transient sources and the associated nebulae in the mass ranges above and below 8 M_☉. Stellar mergers and tidal encounters represent another attractive explanation for these transients and other SN impostors, since there is no clear obstacle to binary encounters above or below ∼8 M_☉.

In summary, we find that based on criteria such as peak absolute magnitude, rate of fading, light-curve shape, or even colour and spectra, it is difficult to reliably distinguish LBV eruptions from non-LBVs (if the objects discussed in this section are in fact a distinct set of events). The only reliable way to establish a difference is based on having adequate information about their faint progenitor stars or their progenitor environment. (Indeed, when one considers the possibility that they may be obscured at visual wavelengths by CSM dust, we must also include deep IR data.) Such detailed information is rarely available except for nearby objects, but without it, claims of new types of transients may be questionable. This is a sobering fact to keep in mind as we embark on an era of more intensive transient studies.

Caveat. An interesting twist involves binary evolution, which should not be overlooked. We have emphasized that estimates of a progenitor star’s initial mass based on studies of the surrounding stars (e.g. Gogarten et al. 2009) provide some of our most important constraints on the nature of the progenitor stars. One potential pitfall, however, is the following. A star with an initial mass below 8 M_☉ may accrete a substantial amount of mass from its companion, raising it to more than 12 M_☉ and changing its evolutionary fate, perhaps leading to the types of eruptions encountered in initially more massive stars. Similarly, a secondary star with an initial mass of, say, 12–15 M_☉ may gain enough mass to raise its luminosity and make it behave like a 20–25 M_☉ star, and so on. The point is that even in cases where we have good constraints on the surrounding stellar population, the progenitor star may actually have been more massive than we are led to believe. This complexity is somewhat unsettling.

4.6 What is the underlying mechanism?

After more than a half century of research since the Hubble–Sandage variables were first identified (Hubble & Sandage 1953), the underlying cause and trigger of LBV giant eruptions remains unexplained. This makes it very difficult to say whether a given observed non-SN transient event is or is not an LBV, and this is exacerbated by the huge diversity in observed LBV-like properties demonstrated in this paper. Some LBVs are highly obscured by their own ejected dust shells (some are even completely obscured for decades), while others show no sign of dust whatsoever; some LBV giant eruptions involve ∼10^{49} erg explosions and 10–20 M_☉ of ejected mass, while others have only 10^{47} erg and 0.01 M_☉, and so on. As described in the previous section, there is considerable overlap with transients that are purported to be non-LBVs.

As with the case of distinguishing between Type Ia SNe and all other types of SNe, some clue of the physical mechanism is needed before we can reliably differentiate LBV giant eruptions from other transient events arising in moderately massive and intermediate-mass stars. Unfortunately, we do not yet have a clear working hypothesis for the physical mechanism behind LBV eruptions, so one hopes that observational clues can help narrow the field. Among the most important observational clues are the ejection speed of the material launched from the star, as well as the total mass and energy budget. As discussed in Section 4.3, the outflow velocities observed in most sources range from a few 100 km s^{-1} to a little more than 10^3 km s^{-1}, suggestive of either strong supergiant winds or CSM interaction, whereas some sources (e.g. η Car and SN 2009ip) show evidence for a small mass of much faster material moving at ∼5000 km s^{-1} (Smith 2008; Smith et al. 2010a; Foley et al. 2011), probably requiring the presence of a leading blast wave as well. Whether or not impulsive or explosive acceleration of the envelopes is at work in all SN impostors is uncertain, but shock waves are clearly present in a few of them, and so any successful theory must incorporate this. The total mass and energy budgets are harder to evaluate. Nearby examples with resolved nebulae from past outbursts allow us to measure the ejecta mass directly, and here we see a huge range from 0.01 to 10 M_☉ ejected in a single event. Unfortunately, the mass ejected in distant SN impostors is poorly constrained.

We can, however, estimate the total escaping radiated energy budget for each object, which is given roughly by $E_{\text{rad}} = \xi_1 L_{\text{peak}}$, where $\xi$ is a factor of the order of unity that depends on the exact shape of the light curve and $L_{\text{peak}}$ is the luminosity corresponding to the inferred peak absolute bolometric magnitude corrected for extinction. From Table 9, then, one can deduce a huge range in values of $E_{\text{rad}}$ from ∼2 × 10^{49} erg (η Car) down to ∼10^{46} erg. A caveat is that we must remember a lesson from nearby examples such as η Car, where the kinetic energy budget of ∼10^{46} erg greatly outweighs the escaping radiative energy budget of ∼10^{49} erg.

An interesting time-scale to consider is the ‘buildup’ or ‘recovery’ time-scale for the radiated energy budget, which is the time the star would require to supply $E_{\text{rad}}$ in its quiescent state, given by $t_{\text{rad}} = \frac{E_{\text{rad}}}{L_*} = t_{1.5} L_{\text{peak}}^{1.5} L_*$. where $L_*$ is the quiescent pre-outburst bolometric luminosity of the progenitor star. This is relevant in a type of model where the output core luminosity of the star is constant over a long timescale compared to the event and where the extra radiated energy is presumed to be the result of the thermal energy being stored in the star’s envelope and then released suddenly by some mechanism. It is also relevant for the time it takes the star to re-establish thermal and radiative equilibrium after a disruptive event. Here, too, we see a wide range of values, with $t_{\text{rad}} \approx 40$ yr for η Car, ∼1.1 yr for SN 2009ip and 32 yr for SN 2008S. If one can establish that $t_{\text{rad}}$ is considerably longer than any observed variability timescale in the progenitor, then it is likely that an additional energy reservoir is required (the need for extra energy obviously increases if one makes an allowance for kinetic energy as mentioned above). It also seems likely that $t_{\text{rad}}$ may be related to the amount of mass ejected from the star or the amount of the envelope mass involved in the adjustment of the star, although this is based only on the vague notion that the Kelvin–Helmholtz time-scale for the ejected mass plays a critical role. These considerations, while not conclusive, may be kept in mind when thinking about various models mentioned below.

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Investigating and thoroughly evaluating theoretical possibilities is far beyond the scope of this paper, but here we list some hypothetical mechanisms, as well as their pros and cons from the perspective of explaining the observed phenomena associated with SN impostors.

**Continuum-driven SE winds.** In addition to η Car, all of the luminous SN impostors clearly exceed the classical (i.e. electron-scattering) Eddington limit during the brightest phases of their outbursts. In the case of η Car, the star was apparently SE by a factor of Γ = 5 for more than a decade. Other SN impostors that appear to have lower progenitor masses but similar peak luminosities can achieve much more extreme values of Γ = 40–80. Regardless of the origin of this SE luminosity, it is unavoidable that such sustained high luminosities will in fact drive a strong wind from the star (unless of course the emerging radiation is from an already-successful hydrodynamic explosion). A few examples that have been studied in detail (e.g. V1 in NGC 2366; U2773-OT) are clearly consistent with wind-like spectra rather than explosions, so models of SE winds are certainly applicable to at least some of the SN impostors. Much of the work on the properties of SE winds so far has been conducted by Owocki and collaborators (Owocki et al. 2004; van Marle et al. 2008, 2009; see also Shaviv 2000). These studies of continuum-driven SE winds assume a strong increase in luminosity as a pre-condition for the models, concentrating primarily on the physics of driving mass from the surface of the star in quasi-steady state. These models do not, however, address the deeper question of what triggers the required increase in bolometric luminosity or what the ultimate energy source is.

**Runaway pulsations.** Following early work on the pulsational instability of massive stars (Ledoux 1941; Schwarzschild & Härm 1959; Appenzeller 1970), there is an expectation that the outer envelopes of massive stars should be quite unstable. Can runaway pulsational instability give rise to sudden mass ejections and luminous transients like SN impostors? Stothers & Chini (1993) proposed that an ionization-induced dynamical instability in their models of very massive stars could lead to violent outbursts such as that experienced by η Car, but Glatzel & Kiriakidis (1998) criticized this model because the adiabatic approximation is not valid for the envelopes of these stars, and their non-adiabatic models could not reproduce the instability except at very low temperatures. Non-linear growth of non-adiabatic strange-mode pulsations, however, may occur in the envelopes of luminous stars where the thermal time-scale is short and comparable to the dynamical time-scale (e.g. Glatzel & Kiriakidis 1993; Kiriakidis, Fricke & Glatzel 1993; Gautschy & Saio 1995, 1996; Glatzel et al. 1999). Non-linear growth of strange-mode pulsations is expected in very luminous stars, but may also occur in less-massive stars such as AGB stars (Gautschy & Saio 1995, 1996); thus, the full range of initial mass over which these pulsations are effective at triggering instability is uncertain, but potentially interesting for SN impostors and related transients.

Strange-mode instabilities depend on the iron opacity bump and occur primarily in the outer envelope of standard stellar evolution models (containing less than 1 per cent of the stellar mass); they therefore lead only to relatively minor increases in luminosity (a few tenths of a magnitude) and perhaps somewhat enhanced wind mass-loss. It has therefore been challenging to explain the major outbursts characteristic of SN impostors with the strange-mode instability. (Strange-mode pulsations may help trigger the normal S Dor variations of LBVs, however, and can potentially account for their observed microvariations.)

Further work is needed to determine if similar instabilities might occur deeper in the star, if they are to explain the ejection of several $\mathrm{M}_\odot$ and $10^{53}$–$10^{59}$ erg, as in a major outburst like that of η Car. For example, Young (2005) has described alternative stellar evolution models that include the effects of wave-driven mixing and rotation in the core evolution; he finds that these stars are more extended and that they therefore have the iron opacity bump deeper in the star. With the critical opacity bump in deeper layers, more mass and thermal energy are above the potentially unstable region, and Young (2005) hypothesizes that this stellar structure might give rise to more energetic and massive eruptions like SN impostors.

**Runaway mass-loss and the Geyer model.** Much of the observed phenomenology of LBV eruptions is reminiscent of geophysical geysers or volcanoes (see Humphreys & Davidson 1994). As described above, LBVs sometimes are seen to exhibit growing instability leading up to a large eruption. The occurrence of multiple shells in some cases suggests that eruptions may be followed by a more quiescent recovery time before the instability builds again. This has led to the suggestion of a geyser-like model for LBV giant eruptions (Maeder 1992), where very luminous stars reach cool temperatures in their post-main-sequence evolution, allowing a recombination front (akin to a boiling front in a geyser) to proceed into the star, thereby initiating a rise in mass-loss because of the change in opacity. This increased mass-loss continues until the star contracts to warmer temperatures, when the cycle begins again.

The simplicity of such a thermal engine is appealing, although more detailed calculations are needed to study the hydrodynamic response of a star in these conditions. It seems unlikely that this mechanism can explain the extreme amounts of mass ejected in brief energetic events, the sharp increases in bolometric luminosity or the explosive property of some eruptions. Another potential drawback of this mechanism is that it will only occur in very luminous stars near the classical Eddington limit and so cannot explain the full diversity of SN impostor eruptions, some of which apparently occur at relatively modest initial masses below 20 $\mathrm{M}_\odot$. It is nevertheless an interesting possibility for eruptions in the most luminous stars.

**Critical rotation limit.** In addition to the classical Eddington luminosity limit and the opacity-modified version, a star may reach instability due to rapid rotation. As single stars evolve off the main sequence, their cores contract and spin up the star. Langer (1998) proposed that luminous single stars may eventually reach a critical rotation limit before they will exceed the true classical Eddington limit and suggested that LBV eruptions might be associated with encountering this limit. It may be particularly applicable in cases where a mass gainer in a close binary system accretes mass and angular momentum (Langer et al. 2008). It is not clear how reaching this critical rotation will induce a sudden outburst of mass-loss, and it does not explain the observed increase in the bolometric luminosity of giant eruptions. Nevertheless, rotation may play a key role in the instability leading to these outbursts. Asymmetric nebulae are seen around nearby LBVs, and we have discussed above how changes in the viewing angle might factor into the observed diversity of SN impostors if the mass-loss is asymmetric.

**Pulsational pair-instability ejections.** Heger & Woosley (2002) have described a type of severe mass-loss event known as pulsatinal pair-instability (PPI) ejections, when a very massive star can eject of the order of 10 $\mathrm{M}_\odot$ in an explosive but non-terminal event. This is the same pair-formation instability that leads to a pair-instability SN (PISN; Barkat, Rakavy & Sack 1967; Rakavy & Shaviv 1967; Bond, Arnett & Carr 1984; Heger & Woosley 2002), but it occurs in a mass range below that of successful PISNe; the explosive burning is not enough to completely unbind the star, resulting in a $10^{50}$–$10^{59}$ erg ejection of only the outer envelope. Woosley, Blinnikov & Heger (2007) and Smith et al. (2007, 2010b) have mentioned the PPI as an
attractive explanation for the LBV-like mass ejections that precede some very luminous Type IIn SNe such as SN 2006gy.

Smith et al. (2010b) emphasized that expectations for PPI events match properties of some giant LBV eruptions in every observable way (large mass ejected, H-rich envelopes, total energy of $\sim 10^{50}$ erg, etc.), but also noted several problems with attributing PPI events as a general explanation for all LBV giant eruptions. First, the PPI occurs during the final burning phases and is expected to transpire in the few years to decades immediately before core collapse. However, many LBVs have massive shells with dynamical ages of $10^7$–$10^8$ yr, indicating that they have survived for millennia after the giant eruption that ejected their shells. Secondly, the PPI is only predicted to occur for extremely massive stars with initial masses above $\sim 95 M_{\odot}$ and usually only at low metallicity, whereas LBVs are known to arise from stars having initial masses as low as $20$–$25 M_{\odot}$ (Smith et al. 2004). Recent observations of low-luminosity progenitors may extend this mass range even lower, to within $10$–$20 M_{\odot}$, as described above. These lower mass LBVs will never encounter the PPI, so the PPI can only provide a possible explanation for the most extreme LBV giant eruptions in superluminous stars like $\eta$ Car, not the full range of the observed LBV-like eruption phenomenon.

Other shell-burning explosions. What about other types of explosive burning events, analogous to the PPI, but not necessarily restricted to the late-phase O or Si burning? This may relax the requirements for the very high core temperatures needed for the PPI and hence also the restrictions on initial masses that experience explosive burning instabilities. This is an old idea, first suggested (somewhat ironically) as a possibility for SN 1961V by Branch & Greenstein (1971) and revisited several times since then (Guzik, Cox & Despain 1999; Smith et al. 2003a; Guzik 2005; Smith & Owocki 2006; Smith 2008; Dessart et al. 2010). Substantive models for such events do not yet exist, but should be pursued.

Hypothetically, one can imagine that the energy source could be nuclear fusion of a small amount of material, if oscillations (e.g. non-radial g modes, unsteady convection, external perturbations, etc.) in the lower envelope mix fresh H-rich fuel into deeper and hotter layers of the star, triggering explosive burning. Initial simulations suggest that boundary layers within the star may be susceptible to dynamic disturbances (Guzik et al. 1999, 2005; Meakin & Arnett 2007). Even a few per cent of a solar mass of burnt H, for example, or a few tenths of a solar mass in silicon burning, would be sufficient to provide the extra energy inferred for giant LBV eruptions.

Different amounts of energy deposited at different depths within the star could conceivably account for the wide diversity in observed properties of SN impostors, over a wide range of masses, as suggested by some recent exploratory models (Dessart et al. 2010). A relatively large amount of deposited energy compared to the binding energy would initiate a large hydrodynamic explosion, whereas a smaller amount of deposited energy may just temporarily increase the luminosity of the star above the Eddington limit, at which point the physics of continuum-driven SE winds becomes relevant, as discussed above. Observations show evidence for both phenomena. Further progress in this direction requires substantial effort in multi-dimensional and hydrodynamic simulations of stellar interiors, plus estimates of the resulting observables. The observed radiation from SN impostor events, coupled with the detailed kinematics of nearby circumstellar shells, can provide important constraints on such models. Dessart et al. (2010) have argued that this type of energy deposition may be particularly likely in stars with initial masses of $8$–$12 M_{\odot}$, with obvious possible implications for SN 2008S, N300-OT and some of the sources discussed in the preceding section.

Failed SNe. Models that fail to generate successful core-collapse SNe may nevertheless produce partial explosions, and thus observable transient sources, as discussed recently by Fryer et al. (2009; see also Moriya et al. 2010). With a wide range of possible absolute magnitudes around $-14$, these certainly may be applicable to some of the observed SN impostors, especially in cases with dense CSM discussed by Fryer et al. (2009). Such mechanisms are unlikely to explain the full diversity of SN impostors, however, since several examples exist of LBVs that have survived giant eruptions as relatively stable hot supergiant stars, and there is considerable evidence that these eruptions can repeat multiple times on a variety of timescales up to millennia. Nevertheless, such failed SNe remain viable explanations for distant SN impostors, unless deep follow-up observations are available to establish the post-eruption state of the surviving star.

Electron-capture SNe. This idea has been discussed above. It does not offer an attractive explanation for the diversity observed in most SN impostors, because this type of event is only expected for a narrow range of initial masses around $8 M_{\odot}$. It does, however, provide a potential explanation for either faint Type II-P SNe (not discussed here) or some of the relatively faint transients considered in Section 4.5.

Close binary interaction events. Through the course of the post-main-sequence evolution of a massive star, its luminosity increases as the core contracts, its total mass decreases due to mass-loss, and so its proximity to the Eddington limit becomes more precarious. This is presumed to lead – somehow – to the instability we see as LBVs, by making the star more susceptible to internal or external disturbances. However, in addition, as a massive star evolves off the main sequence, it migrates to cooler temperatures, and so its radius increases by a huge factor. An increasing radius leads to inevitable dangerous encounters in binary systems with periods less than several years. Smith (2011) notes that in the case of $\eta$ Car (5.5 yr orbital period), even with the quiescent pre-outburst luminosity of $\eta$ Car and a likely temperature around 7000 K, the companion star would plunge well inside the apparent photosphere of the primary during periastron passages. A violent periastron collision is therefore inevitable and may help explain the brief brightening episodes that occurred in 1838 and 1843; these two events are, in fact, closely associated with times of periastron (Smith & Frew 2011). Exactly how this works in unclear, and explaining the energetics is not trivial. Similarly, in the case of the eclipsing binary HD 5980, Koenigsberger (2004) and collaborators have proposed that tidal interactions in the close binary may have triggered the eruption observed in the 1990s.11

Interacting binary events are attractive in the sense that the seemingly endless free parameters in binary models (mass ratios, ...

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9 Heger & Woosley (2002) did note a rare case where the PPI eruption can delay the resumption of nuclear burning, leading to intervals of as much as $10^9$ yr between bursts, but this is not generally the case.

10 This exact mass range, however, depends on mass-loss rates assumed in stellar evolution models throughout the lifetime of the star.

11 Soker (2001) and collaborators have envisioned a much more complicated model for $\eta$ Car, where the main-sequence secondary star accretes from the primary wind during close passages and blows out a pair of collimated jets, as an attempt to explain the bipolar shape and kinematics of the $\eta$ Car nebula; in their model, however, an eruption from the primary star was an assumed and necessary pre-condition.
stellar radii, orbital period, eccentricity, conservative versus non-conservative mass-transfer and mass-loss, possible instability of either star, etc.) may provide a natural origin for the wide diversity observed in SN impostor outburst properties. Furthermore, close binary interactions could conceivably operate over a wide range of initial masses, even in stars that are not dangerously close to the Eddington limit on their own. Specifically, these encounters may occur for initial masses both above and below 8 M⊙, regardless of differences in core evolution, providing a possible link between LBV eruptions and very similar transients from lower mass stars (see Section 4.5). The detailed way in which binary encounters could account for the energetics of SN impostor events looms on the horizon as a major open question. A fruitful possibility for explaining SN impostors is that such a model would require two suitable conditions: (1) an evolved primary star that approaches instability anyway; and (2) a rather sudden increase in the stellar radius so as to initiate a catastrophic encounter. Whether such binary interactions are the key to causing LBV eruptions, or simply modify the temporal behaviour by triggering an instability that would have occurred anyway, is obviously a key question for future theoretical research. In the case of η Car, though, it seems clear that a simple mechanism such as the kinetic heating of the primary star’s envelope by the invading secondary is insufficient, since the gravitational binding energy of the binary orbit is substantially less than the kinetic energy of its expanding nebula (Smith et al. 2003a). It must also be noted that binary interactions such as this are unlikely to explain all LBV eruptions; P Cygni, for example, has shown no evidence of binarity despite decades of detailed study. There must be some mechanism that can lead to eruptions of single massive stars as well.

The main emphasis of this paper has been to demonstrate the wide diversity in observed properties of SN impostors and their progenitors, but a fair question is whether the group is too diverse. In other words, can this group be explained by a single mechanism operating over a wide range of energy and mass or must it be a collection of different mechanisms operating in different stars that are susceptible to perturbations? Can these different mechanisms give rise to transient sources that overlap in Fig. 13 and have similar spectra? Is it required that multiple mechanisms work together to initiate an eruption? Since several potential mechanisms listed above seem at least plausible, there may be more than one cause of SN impostors. Inventing ways to connect observations to theory and to distinguish between these will be a major task for future work.

4.7 Summary and future directions

While SN impostors are intrinsically fainter than SNe and are therefore discovered less easily, their numbers are growing. They will continue to be discovered with increasing frequency in current and upcoming surveys, and so a better framework to understand them is needed. In this paper, we have attempted to compile some of the basic observables of SN impostors and related transients known to date, including nearby historical examples and more recent events discovered in modern SN/transient searches. We also presented new spectra and light curves for a number of SN impostors.

Examining the full distribution of observed properties—including peak absolute magnitude, characteristic fading time-scale, outflow velocity, spectral morphology and progenitor properties—the most striking result is that SN impostors are extremely diverse, filling essentially all of the available parameter space between SNe and novae. We find no clear correlations between spectral morphology, luminosity, or fading time-scale, unlike the case for other transients like SNe and novae. Moreover, the diversity exhibited by well-studied objects, where the progenitor is known to be an LBV, fully encompasses the range of parameter space occupied by transients that are supposedly not LBVs. In some cases, therefore, previous claims of new types of transients based on observed properties of the eruption appear to have been too strong. On the other hand, the mechanism behind these eruptions is still unknown, and so multiple different types of outburst phenomena may overlap in parameter space. Thus, we are not arguing that all of these sources are necessarily LBV giant eruptions—indeed, LBVs may be a subset of a larger group of non-terminal eruptive phenomena. A great deal of theoretical work is needed before confident conclusions can be drawn.

Nevertheless, even though the distribution of SN impostor properties is very diverse, we did find one extreme outlier among the sample, which stood out in every measurable way: the supposedly prototypical impostor SN 1961V. We find that SN 1961V is more naturally explained as a true core-collapse SN of Type IIn, similar to SN 2005ip and SN 1988Z, but with delayed CSM interaction. We propose that the strange light-curve shape of SN 1961V can be explained by a relatively normal Type II SN, followed by a late turn-on of CSM interaction luminosity that causes its rise to its peak luminosity after ~100 d. That late peak luminosity was the same as that of SN 2005ip, and comparable late turn-on of CSM interaction has been documented in previous SNe IIn. This requires that the CSM shell had an interior cavity, and reasonable velocities would imply that the shell would have been ejected within a few years before the core collapse. Indeed, the progenitor of SN 1961V was observed at an absolute magnitude of roughly −14 mag about a year before its main brightening, and we suspect that this was the direct detection of a precursor LBV-like outburst. This eradicates the notion that the progenitor of SN 1961V must have been an astounding massive star; instead, we suggest that it had an initial mass and luminosity comparable to those of η Car.

There is considerable room for improvement in our understanding of LBV eruptions and SN impostors. The most glaring deficiency is in our theoretical explanations. A theory for these eruptions should strive to identify a physical mechanism that can account for a range of ejected mass (0.01–10 M⊙) and kinetic energy (10⁵⁰–10⁵⁵ erg), total radiated energy (10⁴⁰–10⁵⁰ erg), peak luminosity (~10–15 mag), outflow speeds (100–1000 km s⁻¹) and different spectral properties through all luminosities (relatively cool and hot, varying emission-line strengths, etc.). This is admittedly a tall order. Although more realistic models for the structure of post-main-sequence massive stars are needed to assess the susceptibility and outcomes of various instabilities, it is also likely that simple toy models can be useful to investigate the hydrodynamics of envelope ejection and the star’s dynamical and thermal response. Detailed radiative transfer calculations for these ejections are needed in order to connect observable spectra and luminosities to derived properties (see e.g. Dessart et al. 2010). Finally, dynamical models of close binary interactions and the transients they might produce are sorely needed.

On the observational front, our understanding of SN impostor statistics will improve in the near future, since these kinds of transients are a major emphasis of current wide-angle surveys (e.g. the Palomar Transient Factory—Rau et al. 2009, Law et al. 2009; Pan-STARRS—Kaiser et al. 2002) and future ones (e.g. Large Synoptic Survey Telescope, Tyson 2002). In this paper, we have only examined about two dozen SN impostors and a few additional cases whose nature is debated. While this has been sufficient to demonstrate the diversity in observed properties, it is insufficient to
examine their intrinsic statistical distribution. A prohibitive weakness is that this sample is not drawn from a uniform survey with well-understood systematics, so we have been careful not to draw conclusions about (for example) how common are SN impostors having various peak luminosities or how common they are compared to core-collapse SNe. Understanding the intrinsic rates of SN impostors is key, as has been done for SNe (e.g. Li et al. 2011), but it has been difficult to address for SN impostor statistics because they are so faint. The surveys mentioned above will provide critical advances in this area, allowing estimates of control times and completeness of a large sample.

It may seem discouraging that the diversity of SN impostors is so large, because it follows that there is limited utility from spotty observations of a transient’s spectrum or a monochromatic light curve of only the time around peak luminosity. Follow-up spectroscopy and photometry are extremely useful, however, when combined with good coverage at late times or in cases where detections of a progenitor star are available. In particular, long-term monitoring that may (eventually) detect a second outburst or multiple eruptions can be extremely useful for understanding the phenomenon, although this may take several years of observations. We should keep a watchful eye on all nearby and historical examples, in case they erupt again or explode as real SNe. Late-time data and upper limits can potentially help us understand the recovery of a star after a disruptive event, which is a problem that has received little attention so far.

Lastly, these transient sources are associated with substantial mass ejection. The resulting circumstellar shells are potentially observable for a much longer time than the outburst itself. Thus, continued detailed study of nearby examples of resolved circumstellar shells around all types of stars is needed, as it offers our only way (in the absence of good models for the outbursts) to evaluate the amount of ejected mass. Comparing the statistics of circumstellar shells to the properties of SN impostors and other transients may prove enlightening when a statistical sample becomes available. If nearby examples are any guide, then the mass ejection of SN impostors is probably not spherical. It is therefore likely that considerations associated with asymmetry (spectropolarimetry, detailed line profiles, rotation, asymmetric explosions and winds, binary encounters) will figure more prominently in upcoming studies.

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Because we cannot rely on the World Coordinate System (WCS) data, we need to first transform our images to high precision. This procedure is similar to what is generally used in the discovery of SN progenitors (e.g. Li et al. 2007, 2008). In this appendix, we describe how we analyze these images to derive magnitudes or upper limits on the brightness of the sources of their progenitor stars.

In order to measure the brightness of the impostors, we first need to locate them with high precision in the HST images. Because of the precision of reported coordinates for the impostors and their absolute HST pointings, we cannot rely on the World Coordinate System (WCS) information in the HST images to locate the impostors. Instead, we need to use ground-based images with detections of the impostors and do astrometric transformations to achieve a sufficiently high precision. This procedure is similar to what is generally used in the discovery of SN progenitors (e.g. Li et al. 2007, and references therein).

Our images with the detections of impostors are often taken with KAIT and the Lick Observatory Nickel 1-m telescope, which have relatively poor angular resolutions (0.80 and 0.37 arcsec pixel$^{-1}$) and depth compared to HST. As a result, we choose to use Option 2 (turn on local sky determination) as recommended by Dolphin (2000a,b). For our reduction, we chose to include Option 2 (turn on local sky determination) as recommended by Dolphin.

For our reduction, we chose to include Option 2 (turn on local sky determination) as recommended by Dolphin.
by the HST_HOT manual for images of galaxies well beyond the Local Group and Option 8 (turn off aperture corrections) as there are no good aperture-correction stars in our images. HST_HOT then uses the default aperture corrections for the filters, which are probably accurate in general to 0.02 mag. We also used an independent detection threshold of 2.5σ (the minimum S/N for a given image or filter for star detection) and a total detection threshold of 3.0σ (the minimum total S/N for a star to be kept in the final output). All photometry was performed on the co-added images in each filter. Table A1 lists the results of our analysis. Details of the reductions for each object are described in the following sections.

A1 SN 1999bw

A combined R-band image from KAIT data taken between 1999 April 20 and May 18, wherein SN 1999bw was detected, is matched to an R-band image taken with the Kitt Peak National Observatory (KPNO) 2.1-m telescope on 2001 March 3 (Dale et al. 2009, downloaded from the NED). Six stars are used in the astrometric solution, with a precision of 0.05 arcsec. The Bok image is then matched to the HST/WFPC2 F814W image taken on 2008 November 18. Five stars are used in the solution, with a precision of 0.12 arcsec. The total uncertainty in the astrometric solution is 0.13 arcsec. Within the 1σ error radius, there is a bright object that we identify as SN 2000bw. A finder chart is provided in Fig. A1.

A2 SN 2000ch

A combined unfiltered image from KAIT data taken between 2000 May 3 and 14, wherein SN 2000ch was detected, is registered to an R-band image taken with the Bok 2.3-m telescope on 2001 March 3 (Dale et al. 2009, downloaded from the NED). Six stars are used in the astrometric solution, with a precision of 0.05 arcsec. The Bok image is then matched to the HST/WFPC2 F814W image taken on 2008 November 18. Five stars are used in the solution, with a precision of 0.12 arcsec. The total uncertainty in the astrometric solution is 0.13 arcsec. Within the 1σ error radius, there is a bright object that we identify as SN 2000ch. A finder chart is provided in Fig. A1.

A3 SN 2001ac

A combined R-band image from KAIT data taken between 2001 March 13 and 30, wherein SN 2001ac was detected, is matched to an R-band image taken with the 2.5-m Isaac Newton Telescope (INT) on 2005 March 29 (downloaded from the ING data archive12). Four stars are used in the astrometric solution, with a precision of 0.17 arcsec. The INT image is then matched to the HST/WFPC2 F814W image taken on 2008 November 18. Eight stars are used in the solution, with a precision of 0.06 arcsec. The total uncertainty in the astrometric solution is 0.18 arcsec. SN 2001ac was not detected in any of the HST images. A finder chart is provided in Fig. A1.

A4 SN 2003gm

For SN 2003gm, HST data taken before 2008 were analysed by Maund et al. (2006), so here we only reduced the data taken in

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12 http://casu.ast.cam.ac.uk/casuadc

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Table A1. Photometry and upper limits for the impostors in the HST archive.

<table>
<thead>
<tr>
<th>Object</th>
<th>Observation date$^a$</th>
<th>Exposure (s)</th>
<th>Instrument/filter</th>
<th>Prog.$^b$</th>
<th>Phot.$^c$ (mag)</th>
<th>Data sets$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 1999bw</td>
<td>2006-10-23</td>
<td>1275</td>
<td>ACS/HRC/F606W</td>
<td>10607</td>
<td>&gt;27.7</td>
<td>J9F03010</td>
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<td>SN 1999bw</td>
<td>2008-04-03</td>
<td>1600</td>
<td>WFPC2/F606W</td>
<td>11229</td>
<td>&gt;27.8</td>
<td>U2A0301M...0302M, 0303M, 0304M</td>
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<tr>
<td>SN 2000ch</td>
<td>2008-11-18</td>
<td>460</td>
<td>WFPC2/F555W</td>
<td>10877</td>
<td>21.72(0.02)</td>
<td>U9NW5401M, U9NW5402M</td>
</tr>
<tr>
<td>SN 2000ch</td>
<td>2008-11-18</td>
<td>700</td>
<td>WFPC2/F814W</td>
<td>10877</td>
<td>21.16(0.04)</td>
<td>U9NW5403M, U9NW5404M</td>
</tr>
<tr>
<td>SN 2001ac</td>
<td>2008-11-22</td>
<td>800</td>
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<td>26.5</td>
<td>U9NW5401M, U9NW5403M</td>
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<tr>
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<td>360</td>
<td>WFPC2/F675W</td>
<td>10877</td>
<td>25.8</td>
<td>U9NW5403M, U9NW5404M</td>
</tr>
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<td>SN 2001ac</td>
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<td>700</td>
<td>WFPC2/F814W</td>
<td>10877</td>
<td>26.1</td>
<td>U9NW5403M, U9NW5404M</td>
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<td>WFPC2/F450W</td>
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<td>&gt;26.0</td>
<td>U9NW6701M, U9NW6702M</td>
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<td>25.28(0.25)</td>
<td>U9NW6801M, U9NW6802M</td>
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<tr>
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<td>U9NW5703M, U9NW5704M</td>
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<tr>
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<tr>
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<td>600</td>
<td>WFPC2/F814W</td>
<td>9041</td>
<td>&gt;26.0</td>
<td>U6BR010ER, U6BR010FR</td>
</tr>
</tbody>
</table>

$^a$ UT date of the observations.
$^b$ The HST programme proposal number.
$^c$ The 3σ upper limits are marked with a ‘>’. The uncertainties of the magnitudes are listed in parentheses.
$^d$ The data set name for each observation.
$^e$ The transient in NGC 4656. The object was not given an official SN name by the Central Bureau of Astronomical Telegrams.
Figure A1. Finder charts for SN impostors. Each panel is $4 \times 4$ arcsec$^2$ in size. North is up and east is to the left. For SNe 1999bw, 2001ac and 2010dn, the circle has a radius equal to the 1$\sigma$ uncertainty in the astrometric solution. For SN 2000ch, the circle is three times the 1$\sigma$ uncertainty in the astrometric solution.

Figure A2. HST images of SN 2003gm. Each panel is $2 \times 2$ arcsec$^2$ in size. The circles have a radius of 0.1 arcsec, which is seven times the 1$\sigma$ uncertainty in the astrometric solution.
program GO-10877 on 2008 December 18 and 19. SN 2003gm was detected by HST/ACS/HRC on 2004 May 24, and we are able to locate its position in the 2008 December WFPC2 images to high precision ($1\sigma = 0.013\text{ arcsec}$). An object is found ($8.4\sigma$) within 2$\sigma$ of the nominal SN location in the $F_{814W}$ image. The same object was detected at 4.3 and 3.5$\sigma$ in the $F_{555W}$ and $F_{675W}$ images, respectively, but not in the $F_{450W}$ image. Fig. A2 shows a comparison of the sites of SN 2003gm taken on 2001 August 29 (pre-SN), 2004 May 24 (with SN 2003gm detected) and 2008 December 19 (images analysed in this paper). We identify the object detected in the 2008 December images as SN 2003gm, because in the $F_{814W}$ image, it is an obvious new object compared to the pre-SN image taken on 2001 August 29.

A5 NGC 4656 OT

We were able to find a high-resolution ground-based image of NGC 4656 taken with MegaCam on the 3.6-m Canada-France-Hawaii Telescope (CFHT) on 2005 June 11, when the transient was still active and detected. 12 stars are used to match the CFHT image to the HST/WFPC2 $F_{814W}$ image taken on 2008 November 20, with a precision of 0.05 arcsec. The transient is not detected in any of the HST images. Fig. A3 shows the CFHT image of the source and a finder chart for its location in the HST image. Using the zero-point of the CFHT images, we measured photometry of $r = 19.81 \pm 0.5\text{ mag}$ on 2005 June 11.

A6 SN 2010dn

An $R$-band image taken with the Lick Observatory 1-m Nickel telescope on 2010 June 23, wherein SN 2010dn was clearly detected, is matched to an $R$-band image taken with the 2.56-m Nordic Optical Telescope (NOT) on 2000 November 10 (Larsen & Richtler 1999, downloaded from the NED). Eight stars are used in the solution, with a precision of 0.133 arcsec. The NOT image is matched to the HST/WFPC2 $F_{555W}$ image taken on 2001 January 24. Eight stars are used in the solution, with a precision of 0.044 arcsec, and the total astrometric uncertainty is 0.14 arcsec. SN 2010dn was not detected in any of the HST images. A finder chart is provided in Fig. A1.