Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **454,** 2580–2585 (2015) doi:10.1093/mnras/stv2098

Did the progenitor of SN 2011dh have a binary companion?*

J. R. Maund,[1]†‡ I. Arcavi,[2,3] M. Ergon,[4] J. J. Eldridge,[5] C. Georgy,[6] S. B. Cenko,[7] A. Horesh,[8] R. G. Izzard[9] and R. J. Stancliffe[10]

[1]*Department of Physics and Astronomy, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK*
[2]*Las Cumbres Observatory Global Telescope Network, 6740 Cortona Dr., Suite 102, Goleta, CA 93117, USA*
[3]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*
[4]*Stockholm University, The Oskar Klein Centre, AlbaNova, SE-106 91 Stockholm, Sweden*
[5]*Department of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand*
[6]*Astrophysics group, EPSAM, Keele University, Lennard-Jones Labs, Keele, ST5 5BG, UK*
[7]*Goddard Space Flight Center, Mail Code 661, Greenbelt, MD 20771, USA*
[8]*Department of Astronomy, California Institute of Technology, MC 249-17, 1200 East California Boulevard, Pasadena, CA 91125, USA*
[9]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[10]*Argelander-Institut für Astronomie, Auf dem Hügel 71, D-53121 Bonn, Germany*

Accepted 2015 September 7. Received 2015 September 6; in original form 2015 August 11

ABSTRACT

We present late-time *Hubble Space Telescope* ultraviolet (UV) and optical observations of the site of SN 2011dh in the galaxy M51, ∼1164 days post-explosion. At the supernova (SN) location, we observe a point source that is visible at all wavelengths, which is significantly fainter than the spectral energy distribution (SED) of the yellow supergiant progenitor observed prior to explosion. The previously reported photometry of the progenitor is, therefore, completely unaffected by any sources that may persist at the SN location after explosion. In comparison with the previously reported late-time photometric evolution of SN 2011dh, we find that the light curve has plateaued at all wavelengths. The SED of the late-time source is clearly inconsistent with an SED of stellar origin. Although the SED is bright at UV wavelengths, there is no strong evidence that the late-time luminosity originates solely from a stellar source corresponding to the binary companion, although a partial contribution to the observed UV flux from a companion star cannot be ruled out.

Key words: supernovae: general – supernovae: individual: 2011dh.

1 INTRODUCTION

Most massive stars with $M_{\rm ZAMS} > 8\,{\rm M}_{\odot}$ are expected to end their lives as core-collapse supernovae (SNe; Smartt 2009). While there has been major success in the direct identification of the red supergiant (RSG) progenitors of the H-rich Type IIP SNe, attempts to identify the progenitors of the H-deficient Type Ibc SNe have been less conclusive (Eldridge et al. 2013). There are predicted to be two distinct progenitor channels for these SNe: extremely massive stars (>30–40 $\rm M_{\odot}$) which lose their hydrogen envelopes through intense stellar winds and lower mass stars undergoing a binary interaction. Eldridge et al. (2013) showed that, given the available pre-explosion detection limits for nearby Type Ibc SNe, the underlying population of progenitors was required to come from a mixture of the two progenitor channels. Evidence from the sole detection of the progenitor of a Type Ib SN, iPTF 13bvn, suggests that a lower mass binary progenitor may be responsible, rather than a single massive star (Cao et al. 2013; Groh, Georgy & Ekström 2013a; Bersten et al. 2014; Fremling et al. 2014; Eldridge et al. 2015).

SNe of Type IIb initially display hydrogen in their early spectra; however, with time these H features grow weaker until the SN transitions to an H-deficient Type Ib SN. Type IIb SNe may, therefore, be considered 'transition' SNe connecting the H-rich and H-poor SNe (Filippenko, Matheson & Ho 1993; Filippenko 1997). It is thought that the progenitors of Type IIb SNe have been stripped of all but ∼0.1 $\rm M_{\odot}$ of their H-envelope (Smith 2014), highlighting the importance of mass-loss, either through winds or binary interaction, to the origin of the subtypes in the SN classification scheme (Nomoto et al. 1996). Unlike their completely H-deficient cousins, however, there has been significant success in the identification of the progenitors stars of Type IIb SNe in pre-explosion observations (Aldering, Humphreys & Richmond

* Based on observations made with the NASA/ESA *Hubble Space Telescope*, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with programme GO-13433 and GO-13345.
† E-mail: j.maund@sheffield.ac.uk
‡ Royal Society Research Fellow.

© 2015 The Authors
Published by Oxford University Press on behalf of the Royal Astronomical Society

Downloaded from http://mnras.oxfordjournals.org/ at NASA Goddard Space Flight Ctr on March 8, 2016

1994; Crockett et al. 2008; Maund et al. 2011; Van Dyk et al. 2011, 2014).

The small amount of residual hydrogen on the progenitor means that the degree of mass-loss prior to explosion required to reproduce both the progenitor and SN characteristics must be very finely tuned in theoretical models. This makes the progenitors of Type IIb SNe exquisite probes of stellar mass loss through both binary interactions and winds. As demonstrated by Maund & Smartt (2009), late-time observations of the sites of SNe, for which the progenitors have been identified in fortuitous pre-explosion images, allow for an enhanced analysis of the progenitor by studying what is left over after the explosion. This approach permits confirmation of the original identification of the progenitor candidate (through its disappearance), the search for any remaining stellar components (a binary companion) and enhanced photometric accuracy (through the use of image subtraction techniques). Here, using late-time *Hubble Space Telescope* (*HST*) observations, we apply these techniques to the study of the progenitor of SN 2011dh.

SN 2011dh was discovered on 2011 May 31 in the galaxy M51 (Arcavi et al. 2011). A yellow stellar source was detected at the SN location in pre-explosion *HST* images, and interpreted as a supergiant by Maund et al. (2011) and Van Dyk et al. (2011). The SN exhibited rapid temperature evolution, however, during the shock cooling phase (Arcavi et al. 2011) which indicated the possible explosion of a compact progenitor rather than an extended supergiant. Late-time observations by Van Dyk et al. (2013b) demonstrated the disappearance of the yellow source in late-time observations, confirming the conclusion of Maund et al. that the progenitor of SN 2011dh was a yellow supergiant (YSG). Theoretical models by Bersten et al. (2012) and later Nakar & Piro (2014) were able to reconcile the SN shock cooling behaviour with the extended progenitor observations, concluding that the progenitor had a compact core with a very low mass extended H-envelope. In keeping with the study of Maund et al., we adopt a distance to M51 of 7.1 ± 1.2 Mpc (Takáts & Vinkó 2006) and a foreground reddening of $E(B-V) = 0.032$ (Schlafly & Finkbeiner 2011).

2 OBSERVATIONS

Details of the pre-explosion and late-time *HST* observations of the site of SN 2011dh are presented in Table 1. The late-time WFC3/UVIS and ACS/WFC observations were acquired 1164 and 1167 d post-explosion, respectively (Ergon et al. 2014). The pre-explosion observations of the site of SN 2011dh were acquired with the *HST* Advanced Camera for Surveys (ACS) Wide Field Channel (WFC) and Wide Field Planetary Camera 2 (WFPC2). Details of the pre-explosion *HST* observations used here (and their reduction and analysis) are presented by Maund et al. (2011). The late-time observations of the site of SN 2011dh were conducted in the optical/near-infrared with the ACS/WFC and in the ultraviolet (UV) with the Wide Field Camera 3 (WFC3) Ultraviolet and Visible Channel (UVIS), as part of programme GO-13433 (PI: Maund) shared with programme GO-13345 (PI: Arcavi). The filters utilized for the late-time observations were specifically selected to match the filters of the available pre-explosion observations as closely as possible. The late-time observations for each filter, with both instruments, were acquired using a sequence of four dithered exposures, permitting the rejection of cosmic rays and hot pixels and also providing finer sampling of the point spread function (PSF). The dithered exposures were combined using the ASTRODRIZZLE package, running under PYRAF,[1] with final pixel scales of 0.02 arcsec pixel^{-1} for the WFC3/UVIS observations and 0.025 arcsec pixel^{-1} for the ACS/WFC observations. Photometry of the late-time observations was conducted using DOLPHOT[2] (Dolphin 2000) with the specific ACS and WFC3 modules.

The position of SN 2011dh on the late-time *F555W* image was determined with respect to the pre-explosion source, previously identified by Maund et al. (2011) in the pre-explosion *F555W* image, to within 0.016 arcsec (using $N = 23$ stars). The position of the SN on the late-time WFC3/UVIS *F336W* image was determined using a geometric transformation calculated between that image and the late-time ACS/WFC *F555W* image, to within an uncertainty of 0.018 arcsec ($N = 20$). The PYRAF task *crosscor* was used to refine the offset in the registration between the late-time observations that were, nominally, acquired at the same pointing.

Table 1. Pre-explosion and late-time *HST* observations of the site of SN 2011dh in M51.

Date (UT)	Filter	Instrument	Exposure time (s)	Pixel scale (arcsec)	Programme
		Pre-explosion			
21 Jan 2005	*F435W*	ACS/WFC	2720	0.025	10452[a]
21 Jan 2005	*F555W*	ACS/WFC	1360	0.025	10452
21 Jan 2005	*F658N*	ACS/WFC	2720	0.025	10452
21 Jan 2005	*F814W*	ACS/WFC	1360	0.025	10452
13 Nov 2005	*F336W*	WFPC2/WF2	2600	0.1	10501[b]
		Late-time			
07 Aug 2014	*F225W*	WFC3/UVIS	3772	0.02	13433[c]
07 Aug 2014	*F336W*	WFC3/UVIS	1784	0.02	13433
10 Aug 2014	*F435W*	ACS/WFC	1072	0.025	13433
10 Aug 2014	*F555W*	ACS/WFC	1232	0.025	13433
10 Aug 2014	*F814W*	ACS/WFC	2176	0.025	13433

Notes. [a]PI: S. Beckwith.
[b]PI: R. Chandar.
[c]PI: J. Maund.

3 RESULTS AND ANALYSIS

A selection of the pre-explosion and late-time observations of the site of SN 2011dh is presented in Fig. 1. In all the late-time observations, from the UV to the near-infrared, a source is clearly recovered at the SN position. The late-time source is clearly resolved from nearby sources and DOLPHOT PSF-fitting photometry reported the shape of the source (evaluated using the sharpness and χ^2 values) to be consistent with a single point source in all bands. Photometry of the late-time source, in comparison with the pre-explosion observations, is presented in Table 2. The photometry of the late-time source shows that it is significantly fainter than the pre-explosion source in all of the shared photometric bands (see Fig. 2), confirming the previous observations of Van Dyk et al. (2013a) and Ergon et al. (2014) that the YSG observed at the SN position prior to explosion is no longer present and, hence, was the progenitor. The relative faintness of the late-time source also implies that any remaining component of the progenitor system (i.e. a binary companion) was not a major contributor to the brightness of the pre-explosion source, in particular in the *F336W* band (where the late-time flux is lower than the observed pre-explosion flux by a

[1] STSDAS and PYRAF are products of the Space Telescope Science Institute, which is operated by AURA for NASA.
[2] http://americano.dolphinsim.com/dolphot/

Downloaded from http://mnras.oxfordjournals.org/ at NASA Goddard Space Flight Ctr on March 8, 2016

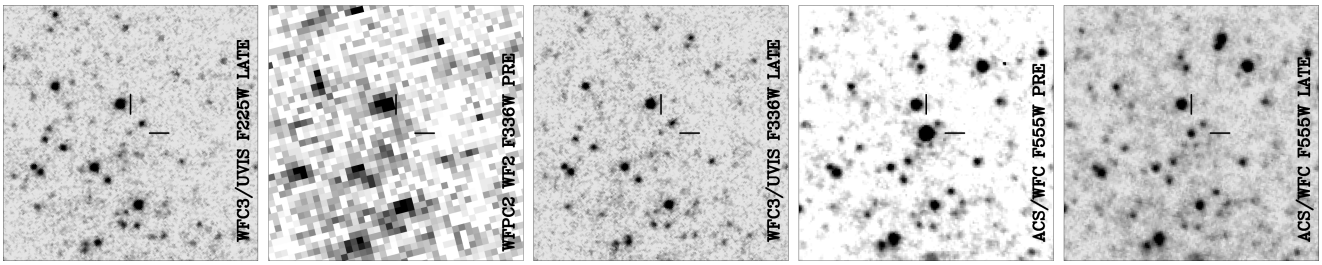

Figure 1. The site of SN 2011dh observed prior to explosion and at late times with *HST*. Each image panel is centred on the SN position (indicated by the cross hairs), with dimensions 4 arcsec × 4 arcsec and is oriented such that north is up and east is to the left. The panels are, from left to right: late-time WFC3/UVIS *F*225*W* observation; pre-explosion WFPC2/WF2 *F*336*W* observation; late-time WFC3/UVIS *F*336*W* observation; pre-explosion ACS/WFC *F*555*W* observation; and late-time ACS/WFC *F*555*W* observation.

Table 2. Photometry of the sources at the position of SN 2011dh in pre-explosion and late-time *HST* observations.

Filter	Pre-explosion (mag)	Late-time (mag)
*F*225*W*	–	24.61(0.11)
*F*336*W*	23.39(0.25)	24.89(0.11)
*F*435*W*	22.36(0.02)	24.63(0.04)
*F*555*W*	21.83(0.04)	24.31(0.03)
*F*658*N*	21.28(0.04)	–
*F*814*W*	21.20(0.03)	23.83(0.02)

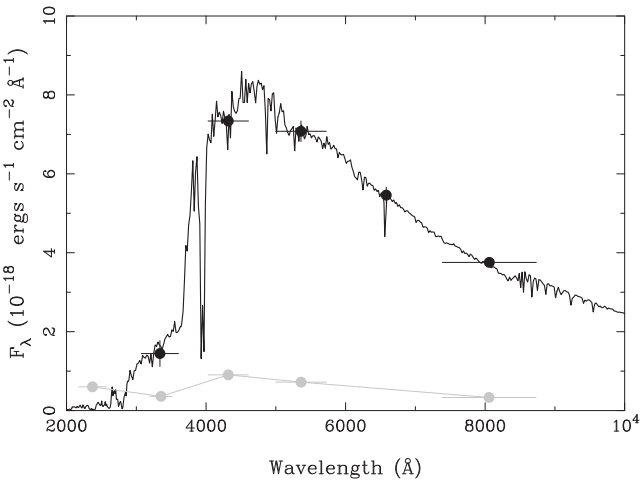

Figure 2. The observed SED of the pre-explosion (heavy points) and late-time (light points) sources at the position of SN 2011dh. Overlaid is a Castelli & Kurucz (2004) ATLAS9 synthetic spectrum ($T_{\rm eff} = 6000$ K) appropriate for the best-fitting solution for the pre-explosion photometry derived by Maund et al. (2011).

factor of ∼4). This implies that the analysis of the pre-explosion observation of the YSG progenitor, presented by Maund et al. (2011), is still valid: $\log(L/L_\odot) = 4.92 \pm 0.20$, $T_{\rm eff} = 6000 \pm 280$ K and subject to $E(B-V) = 0 - 0.032$ mag. In all the late-time observations, we see no evidence for spatially resolved light echoes in the vicinity of SN 2011dh, which is consistent with the low degree of reddening reported to SN 2011dh itself.

Utilizing our own spectral energy distribution (SED) fitting code, we attempted to fit the SED of the late-time source with ATLAS9 model SEDs (Castelli & Kurucz 2004) for single supergiant stars. Using the reddening reported for SN 2011dh as a prior, the most likely solution yielded $\chi^2 = 92.4$, implying that the SED of the

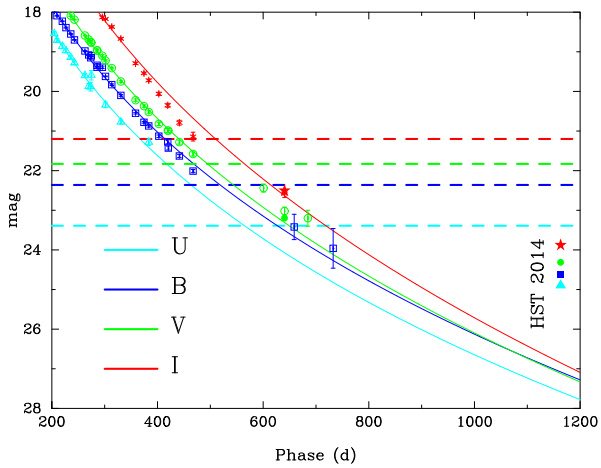

Figure 3. Late-time photometry of SN 2011dh from Ergon et al. (2015) and *HST* (from 2013 and 2014; filled symbols). Solid lines indicate the power-law fits to ground-based and *HST* observations prior to our 2014 observations. Horizontal dashed lines indicate the brightness of the progenitor in the pre-explosion observations.

late-time source is inconsistent with a stellar source. Given the late-time photometric evolution of SN 2011dh reported up to ∼350 d by Shivvers et al. (2013) and ∼700 d by Ergon et al. (2015), the shape of the SED suggests a significant contribution from the still bright SN. Using the late-time photometric observations reported by Ergon et al. (2015), with *HST* photometry from 2013 (Van Dyk et al. 2013a), we find that the behaviour of SN 2011dh at epochs prior to our *HST* observations is inconsistent with a linear decay and is, rather, better approximated by a power law (of the form $m = \alpha t^\beta$; see Fig. 3). The most recent late-time *HST* photometric measurements reported here are, however, even inconsistent with these earlier light-curve trends, and Fig. 3 shows that the light curve has flattened across all wavelengths.

In light of the still significant late-time contribution of the SN at optical wavelengths, it is difficult to place specific constraints on the presence of a binary companion that also contributes to the late-time SED. Under the assumption that the SN component is weakest in the UV, while a companion star's SED might peak in UV, we may attempt to place constraints on the allowed parameters for the companion given these observations. We consider two scenarios for the origin of the late-time UV flux: (1) all of the observed *F*225*W* and *F*336*W* flux arises from a companion star; and (2) all of the *F*225*W* flux and a portion of the *F*336*W* flux arise from a companion. Given these assumptions, the corresponding permitted regions for the companion star on the Hertzsprung–Russell diagram (HRD)

Downloaded from http://mnras.oxfordjournals.org/ at NASA Goddard Space Flight Ctr on March 8, 2016

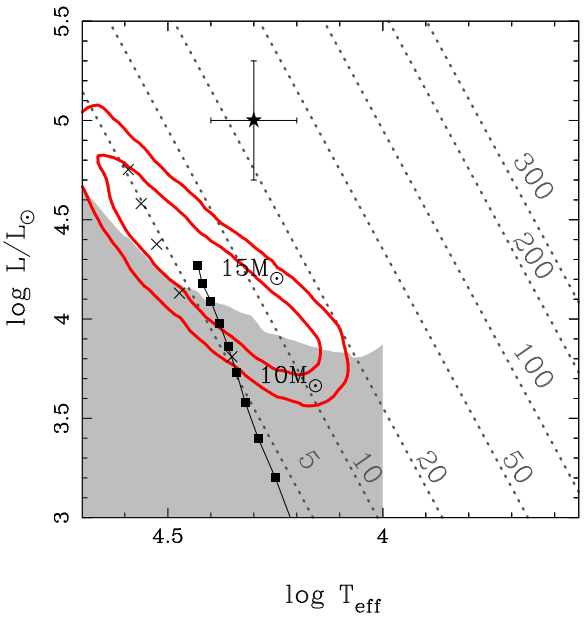

Figure 4. HRD showing the permitted locations for a possible binary companion, given the late-time photometry, under the assumptions: (1) all UV flux arises from the companion (red contours) and (2) only the *F*225*W* flux arises from the companion (grey shaded region). The upper limit of the grey shaded region corresponds to position on the HRD where the probability of detection of such a star is 50 per cent. The starred point corresponds to the position of the companion star identified for the progenitor of Type IIb SN 1993J (Maund et al. 2004). The positions of possible binary companions predicted by Benvenuto et al. (2013) are indicated by the crosses (×) and those of main-sequence stars with $M_{\rm ZAMS} \leq 15\,{\rm M}_{\odot}$, for integer masses from the STARS stellar evolution code (Eldridge & Tout 2004), are shown by the filled squares. The dotted lines indicate lines of constant radius (as labelled in solar radii).

are presented in Fig. 4. For the second scenario, we utilized the ACS/WFC *F*435*W* photometry as a further constraint on the temperature, as stars cooler than $T \sim 10\,000$ K would be brighter than the observed SED at that wavelength. Under the first assumption, due to correlations between luminosity and temperature, all of the Benvenuto, Bersten & Nomoto (2013) models for the companions, covering a range of mass accretion efficiencies, fit the observed UV photometry. Under the second assumption, only the binary companion models with the smallest mass accretion efficiencies ($\beta \leq 0.25$) or main-sequence companions with $M \leq 13\,{\rm M}_{\odot}$ are allowed.

4 DISCUSSION AND CONCLUSIONS

Previously, using the subset of late-time *F*225*W* and *F*336*W* observations presented here, Folatelli et al. (2014) claimed the detection of a hot, compact companion as predicted by Benvenuto et al. (2013). In the course of their analysis, however, Folatelli et al. had to make the key assumption that the UV flux *only* originated from the binary companion, and then were only able to constrain the properties using two photometric data points. A fundamental test of this hypothesis would be the decreasing flux at redder wavelengths, which is clearly at odds with the observed non-stellar optical SED (see Fig. 5). The late-time brightness of SN 2011dh at optical wavelengths is unexpected given the late-time evolution reported by Shivvers et al. (2013) and Ergon et al. (2015), but also raises serious concerns about the degree of the SN contribution at UV wavelengths, specifically where Folatelli et al. have claimed to observe the binary companion.

Ergon et al. (2015) discuss the late-time evolution of SN 2011dh and find that the radioactive energy deposition is likely insufficient to reproduce the late-time (600–750 d) optical luminosity. 'Freeze-out' in the helium envelope could also be a possible additional energy source. Ergon et al. (2015) also report strong flattening of the observed mid-infrared (MIR) light curve after 750 d. If we use the optical decline rate before 750 d and the MIR decline rate thereafter, we find a drop of 1.0 mag between 640 and 1166 d, which is in good agreement with the observed drop of 1.1–1.2 mag in the late-time (2014) *F*555*W* and *F*814*W* photometry and suggests that the flattening of the light curve is relatively wavelength independent (see Fig. 3).

In Fig. 5, we show the SEDs for the steady-state non-local thermodynamic equilibrium models 12C and 12B of Jerkstrand et al. (2015) at 500 d, who provide examples of how the SED of the SN would look in the radioactively powered scenario. These models only differ in the treatment of positron trapping (local or non-local), and are able to reproduce the light curve (Ergon et al. 2015) and spectra (Jerkstrand et al. 2015) of SN 2011dh over the period of 100–500 d. We also show the observed SED of SN 1993J at 674 d (Van Dyk et al. 2002), which provides an example of how the SED would look like if there were a contribution from the strong interaction of the ejecta with the circumstellar medium (CSM). As seen in Fig. 5, the shape of the observed SED in the optical is consistent with what could be expected for the SN in the radioactively powered scenario, but does not explain the UV portion of the SED (and could, possibly, require a binary companion). This requires, however, that there is no contribution due to the any late interaction with the CSM and that the $F225W - F336W$ colour for the freeze-out powered scenario is not considerably bluer than for the radioactively powered scenario. As discussed in Ergon et al. (2015), there are no clear signs of significant CSM interaction in the spectrum of SN 2011dh acquired at 678 d presented by Shivvers et al. (2013), which disfavours the CSM powered scenario. While an investigation of how the SED would look in the freeze-out powered scenario is outside the scope of this paper, at this point we cannot rule out that the observed flux in the *F*225*W* filter, and any of the other filters, originates solely from the SN. If the optical flux is dominated by the SN at 1164 d, the radioactively powered scenario can be ruled out, as the optical luminosity alone would then be 1.9 mag higher than the bolometric luminosity in models 12C and 12B.

To consider the role of CSM interaction in the behaviour of the late-time light curve of SN 2011dh, we obtained target-of-opportunity X-ray observations at the position of SN 2011dh with the X-ray telescope (XRT; Gehrels et al. 2004) on board the *Swift Gamma-Ray Burst Explorer* (Gehrels et al. 2004) on 2014 September 17 (4.9 ks) and 2014 September 24 (4.9 ks). While generally following the standard algorithm for automated analysis of XRT data (e.g. Evans et al. 2009), we manually selected background regions due to the complex nature of diffuse and/or unresolved emission from M51.[3] We find no evidence for significant point source emission (i.e. above and beyond the underlying background) at the position of SN 2011dh, down to a 3σ limit of 2×10^{-13} erg s^{-1} cm^{-2}, which corresponds to a luminosity of $\sim 1.22 \times 10^{39}$ erg s^{-1}.

We also obtained late-time radio observations of SN 2011dh with the Jansky Very Large Array. The observations were performed on

[3] Note that we verified that this diffuse component is unrelated to SN 2011dh by examining *Swift*-XRT observations of the field from 2005.

Downloaded from http://mnras.oxfordjournals.org/ at NASA Goddard Space Flight Ctr on March 8, 2016

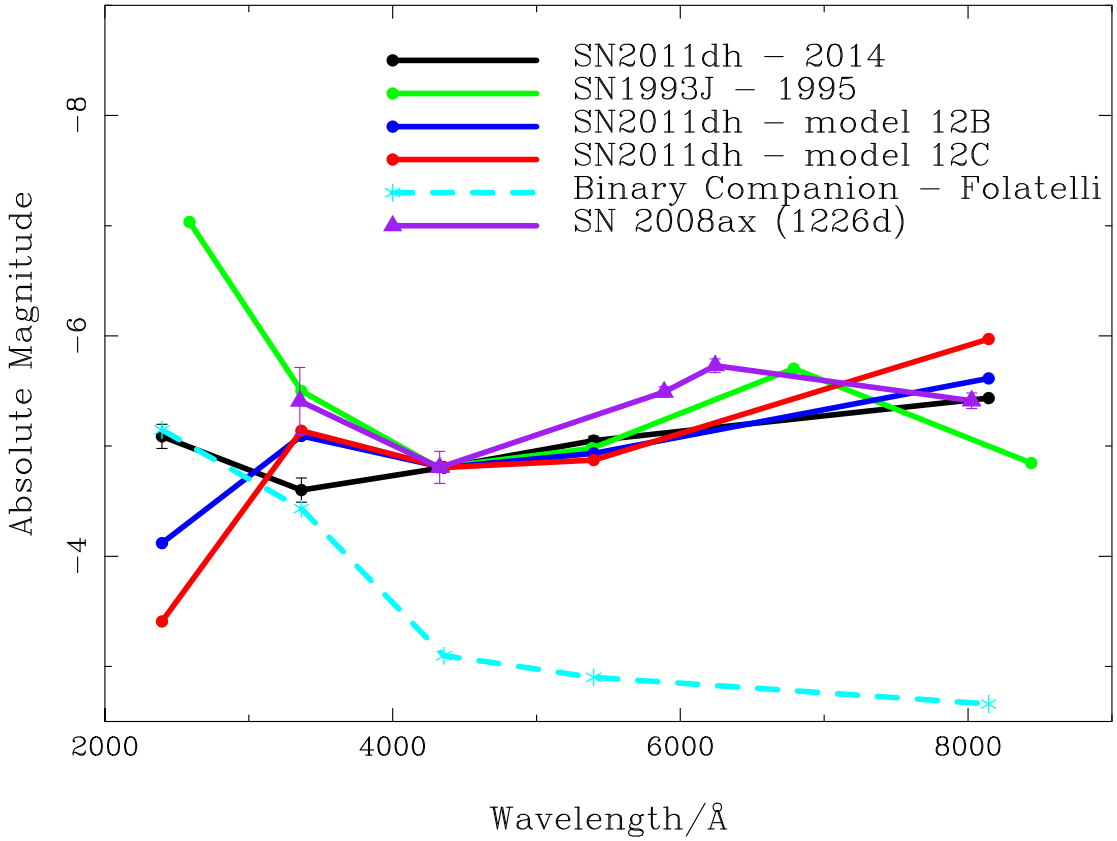

Figure 5. Theoretical and observed late-time SEDs, in units of absolute Vega magnitudes, for Type IIb SNe compared to the observed late-time SED of SN 2011dh. The SEDs are normalized to the brightness of the late-time source recovered at the position of SN 2011dh, as observed in the ACS/WFC *F*435*W* band. Also overlaid are the SED of the binary companion proposed by Folatelli et al. (2014) and the observed SED of SN 2008ax at 1226d (corrected for $E(B-V) = 0.4$; Maund et al., in preparation).

2014 October 18 UT at central frequencies of 6.1 GHz (*C* band) and 22 GHz (*K* band) using 3C 286 as a flux calibrator and J1349+5341 as a phase calibrator. We detect weak radio emission from the SN at flux levels of 459 ± 93 and 109 ± 17 μJy at the *C* band and *K* band, respectively. Past radio observations, from day ∼4 until day ∼90 after explosion, have already shown radio emission thus indicating interaction of the SN ejecta with CSM (Krauss et al. 2012; Soderberg et al. 2012; Horesh et al. 2013). Our late-time radio measurements are well within the expectations based on the earlier measurements, assuming that the CSM has an extended wind-like structure. The lack of excess in radio emission thus suggests that there is no additional interaction with an enhanced CSM.

While the X-ray and radio observations rule out strong ongoing CSM interaction at the time of the late-time *HST* observations, portions of the UV and optical SED could be enhanced by emission lines generated in some low-level interaction. Lines such as C II λλ2324, 2325 and [Ne III] λλ3868, 3869 (Fesen et al. 1999) could contribute flux to the observed *F*225*W* and *F*336*W* photometry. Ultimately, a UV late-time spectrum of SN 2011dh, which is unfortunately unfeasible with *HST*, would be required to establish if such emission lines are present, without a commensurate signal for CSM interaction in the X-ray and radio regimes. While earlier CSM interaction is ruled out by the spectra presented by Shivvers et al. (2013), without similar spectra at epochs comparable to our late-time *HST* observations it is difficult to assess whether any interaction might have started in the intervening period between those observations and our 2014 observations when the light curve appears to have flattened (which could mark a period of earlier enhanced mass-loss in the history of the progenitor).

Alternatively, the late-time flux could arise from early SN flux scattered into the line of sight by dust, forming a light echo (Rest et al. 2011). We note, however, that in all the late-time observations SN 2011dh appears point-like, which would require the scattering dust to have a very specific arrangement, lying behind the SN and exactly along the line of sight, which would be unlikely to occur by chance. In addition, given the low reddening estimated towards SN 2011dh, there is no evidence for large amounts of dust in the SN locality. We therefore discount the possibility of a light echo being the origin of the observed late-time brightness of SN 2011dh.

Based on the late-time *HST* observations presented here, there is, as yet, no conclusive evidence for the recovery of a binary companion associated with SN 2011dh. The presence of significant late-time flux at optical wavelengths for SN 2011dh suggests that the origin of the UV flux is highly uncertain and not necessarily attributable to a binary companion. *HST* observations of SN 2008ax at a similar epoch in its evolution (Maund et al., in preparation) exhibited a similar rise at UV wavelengths (see Fig. 5); however, there is no comparable observation with shorter wavelength filter to confirm that this rise in the SED continues in the UV as observed for SN 2011dh. In the case of SN 2008ax, even later *HST* observations confirmed the disappearance of the progenitor star, with no stellar residual at the SN location, corresponding to a binary companion, at UV or optical wavelengths. Alternatively, given the

Downloaded from http://mnras.oxfordjournals.org/ at NASA Goddard Space Flight Ctr on March 8, 2016

late-time brightness of SN 2011dh, a binary companion could still be 'hidden' by the SN, in which case its luminosity and, hence, mass would be lower than the optimistic interpretation of the UV observations presented by Folatelli et al. (2014) and its role in the evolution of the progenitor might be diminished. Constraining the progenitor to a lower mass has important implications for interacting binary evolution models. A lower mass would indicate that the mass transfer responsible for removing the hydrogen envelope was less efficient than for the case of SN 1993J, with most of the mass lost from the binary system rather than ending up in the companion star. Later, deeper observations once SN 2011dh has faded even more may permit the detection of a lower mass binary companion if it is present.

A fundamental question raised by these observations, however, is whether a binary companion is a prerequisite for the final appearance of the progenitor of SN 2011dh. There is significant evidence for the presence of a hot binary companion to the progenitor of SN 1993J (Aldering et al. 1994; Maund et al. 2004; Fox et al. 2014), the class prototype of Type IIb SNe. Georgy (2012), however, found that it was possible to produce YSG progenitors through single star evolution through the inclusion of rotation and by enhancing the mass-loss for an $M_{\rm ZAMS} = 15\,{\rm M}_{\odot}$ star by a factor of 10. This enhanced mass-loss rate is, however, consistent with the observed levels of mass-loss for some RSGs (van Loon et al. 2005) and given the measured luminosity of the progenitor of SN 2011dh the expected mass-loss rate of $\sim 10^{-5}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ (Georgy et al. 2012) is consistent with the mass-loss rate inferred from radio observations of the SN itself (Soderberg et al. 2012). In isolation, for a rotating $M_{\rm ZAMS} = 18\,{\rm M}_{\odot}$ star, Groh et al. (2013b) found that the progenitor evolved to become a YSG, instead of exploding as an RSG. This may suggest that new mass-loss rate prescriptions and rotation may make YSGs the natural endpoint for some stars of mass $\sim 13\,{\rm M}_{\odot}$, such as the progenitor of SN 2011dh. It should be noted that the mass-loss rates of RSGs are poorly known; even for stars of similar luminosities, mass-loss rate determinations from the literature (van Loon et al. 2005; Mauron & Josselin 2011) vary over several orders of magnitudes. The reason for the scatter is unclear, which could be due to unseen companions, eruptive episodes of mass-loss or a yet to be identified physical process, but could lead to stars of similar initial mass evolving very differently towards the ends of their lives.

While mass transfer in binary systems can be invoked to explain the observed properties of H-poor YSG progenitors, there is a significant increase in the parameter space in which acceptable models might arise. From the perspective of stellar evolution models, in both the single and binary scenarios, predicting the final temperature of a YSG progenitor requires fine tuning the adopted mass-loss rate. The case of the progenitor of SN 2011dh may serve to highlight the importance of understanding gaps in our knowledge of single star evolution and of how the light curves of SNe at late times are powered.

ACKNOWLEDGEMENTS

We are very grateful to Anders Jerkstrand for providing us with access to his late-time model spectra of SN 2011dh. The research of JRM is supported by a Royal Society University Research Fellowship. CG acknowledges support from the European Research Council under the European Union's Seventh Framework Program (FP/2007-2013)/ERC Grant Agreement No. 306901.

REFERENCES

Aldering G., Humphreys R. M., Richmond M., 1994, AJ, 107, 662
Arcavi I. et al., 2011, ApJ, 742, L18
Benvenuto O. G., Bersten M. C., Nomoto K., 2013, ApJ, 762, 74
Bersten M. C. et al., 2012, ApJ, 757, 31
Bersten M. C. et al., 2014, AJ, 148, 68
Cao Y. et al., 2013, ApJ, 775, L7
Castelli F., Kurucz R. L., 2004, preprint (arXiv: e-prints)
Crockett R. M. et al., 2008, MNRAS, 391, L5
Dolphin A. E., 2000, PASP, 112, 1383
Eldridge J. J., Tout C. A., 2004, MNRAS, 353, 87
Eldridge J. J., Fraser M., Smartt S. J., Maund J. R., Crockett R. M., 2013, MNRAS, 436, 774
Eldridge J. J., Fraser M., Maund J. R., Smartt S. J., 2015, MNRAS, 446, 2689
Ergon M. et al., 2014, A&A, 562, A17
Ergon M. et al., 2015, A&A, 580, A142
Evans P. A. et al., 2009, MNRAS, 397, 1177
Fesen R. A. et al., 1999, AJ, 117, 725
Filippenko A. V., 1997, ARA&A, 35, 309
Filippenko A. V., Matheson T., Ho L. C., 1993, ApJ, 415, L103
Folatelli G. et al., 2014, ApJ, 793, L22
Fox O. D. et al., 2014, ApJ, 790, 17
Fremling C. et al., 2014, A&A, 565, A114
Gehrels N. et al., 2004, ApJ, 611, 1005
Georgy C., 2012, A&A, 538, L8
Georgy C., Ekström S., Meynet G., Massey P., Levesque E. M., Hirschi R., Eggenberger P., Maeder A., 2012, A&A, 542, A29
Groh J. H., Georgy C., Ekström S., 2013a, A&A, 558, L1
Groh J. H., Meynet G., Georgy C., Ekström S., 2013b, A&A, 558, A131
Horesh A. et al., 2013, MNRAS, 436, 1258
Jerkstrand A., Ergon M., Smartt S. J., Fransson C., Sollerman J., Taubenberger S., Bersten M., Spyromilio J., 2015, A&A, 573, A12
Krauss M. I. et al., 2012, ApJ, 750, L40
Maund J. R., Smartt S. J., 2009, Science, 324, 486
Maund J. R., Smartt S. J., Kudritzki R. P., Podsiadlowski P., Gilmore G. F., 2004, Nature, 427, 129
Maund J. R. et al., 2011, ApJ, 739, L37
Mauron N., Josselin E., 2011, A&A, 526, A156
Nakar E., Piro A. L., 2014, ApJ, 788, 193
Nomoto K., Iwamoto K., Suzuki T., Pols O. R., Yamaoka H., Hashimoto M., Hoflich P., Van den Heuvel E. P. J., 1996, in van Paradijs J., van den Heuvel E. P. J., Kuulkers E., eds, Proc. IAU Symp. 165, Compact Stars in Binaries. Kluwer, Dordrecht, p. 119
Rest A., Sinnott B., Welch D. L., Foley R. J., Narayan G., Mandel K., Huber M. E., Blondin S., 2011, ApJ, 732, 2
Schlafly E. F., Finkbeiner D. P., 2011, ApJ, 737, 103
Shivvers I. et al., 2013, MNRAS, 436, 3614
Smartt S. J., 2009, ARA&A, 47, 63
Smith N., 2014, ARA&A, 52, 487
Soderberg A. M. et al., 2012, ApJ, 752, 78
Takáts K., Vinkó J., 2006, MNRAS, 372, 1735
Van Dyk S. D., Garnavich P. M., Filippenko A. V., Höflich P., Kirshner R. P., Kurucz R. L., Challis P., 2002, PASP, 114, 1322
Van Dyk S. D. et al., 2011, ApJ, 741, L28
Van Dyk S. D. et al., 2013a, ApJ, 772, L32
Van Dyk S. D., Filippenko A. V., Fox O., Kelly P., Smith N., 2013b, Astron. Telegram, 4850, 1
Van Dyk S. D. et al., 2014, AJ, 147, 37
van Loon J. T., Cioni M.-R. L., Zijlstra A. A., Loup C., 2005, A&A, 438, 273

This paper has been typeset from a TEX/LATEX file prepared by the author.

Downloaded from http://mnras.oxfordjournals.org/ at NASA Goddard Space Flight Ctr on March 8, 2016