On the progenitor of the Type Ic SN 2013dk in the Antennae Galaxies

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ABSTRACT

We report the results of our search for the progenitor candidate of SN 2013dk, a Type Ic supernova (SN) that exploded in the Antennae Galaxy system. We compare pre-explosion Hubble Space Telescope (HST) archival images with SN images obtained using adaptive optics at the ESO Very Large Telescope. We isolate the SN position to within 3σ uncertainty radius of 0″02, and show that there is no detectable point source in any of the HST filter images within the error circle. We set an upper limit to the absolute magnitude of the progenitor to be $M_{F555W} > -5.7$, which does not allow Wolf-Rayet (WR) star progenitors to be ruled out. A bright source appears 0″17 away, which is either a single bright supergiant or compact cluster, given its absolute magnitude of $M_{F555W} = -9.02 \pm 0.28$ extended wings and complex environment. However, even if this is a cluster, the spatial displacement of SN 2013dk means that its membership is not assured. The strongest statement we can make is that in the immediate environment of SN 2013dk (within 10 pc or so) we find no clear evidence of either a point source coincident with the SN or a young stellar cluster that could host a massive WR progenitor.

Key words: galaxies: individual (NGC 4038) — stars: evolution — binaries: general — supernovae: general — supernovae: individual (SN 2013dk).

1 INTRODUCTION

Massive stars evolve to an end state that results in the collapse of the stellar core, as hydrostatic pressure no longer balances gravity, producing a core-collapse supernova (CC-SN). These objects show a great diversity in their kinetic energy, luminosity and elemental abundances. This observational heterogeneity is chiefly related to the evolutionary state of the progenitor star at the moment of the explosion. Despite the large number of supernovae (SNe) discovered so far, the link between the progenitor evolution and the consequent explosion is not fully understood. Direct identification of the progenitor stars prior to the explosion have provided the most stringent constraints; we now know with an increasing degree of confidence that single red supergiants in the range of $\sim 8-16$ M$_\odot$ explode as Type II-plateau (II-P) SNe. We have also evidence that the progenitors of a few Type II-narrow (IIn) SNe are massive luminous blue variables, and that those of Type II-linear (II-L) and IIb SNe, are likely yellow supergiants (see e.g. Turatto et al. 2007 for a discussion of SN classification, and Smartt 2009 - and references therein - for a SN progenitor review). However, the origin of the stripped-envelope, hydrogen (or hydrogen and helium) poor Type Ib/c SNe is still debated. For several decades, these have been proposed to originate
from either explosion of massive WR stars (Gaskell et al. 1986), or from lower mass helium stars in interacting binaries (Podsiadlowski et al. 1992). If they are massive, classical WR progenitors, then the absolute magnitude distribution of this system means that we may be able to detect them in pre-explosion imaging (e.g. see Crockett et al. 2007 for the deepest limits set). Nevertheless, there has been no direct detection of their progenitors to date. This is perhaps further evidence that the most massive stars may form quenched, black-hole forming SNe, while the majority of the Ib/c SNe we see come from lower mass helium stars in interacting binaries (e.g. see Eldridge et al. 2013).

Here we present the case of SN 2013dk in NGC 4038, which is part of the well known Antennae galaxy system. SN 2013dk was discovered by the CHASE survey (Pignata et al. 2009) on 2013 June 22.12 (UT dates are used throughout), and was soon after spectroscopically classified as a young stripped-envelope SN (Carrasco et al. 2013, Harutyunyan et al. 2013). The position of SN 2013dk was given as $\alpha = 12^h 01^m 52.72^s \pm 0.2^s$, $\delta = -18^\circ 52' 18.3'' \pm 0.2''$ (J2000.0; Carrasco et al. 2013). A first attempt at identifying the SN location was performed using archival HST images from 2008-2009, with a reference image of the SN obtained at Telescopio Nazionale Galileo (TNG+Dolores) soon after the discovery (Elias-Rosa et al. 2013). Here we present a more detailed study of the SN 2013dk progenitor candidate via further comparison of the HST images with Very Large Telescope (VLT)+Naos-Conica (NaCo) adaptive optics data.

2 THE SPECTRAL TYPE CLASSIFICATION OF SN 2013DK

The classification spectrum reported in Harutyunyan et al. (2013) suggested that SN 2013dk was a Type Ic SN discovered nearly one week before maximum light. However, some stripped-envelope SNe develop weak He i lines at later stages, and distinguishing between Ib and Ic SNe can be difficult. Soon after the announcement, our team started a multi-wavelength monitoring campaign for SN 2013dk, and a detailed analysis of the data obtained will be presented in a forthcoming paper (Takáts et al. in prep.). Here, in order to establish a secure classification of SN 2013dk, we compare in Figure 1 (top) a spectrum obtained on 2013 July 02.36 UT (close to maximum light) with the Faulkes Telescope South equipped with FLOYDS (Brown et al. 2013), to spectra of a sample of Type Ib/c SNe at a similar phase. The spectra of SN 2013dk, and the three Type Ic SNe do not show the evident He i features that are clearly detected in SN 2008D, confirming the initial classification of SN 2013dk as a Type Ic event.

Assuming $E(B-V)_{G} = 0.04 \pm 0.01$ mag as the Milky Way component to the line-of-sight reddening (Schlafly & Finkbeiner 2011), and measuring the $E(B-V)_{host}$ through the equivalent width (EW) of the Na i D line at the host-galaxy redshift ($z_o = 0.0054$; Poznanski et al. 2012) in a set of low-resolution early spectra (Takáts et al. 2013 in prep.), we derive a $E(B-V)_{tot} = 0.24 \pm 0.02$ mag which will be adopted hereafter. However, we caution that due to large scatter seen for SNe in the EW(Na i D) vs. $E(B-V)$ plane (e.g. Elias-Rosa 2007 or Poznanski et al. 2011), the derived extinction should not be considered secure. Indeed, our estimate of the extinction could be underestimated, as suggested by the red colour of SN 2013dk. A detailed analysis of the extinction of this SN will be done after the completion of its monitoring campaign (Takáts et al. 2013 in prep.). We adopt a distance of $22.3 \pm 2.8$ Mpc from Schweizer et al. (2008). The V-band absolute light curve of SN 2013dk (at maximum, on JD=2456476.5, $M_V = -17.02$ mag) is compared in Figure 1(bottom) with those of the Type Ic SNe 1994I (Richmond et al. 1994), 2004aw (Taubenberger et al. 2006), 2006aj (Pian et al. 2006), and 2008D (Malesani et al. 2009). Bottom: Comparison of the early-time and preliminary V-band absolute light curve of SN 2013dk with those of the Type Ib SNe 1994I (Richard et al. 1994), 2008D (Taubenberger et al. 2006), the broad-lined 2006aj (Pian et al. 2006), and the Type Ib SN 2008D (Mazzali et al. 2008). The adopted distance moduli and total interstellar reddening values for the comparison objects were taken from the literature.

3 SEARCHING THE PROGENITOR CANDIDATE AT THE SN LOCATION

Pre-explosion images of the SN site in the HST archive are from the Wide Field Camera 3 (WFC3) Ultraviolet-Visible (UVIS) Channel (pixel scale of 0.064 pix\(^{-1}\)) and the Advanced Camera for Surveys (ACS) Wide Field Channel (WFC) (pixel scale of $\sim 0.05$ pix\(^{-1}\)). The UVIS data are in bands F336W ($\sim V$; 5530 s), F555W ($\sim V$; 1032 s), F625W
lies on the edge of a bright point-like source (labelled as "A") in the NaCo post-explosion image, by geometrically transforming the former to the latter. We registered 30 point-like sources in common between the two datasets and measured their pixel coordinates with the IRAF tasks `imexamine` and `daofind` (within IRAF/DOLPHOT). Then, using `geomap` and `geoxytran` (always IRAF tasks), we carried out a geometrical transformation between the sets of coordinates. The position of the SN (and its uncertainty) is derived by averaging the measurements from the two IRAF centroiding methods above mentioned. As a result, the SN location lies on the edge of a bright point-like source (labelled as "A") in Figure 2 visible in all bands. More precisely, it is located approximately at 0′.15W and 0′.08N from the center of Source "A" (average values of the offsets in the different bands). The total estimated uncertainty in the astrometry is given in Table I. These values were calculated as a quadrature sum of the uncertainties in the SN position, and the $rms$ uncertainty in the geometric transformation.

Source “A” is one of detected sources near the pre-explosion error circle suggested by Elias-Rosa et al. (2013), however, the difference between the locations of “A” and the SN location is now greater than 10σ (see Table I). Hence Source “A” can not be a single stellar precursor to SN 2013dk; however we will consider the possibility that it is a complex or cluster with which the progenitor was associated. Two other “progenitor candidates” were identified in the preliminary analysis of Elias-Rosa et al. (2013) ("B" and "C" in Figure 2), and can now discounted as being related to SN 2013dk.

4 PROGENITOR ANALYSIS

We obtained photometry of the Source “A” close to the SN position in the pre-explosion HST images using the package DOLPHOT 12. No progenitor star is visible at the exact SN position in any of these images. For all filters, it was necessary to measure small dithered offsets between exposures with respect to one fiducial image before running DOLPHOT. We rejected those images with such a low signal-to-noise (<5) that Source “A” was hardly detectable. DOLPHOT does not yet support transformations from WFC3 flight-system magnitudes to the corresponding Johnson-Cousins magnitudes, hence we quote magnitudes in VEGAMAGS flight-system (Table I).

DOLPHOT also reports a set of parameters to interpret the nature of the source, such as the “object type” flag, which in our case was “1” for all cases, meaning that the source is likely stellar. However, another relevant parameter is the “sharpness”, which in our case varies between ~0.18 and 0.13, indicating a likely good star, although negative values could also be signs of a broad source (Dolphin 2000). In addition, the full width half maximum of the stellar point-spread function (PSF) is on average ~2.6 pixels, which at a distance of 22.3 Mpc corresponds to ~11 pc, which is quite large. The residual images, after PSF subtraction by DOLPHOT, are quite clean around the position of source “A” in almost all of the images. We note there is possibly a small residual in the F336W and F555W images, which could result from a poor subtraction due to the low signal-to-noise; however, we can not rule out the possibility of an additional contaminating source. Hence even if Source “A” seems to be a point-like source, the spatial size of the PSF at this distance means that it could be also a compact cluster. In the following, we consider the three possible interpretations of Source “A” and the progenitor of SN 2013dk:

- **Cluster.** While Source “A” is not clearly extended, its absolute magnitude is $M_{F555W} = -9.02 \pm 0.28$ brighter than the threshold of $M_V < -8.6$ mag which [Bastian et al. (2005)] and [Crockett et al. (2008)] suggest for compact star clusters (assuming $F555W \sim V$). The photometry for Source “A” was compared with template cluster SEDs, calculated with Starburst99 (Leitherer et al. 1999), using our own minimisation and fitting code (Maund, 2013, in prep.), with a single instantaneous episode of star formation. The best fit solutions were consistent with moderate reddening $[E(B-V) \sim 0.2]$ and ages in the range $15-22$ Myr. The corresponding $\chi^2$ value of the best-fit solution was 39.1, and Figure 3 shows that the fit is not excellent. If the progenitor of SN 2013dk was a member, and if we could assume that it was born coeval with the cluster, then this would imply a turn-off mass of $10-15$ M$_\odot$ (from the age-mass relations in Eldridge & Tout 2004; Smartt et al. 2009). This would favour a low mass helium star in an interacting binary as the progenitor and not a massive WR star (Podsiadlowski et al. 1992; Eldridge et al. 2013). However, we caution that SN 2013dk is not coincident with Source “A”, and hence it may not even be related. Moreover, the mean half-light or “effective” radius found for young clusters in the Antennae Galaxies by [Whitmore et al. (1999)] was $4 \pm 1$ pc (although clusters can have also radii $\sim 10$ pc; Larsen 2004), and the projected distance from the SN location to the Source “A” is between $9$ and $16$ pc. The strongest statement we can make is that we can find no evidence of a very young stellar population in local vicinity of SN 2013dk.

- **Single star.** As Source “A” is not inconsistent with a point-like source, we can not rule out the possibility that it is a single star. In this scenario, Source “A” would be unre-

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11 [http://hla.stsci.edu/hlaview.html](http://hla.stsci.edu/hlaview.html)

12 IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the AURA, Inc., under cooperative agreement with the National Science Foundation (NSF).

13 DOLPHOT is a stellar photometry package that was adapted from HSTphot for general use [Dolphin 2000]. We used the WFC3 and ACS modules of the v2.0, updated 2013 March. [http://americano.dolphinsim.com/dolphot](http://americano.dolphinsim.com/dolphot). Note that DOLPHOT is not designed to run on the drizzled image mosaics.
high for a single star. We added artificial stars at the precise SN position we can place, and compare to the results in Eldridge et al. single star, then these upper limits are the best restrictions to its magnitudes in each filter. If Source “A” is a single star at the position of SN 2013dk, we can set upper limits for the Position and magnitudes of the Source “A” and SN 2013dk.

Table 1. Position and magnitudes of the Source “A” and SN 2013dk.

| Position(a) | F336W (mag) | F435W (mag) | F555W (mag) | F625W (mag) | F814W (mag) |
|-------------|-------------|-------------|-------------|-------------|-------------|
| Source “A”  | 0′′15E, 0′′08S | 23.13(0.25) | 23.41(0.03) | 23.45(0.05) | 22.83(0.08) |
| Upper limit | ≥27.2       | ≥26.5       | ≥26.8       | ≥26.4       | ≥24.9       |
| Total uncertainty (mas) | 6/6 | 9/8 | 6/6 | 6/6 | 5/6 |
| Diff. position SN/candidate “A” (mas) | 133/85 | 137/88 | 146/83 | 148/87 | 153/83 |

(a) Position of Source “A” with respect to the SN location.

brightness of the artificial star was in all cases fainter than Source “A”. Thus, we reran DOLPHOT adding specific parameters for the insertion and measurement of the synthetic stars. The resulting upper limits are presented in Table 1. Note that this methods works for both WFC3 and ACS HST instruments. Adopting a distance modulus µ = 31.74 ± 0.27 mag, and AV tot = 0.73 ± 0.06 mag as the extinction toward SN 2013dk, we estimate a limit in the absolute magnitude of an undetected progenitor, MF555W ≥ −5.7 mag. The magnitude limits can not rule out massive WC or WO stars as progenitors (WR stars with strong carbon or oxygen emission-lines), since in our Galaxy (see e.g. Sander et al. 2012) and the Large Magellanic Cloud (e.g. Massa et al. 2002) such stars have magnitudes between −2 and −8 mag. Thus, the progenitor of SN 2013dk joins the list of undetected supernova Ib/c progenitors as summarised and described in Eldridge et al. (2013). However, given also the large extinction suffered by this SN, we can not rule out that the progenitor could be hidden by strong foreground dust that we have not accounted for. These magnitude limits alone do not allow us to distinguish robustly between high mass WR stars and lower mass helium star progenitors in interacting binaries (see discussion in Eldridge et al. 2013), but it is useful to add these constraints to that sample. Including SN 2013dk in the same methodology as in Eldridge et al. (2013) reduces the probability that Ib/c SNe come exclusively from the massive WR population to around 12 per cent.

In summary we cannot definitively determine that Source “A”, the closest bright source to SN 2013dk in HST images, is a cluster or single point source. Although it is unresolved, we favour it being a compact cluster given its

Figure 2. Subsections of the post-explosion adaptive optics Ks image of SN 2013dk with VLT + NaCo (panel a), and the pre-explosion HST + WFC3 images in F336W (panel b), F555W (panel c), and F814W (panel d) of NGC 4038. Panel e is a magnification of the HST + WFC3 image in F814W. The positions of the SN is indicated, as well as three neighbouring sources of SN 2013dk, “A”, “B” and “C”.

Figure 3. Left: Observed spectral energy distribution for Source “A”. Overlaid are Starburst 99 model SEDs for clusters, with a single burst of star formation, with ages 15 Myr (heavy line) and 22 Myr (grey line). Right: The joint posterior distribution for the reddening and cluster age for Source “A”. The contours contain 68 and 95% of the probability.

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bright absolute magnitude and more extended wings. We find a reasonable, but not excellent, fit to the cluster SED giving quite an age of 15 – 22 Myrs. If the progenitor of SN 2013dk had been a cluster member, and coeval with cluster formation then this would imply a progenitor mass in the range 10 – 15 M⊙. However even if Source “A” is a cluster, SN 2013dk is not spatially coincident with it, nor is it within the half light radius. This limits what we can definitely determine about the progenitor nature. Future observations of the SN field with HST once we are confident the SN has faded might allow difference imaging to verify if any source in the field has vanished, or at least has significantly weakened (e.g. see Maund & Smartt 2009). 

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