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Letter to the Editor

The impostor revealed: SN 2016jbu was a terminal explosion

S. J. Brennan[1], N. Elias-Rosa[2,3], M. Fraser[1], S. D. Van Dyk[4], and J. D. Lyman[5]

[1] School of Physics, O'Brien Centre for Science North, University College Dublin, Belfield, Dublin 4 D04 V1W8, Ireland
e-mail: sean.brennan2@ucdconnect.ie
[2] INAF – Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, Padova 35122, Italy
[3] Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans s/n, 08193 Barcelona, Spain
[4] Caltech Spitzer Science Center, Caltech/IPAC, Mailcode 100-22, Pasadena, CA 91125, USA
[5] Department of Physics, University of Warwick, Coventry CV4 7AL, UK

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ABSTRACT

In this Letter, we present recent observations from the *Hubble* Space Telescope of the interacting transient SN 2016jbu at +5 yr. We find no evidence for any additional outburst from SN 2016jbu, and the optical source has now faded significantly below the progenitor magnitudes from early 2016. Similar to recent observations of SN 2009ip and SN 2015bh, SN 2016jbu has not undergone a significant change in colour over the past 2 years, suggesting that there is a lack of ongoing dust formation. We find that SN 2016jbu is fading more slowly than expected of radioactive nickel, but faster than the decay of SN 2009ip. The late-time light curve displays a non-linear decline and follows on from a re-brightening event that occurred ~8 months after peak brightness, suggesting CSM interaction continues to dominate SN 2016jbu. While our optical observations are plausibly consistent with a surviving, hot, dust-enshrouded star, this would require an implausibly large dust mass. These new observations suggest that SN 2016jbu is a genuine, albeit strange, supernova, and we discuss the plausibility of a surviving binary companion.

Key words. supernovae: individual: SN 2016jbu – stars: evolution – stars: massive

1. Introduction

The final moments of massive stars' (>8 $M_\odot$; Woosley et al. 2002) lives are often not well understood. While the general picture of massive stars exploding as core-collapse supernovae (CCSNe) is well understood, it is increasingly apparent that some of these stars will experience enhanced mass loss before exploding (Fraser et al. 2013; Yaron et al. 2017).

In recent years, a group of transients has been classified, where it is uncertain whether these are CCSNe or giant non-terminal eruptions. These events have been dubbed SN 2009ip-like transients and include events such as SN 2009ip (Foley et al. 2011; Smith et al. 2010, 2014; Fraser et al. 2013; Pastorello et al. 2013; Mauerhan et al. 2013), SN 2015bh (Elias-Rosa et al. 2016; Thöne et al. 2017; Boian & Groh 2018; Jencson et al. 2022), SN 2016bdu, SN 2005gl (Pastorello et al. 2018), LSQ13zm (Tartaglia et al. 2016), and SN 2016jbu (Kilpatrick et al. 2018; Brennan et al. 2022a,b).

These transients display several peculiar features that are difficult to explain with current stellar evolutionary theory. These include a history of erratic variability, followed by two luminous events known as Event A and Event B, the latter reaching a magnitude comparable to Type IIn supernovae (SNe)[1] (~−18.5 mag, Nyholm et al. 2020), and a bumpy decline in their light curves . The late-time photometric evolution for these objects is slower than that expected for radioactive ^{56}Ni decay (Fox et al. 2015). Additionally, these objects display smoothly evolving asymmetric Balmer emission lines, suggesting a complex, possibly disk-like, circumstellar material (CSM; Brennan et al. 2022b; Reilly et al. 2017). Curiously, their ejected ^{56}Ni mass is constrained to be relatively low (less than a few 0.01 $M_\odot$; Smith et al. 2014; Margutti et al. 2014; Brennan et al. 2022b). This has led some authors to consider whether we are observing a core-collapse event unfold, or a giant stellar eruption, perhaps similar to the non-terminal giant eruption of η Car, or in other words, a SN impostor (Van Dyk & Matheson 2012; Pastorello et al. 2013; Elias-Rosa et al. 2016; Hirai et al. 2021).

SN 2009ip has recently been re-observed by Smith et al. (2022) using the *Hubble* Space Telescope (HST), and they report a source with a luminosity significantly lower than the progenitor observed in 1999 in $F606W$. Critically, Smith et al. (2022) find a constant colour for the late-time light curve of SN 2009ip, indicating an absence of dust formation. This strongly disfavours the possibility that the massive progenitor (~60–80 $M_\odot$, Smith et al. 2010; Foley et al. 2011) is being obscured by large amounts of newly formed dust. Based on these recent observations, Smith et al. (2022) conclude that SN 2009ip was indeed a SN and will continue to fade. Jencson et al. (2022) have concluded a similar fate for SN 2015bh, where the light curve is now significantly fainter than the progenitor and is fading with a constant colour, ruling out a dust-enshrouded surviving star.

This Letter presents new late-time observations of SN 2016jbu. SN 2016jbu (also known as Gaia16cfr) offers a unique opportunity to search for a surviving star, as the progenitor was detected at multiple wavelengths, and was well constrained by Kilpatrick et al. (2018), Brennan et al. (2022b) to have an appearance of a ~22 $M_\odot$ yellow hypergiant (YHG).

[1] SNe showing signs of interaction with circumstellar material, with narrow emission lines seen in their spectra (Schlegel 1990; Filippenko 1997).

Table 1. Observational log for HST + WFC3/UVIS and WFC3/IR images covering the site of SN 2016jbu from December 2021.

Date	Filter	Exposure	Mag (err)
2021-03-02	*F275W*	4 × 450 s	25.305 (0.374)
2021-12-06	*F350LP*	4 × 385 s	25.685 (0.039)
–	*F555W*	4 × 390 s	26.585 (0.112)
–	*F814W*	4 × 390 s	25.855 (0.146)
–	*F160W*	3 × 420 s	23.744 (0.086)

Notes. We also include *F275W* taken ∼9 months before. Measured photometry (in the Vega-mag system) for SN 2016jbu is reported with 1σ errors in parentheses.

Following Brennan et al. (2022a), we take the distance modulus for NGC 2442 to be 31.60 ± 0.06 mag. We adopt a redshift of $z = 0.00489$ and a Milky Way (MW) foreground extinction to be $A_V = 0.556$ mag. We correct for foreground extinction using $R_V = 3.1$ and the extinction law given by Cardelli et al. (1989).

2. Observations

We observed the site of SN 2016jbu in December 2021 during Cycle 29 with HST (ID: 16671, PI: N. Elias-Rosa) using the UV-visible (UVIS) and infrared (IR) channels of the Wide Field Camera 3 (WFC3/UVIS and WFC3/IR, respectively). The objective of our proposal was to re-observe SN 2016jbu with the same filters that were used in early 2016 and 2019. These include WFC3/UVIS *F555W*, *F350LP*, and *F814W*, and WFC3/IR *F160W*. Serendipitously, the host of SN 2016jbu, NGC 2442, was observed with WFC3/UVIS in *F275W* in March 2021 (ID: 16287, PI: J. D. Lyman). Pipeline-reduced images were downloaded from the Mikulski Archive for Space Telescopes (MAST[2]), and photometry was performed on these images using the DOLPHOT package (Dolphin 2016).

In all cases, images were masked for cosmic rays and other artefacts using the associated data quality files. Source detection was performed on a pipeline-drizzled reference image, before PSF-fitting photometry was performed on the individual _FLT/_FLC frames. For the WFC3/UVIS data taken in Dec. 2021, the pipeline-drizzled *F350LP* image was used as a reference frame for source detection; for the WFC3/IR data, the drizzled *F160W* image was used as a reference. The March 2021 *F275W* data were analysed separately, using the drizzled *F275W* image as a reference.

Photometry for the point source at the position of SN 2016jbu is reported in Table 1.

3. Discussion

3.1. Light curve evolution

As shown in Fig. 1, SN 2016jbu has faded significantly since 2019 and its *F555W* magnitude is now ∼2.25 mag fainter than its minimum value seen in early 2016 (Brennan et al. 2022b). Similar to the recent results from Smith et al. (2022) for SN 2009ip, we find a consistent colour (within error) between 2019 and 2021. We measure $(F555W - F814W)_0$ (approximately $V - I$) to be 0.47 ± 0.04 mag in 2019, and 0.46 ± 0.18 mag in 2021. Moreover, we find similar decay rates for *F555W* and *F814W* between 2019 and 2021 (∼991 days) of −0.0027 ± 0.0001 and −0.0026 ± 0.0001 mag day^{-1}, respectively. These decline rates are almost identical for *F555W* and *F814W*, and are roughly ten times faster than those observed for SN 2009ip (Smith et al. 2022) (although still roughly ten times slower than the decline seen in the late-time light curve of SN 1987A; Woosley 1988).

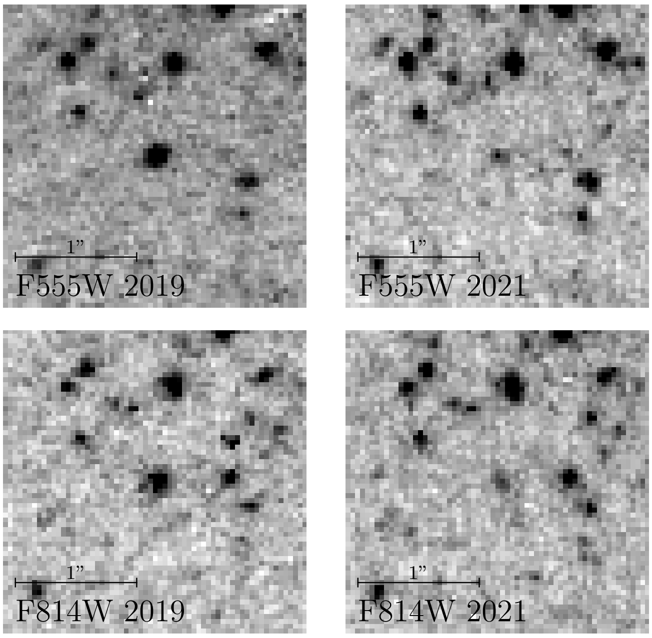

Fig. 1. HST cutouts of SN 2016jbu in *F555W* (*upper*) and *F814W* (*lower*) from 2019 (*left*) and 2021 (*right*). The position of SN 2016jbu is located centre frame. In each panel, north is pointing upwards and east is pointing left.

In Fig. 2 we plot the *V*-band light curve, as well as the HST observations of SN 2016jbu from 2016, 2019, and 2021. From the photometric and spectral features of SN 2016jbu, it is obvious that CSM interaction plays a dominant role in the late-time evolution (Kilpatrick et al. 2018; Brennan et al. 2022b). Amongst other members of the SN 2009ip-like transients, unique to SN 2016jbu is the re-brightening in the light curve seen after ∼+130 d. Notwithstanding this bump, we also see that the decline rate of SN 2016jbu from peak is not linear, with a slower decline between 780 and 1770 days than between 250 and 500 days (Fig. 2).

The progenitor candidate identified by Brennan et al. (2022b) was a ∼22 $M_\odot$ star that exploded as a YHG. One would expect a star with this zero-age main sequence mass to explode as a Type IIP SN, and experience a mass loss rate of ∼10^{-6} $M_\odot$ yr^{-1} before exploding. Binary evolution can strongly affect the location in the Hertzsprung–Russell diagram (HRD) where a star will explode, and therefore we investigate whether the light curve of SN 2016jbu can be used to confirm or rule out the presence of a binary companion.

We compare our 2021 observations to the sample of terminal Binary Population and Spectral Synthesis (BPASS; Eldridge et al. 2017; Stanway & Eldridge 2018) models used in Brennan et al. (2022b) and plot these matching models in Fig. 3. No single-star models match the progenitor of SN 2016jbu. We find one binary model that matches the 2016 progenitor temperature and luminosity. This model comprises a primary (secondary) with a terminal-age main sequence mass of 17 (12) $M_\odot$. Subsequently, the primary becomes a red supergiant, before losing most of its mass to its companion and evolving across the HRD to become a hot stripped star. As it crosses the HRD to

[2] mastweb.stsci.edu/

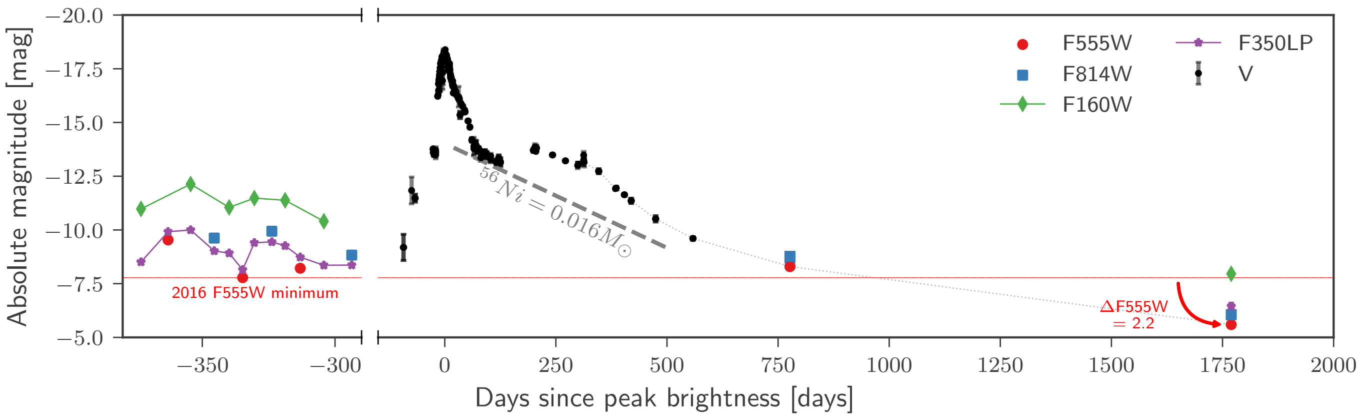

Fig. 2. Light curve of SN 2016jbu including HST observations from Table 1 and Brennan et al. (2022b), and V-band (black markers) observations from Brennan et al. (2022a). We include the expected luminosity from 0.016 $M_\odot$ of ^{56}Ni in the V-band (Hamuy 2003; Brennan et al. 2022b) as the sloped dashed line. We connect points in the late-time light curve to visualise the non-linear decline.

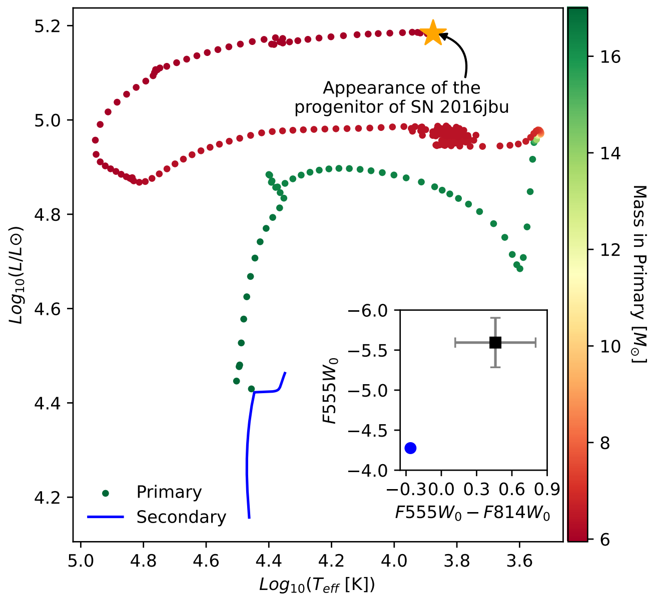

Fig. 3. Terminal model matching the progenitor of SN 2016jbu from BPASS (Eldridge et al. 2017; Stanway & Eldridge 2018). Coloured markers are the primary star ($M_{\rm TAMS}$ = 17 $M_\odot$), assumed to be the progenitor of SN 2016jbu. The blue line is its binary companion ($M_{\rm TAMS}$ = 12 $M_\odot$). We note the evolutionary track for the companion has not reached core collapse, as the BPASS models terminate when the primary reaches the end of its life. The colour of the primary denotes its mass at each evolutionary time step, given in the colour bar. The inset shows a colour magnitude diagram, including the 2021 observations of SN 2016jbu (black marker) and the colour of the binary companion from the BPASS model during the last evolutionary time step (blue marker).

the blue, it begins Helium burning, but then moves back across to the yellow when Carbon burning begins (around 10^4 years before core collapse) where it explodes as a YHG. When the primary explodes, it still has a significant hydrogen surface fraction (∼25%), consistent with a Type IIn SN. Encouragingly, Brennan et al. (2022b) explode this model using the SNEC code (Morozova et al. 2015) and find it can broadly reproduce the Event B light curve shape for SN 2016jbu.

We find the companion colour, taken as the last evolutionary time step in the BPASS model, is too blue to match our 2021 observations, $(F555W - F814W)_0 \approx +0.46$. Additionally, our $F555W_0$ observations are too bright to be associated with the flux from the companion star alone (the companion magnitude in all bands is fainter than our 2021 measurements). However, this claim is very model-dependent, and careful attention is required in order to better understand the appearance of a companion in this case. The 2021 observations of SN 2016jbu are likely consistent with CSM interaction continuing to dominate over any binary companion. Once CSM interaction stops (and if a surviving companion exists), we expect it to be detectable at $F555W \sim 27.8$ mag.

3.2. Modelling the SED

SN impostors, by definition, do not destroy the progenitor star (Van Dyk et al. 2000). We investigated the possibility that the progenitor of SN 2016jbu still exists, but is now enshrouded by dust. Using the DUSTY radiative transfer code (Ivezic & Elitzur 1997), we calculated the observed spectral energy distributions (SEDs) for a grid of progenitor models allowing for different configurations of circumstellar dust, see Brennan et al. (2022b) for further details. To remain open to any sort of surviving source, we employed a range of synthetic stellar spectra covering a wide temperature regime, including models from MARSCS (Gustafsson et al. 2008), PHOENIX (Husser et al. 2013), POWR (Sander et al. 2015), and EMFGEN (Hillier & Lanz 2001).

For each model, we calculated synthetic $F555W - F814W$ and $F814W - F160W$ colours, and compared them to the foreground extinction corrected colours of the remnant of SN 2016jbu, see Table 1[3]. Models with colours matching (within measurement errors) SN 2016jbu remnant were scaled to match the $F814W_0$ 2021 observation. We then calculated the bolometric luminosity by integrating these scaled SEDs. Matching spectra are plotted in Fig. 4.

We find our 2021 optical measurements can only match a dust-enshrouded source with the luminosity of the progenitor if it is much hotter (upper panel, Fig. 4), but re-radiating much of its flux in the IR due to dust (lower panel, Fig. 4).

Matching models require dust with temperatures of between 400 and 1200 K. This is lower than the dust reported for the early

[3] We exclude $F275W$ and $F350LP$ from our colour matching due to the former being measured in early 2021 and the latter likely containing flux from $H\alpha$. We instead use these bands as upper limits.

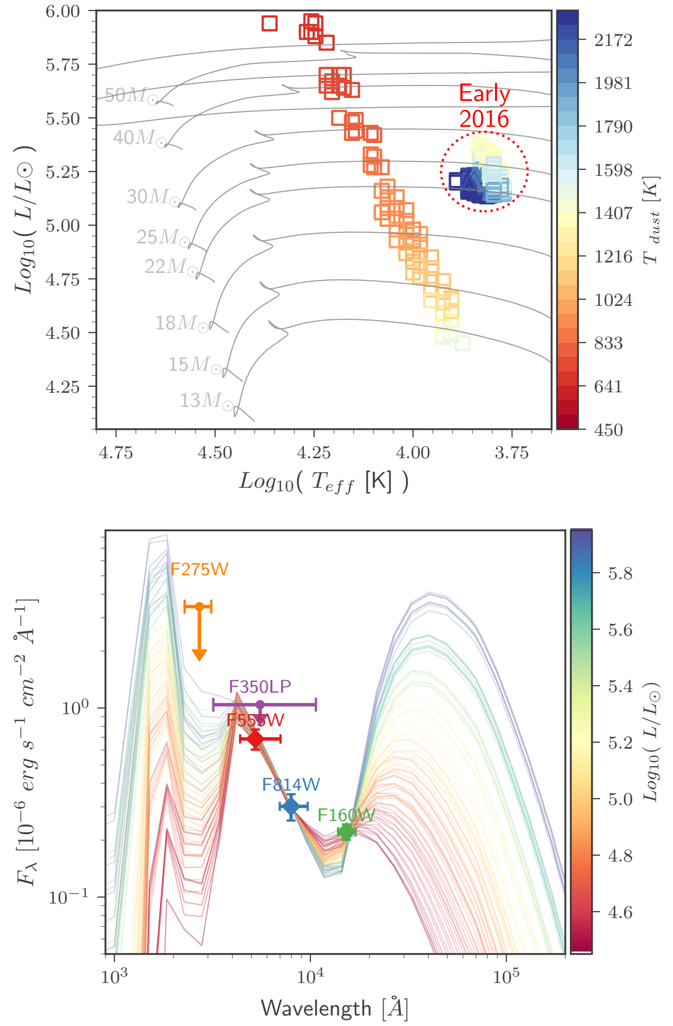

Fig. 4. *Upper panel*: HRD showing model luminosities and effective temperatures. The colour of the markers represents the necessary dust temperature required to match the remnant colours. For reference, we overplot single-star evolutionary tracks from the BPASS models (Eldridge et al. 2017; Stanway & Eldridge 2018). We highlight the progenitor appearance in early 2016 from Brennan et al. (2022b). *Lower panel*: matching spectra from DUSTY. Markers with error bars represent the extinction-corrected flux from the 2021 data given in Table 1. The colour of each spectral energy distribution represents the luminosity of the scaled model. We treat the $F275W$ measurement from March 2021 and the $F350LP$ data from December 2021 as upper limits.

2016 measurements for SN 2016jbu (1400 K–2000 K, with similar values reported for SN 2009ip (Smith et al. 2013)), and one would expect this pre-explosion dust was destroyed in the 2016 and/or 2017 events. A dust temperature of ~1000 K would allow the 2021 measurements to agree with the early 2016 bolometric luminosity. However, maintaining such a high dust temperature 5 years post-explosion is non-trivial and unexpected for SNe (for example, see Gehrz & Ney 1990; Szalai et al. 2011), although a surviving heat source may allow for such conditions.

The most salient parameter in our modelling is the dust mass. Following Kochanek (2011), we find these models require 10^{-2}–10^{-1} $M_\odot$ of graphitic dust to obscure a surviving progenitor[4]. Such a dust mass may be expected ~1800 days after core collapse (Wesson et al. 2015), but producing such a large amount of dust at this phase without core collapse is non-trivial (Kochanek 2011)[5]. Additionally, such a large dust mass would result in a noticeable colour change, which is not seen in SN 2016jbu (or SN 2009ip, Smith et al. 2022).

4. Conclusions

In this Letter, we have presented and analysed HST/WFC3 images of the source at the position of SN 2016jbu taken 5 years after the explosion. Our main conclusion is that the point source is now significantly fainter (~2.2 mag) than the progenitor (Kilpatrick et al. 2018; Brennan et al. 2022b). We find the colour $(F555W - F814W)_0$ has remained roughly constant for ~2 yr, suggesting that significant quantities of dust has not formed.

Motivated by the constant colour and non-linear decay seen in SN 2016jbu's late-time evolution, we also investigated the possibility that the light curve is fading to reveal a binary companion (for example see Zhang et al. 2004; Kashi et al. 2013; Fox et al. 2022). Comparing with models from the BPASS code yields a single matching model. However, the binary companion is too blue and faint to match our 2021 observations, although continued follow-up is needed to confirm this or refute this scenario as the SN fades further.

We attempt to model a surviving progenitor enshrouded by dust using the DUSTY code. While our HST photometry can be modelled with a dust-enshrouded star, we cannot tightly constrain the remnant luminosity due to a lack of coverage in the mid-IR (Fig. 4). However, any model would require a significant dust mass (10^{-2}–10^{-1} $M_\odot$) to obscure the surviving star and match our optical observations. Such high dust masses are difficult to produce in a non-terminal eruption, and a significant colour change would also be expected.

The above arguments strongly suggest that SN 2016jbu was indeed a terminal explosion, and the recent observations of SN 2009ip (Smith et al. 2022) and SN 2015bh (Jencson et al. 2022), strongly support the conclusion that the class of SN 2009ip-like transients are indeed genuine – albeit strange – SNe.

However, a complete understanding of the explosion mechanism for SN 2016jbu (and indeed other SN 2009ip-like events) remains elusive. Additionally, the progenitor scenario for this class of transients is unclear; these transients display relative homogeneity and yet observationally come from a wide range of progenitors (for example a 25 $M_\odot$ YHG for SN 2016jbu and a 60 $M_\odot$ luminous blue variable for SN 2009ip; Smith et al. 2010; Foley et al. 2011; Thöne et al. 2017; Brennan et al. 2022b).

Continued attention towards these transients may reveal a surviving companion, as discussed in Sect. 3.1, and observations spanning a wide portion of the SED are vital. Confirming (or refuting) a binary scenario is an important step in making progress towards[6] fully understanding these transients.

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[4] Assuming an expansion velocity of 5000 km s^{-1}, a travel time of 1790 days, and dust opacity of 500 cm^2 g^{-1} (Kochanek 2011; Brennan et al. 2022b).

[5] η Car has ~0.6 $M_\odot$ of dust, although this is ~150 yr post-eruption (Smith et al. 1998)

[6] http://pollux.oreme.org

Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program GO-16671. This research was achieved using the POLLUX database operated at LUPM (Université Montpellier – CNRS, France with the support of the PNPS and INSU. This work made use of v2.2.1 of the Binary Population and Spectral Synthesis (BPASS) models as described in Eldridge et al. (2017) and Stanway & Eldridge (2018).

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