The Progenitors of stripped-envelope Supernovae

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ABSTRACT: We present the results of our analysis of Hubble Space Telescope (HST) and deep ground-based images, to isolate the massive progenitor stars of two stripped-envelope supernovae (SNe), e.g., the highly-extinguished Type Ic SNe 2003jg in NGC 2997 and 2004cc in NGC 4568.

METHODOLOGY -- DIRECT IDENTIFICATION:

SN Discovery

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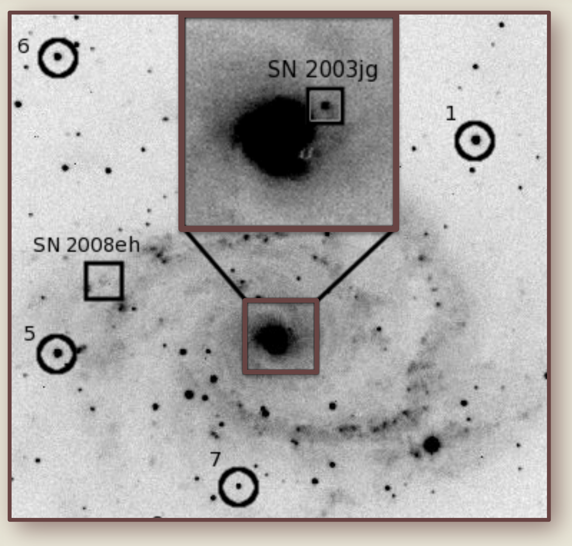
HST Archive hunting pre-SN images of host galaxies

- accurate positions for SNe from ground-based telescopes
- accurate location of SNe on WFPC2/WFC3/ACS chips

- HSTphot [1]
- confirm with post-SN HST or adaptive optics images from > 8m telescopes ... maybe also GTC??!
- ground-based in order to characterize the identified progenitor

Estimation of the progenitor mass and evolutionary state of the star before the core-collapse

SN 2003jg



SN 2003jg is a **highly-reddened** type Ic supernova, discovered[2] in NGC 2997.

This SN was well covered in BVRI bands from Las Campanas Observatory between Nov 8 2003 and Jan 15 2004 (**Fig. 1**). Using the "GELATO" spectrum-comparison code[3] on the SN classification spectrum[4], we are able to estimate the B maximum light of SN 2003jg ~25 days before the discovery. An average **$A_{V,tot}$=4.08 ± 0.59 mag** has been estimated for this SN via the comparison with coeval type Ic SN spectra and with the $(V-I)_0$ of SNe 1994I[5] and 2004aw[6] (**Fig. 1**). In **Fig. 1** we can also see how similar SN 2003jg is to the **slow decliners** SNe 1997ef[7] and 2004aw.

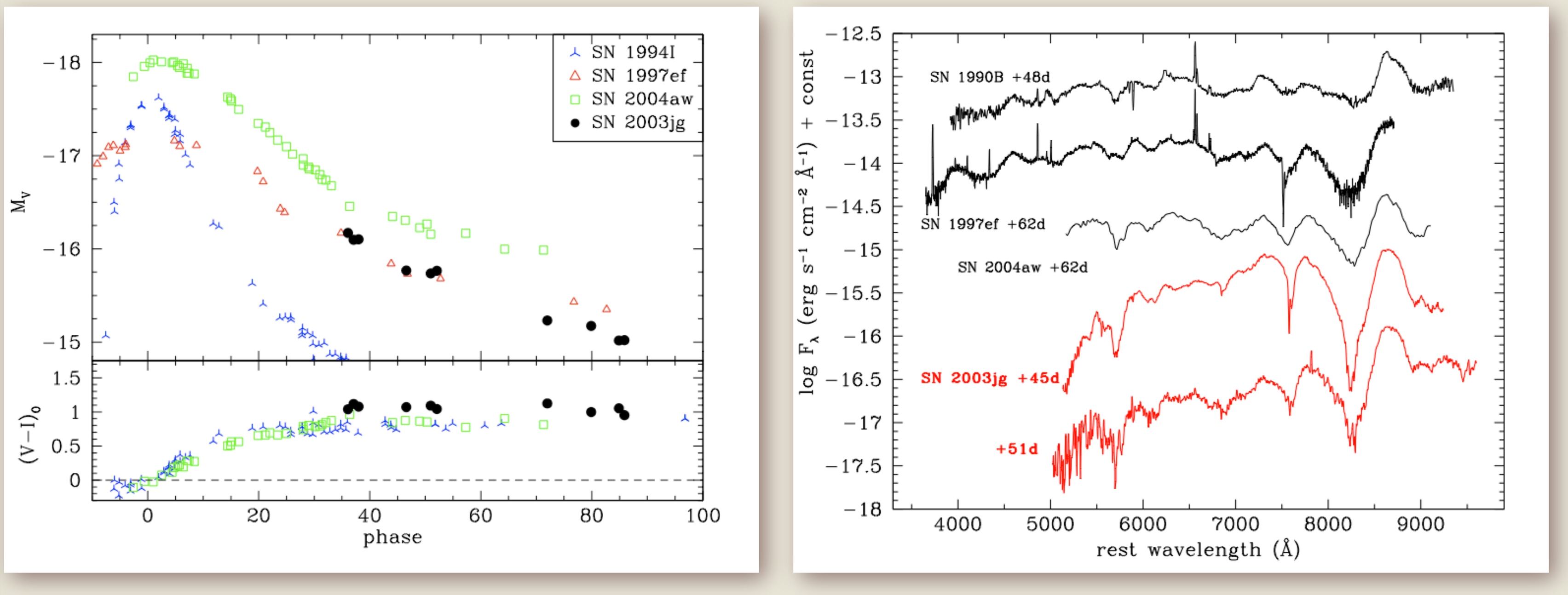


Figure 1. *Left - Top*: Absolute V light curve of SN 2003jg along with those of the normal SN Ic 1994I, and the slow decliner SNe 1997ef and 2004aw. Distances and extinction estimates have been adopted from the literature. *Left - Bottom*: The $(V-I)_0$ color of SN 2003jg (we have used the average $E(V-I)_{tot}$ = 1.68 mag). *Right:* Optical spectral evolution of SN 2003jg, along with comparison spectra of the SNe 1994I, 1997ef and 2004aw. All spectra have been corrected for their host-galaxy recession velocities. Ages are relative to *B maximum.*

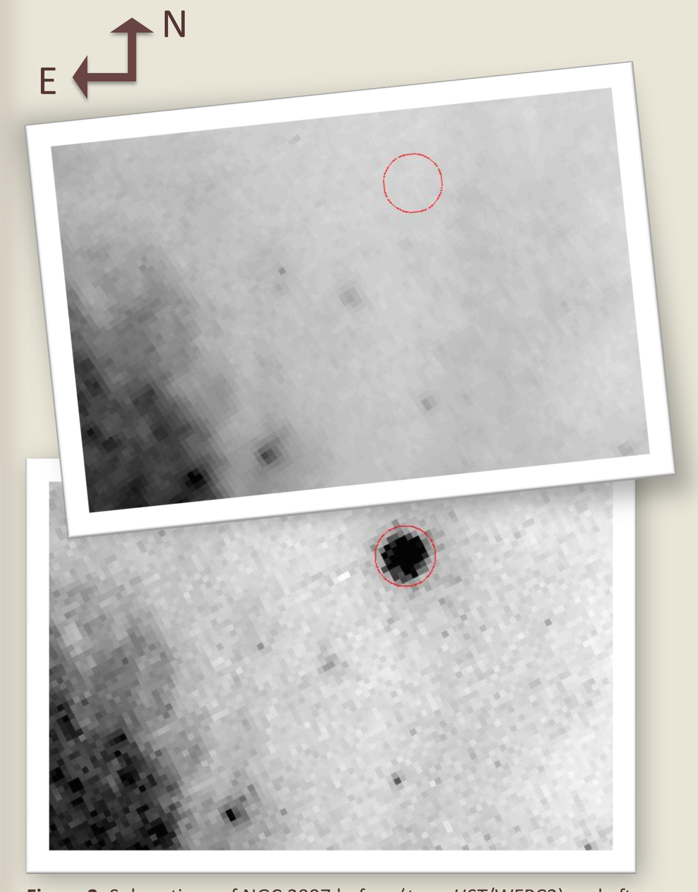


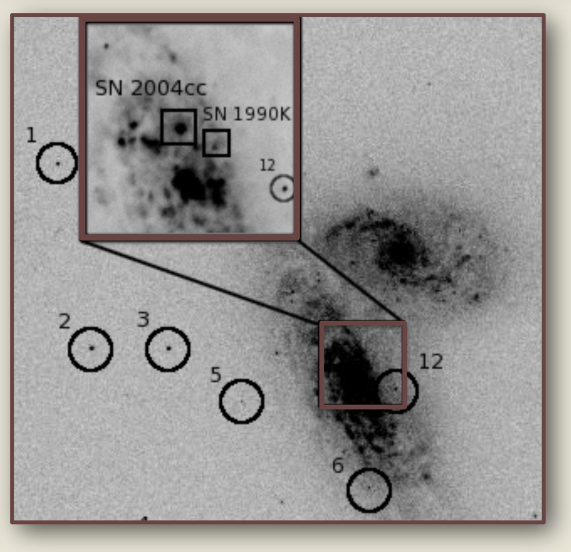
Figure 2. Subsections of NGC 2997 before (*top - HST*/WFPC2) and after (*bottom - HST*/ACS-HRC) the SN 2003jg explosion in F814W. The position of the SN candidate progenitor is indicated by a circle.

Progenitor: Comparing pixel-for-pixel both groups of data (pre- and post-SN explosion), we verify that the position of SN 2003jg (**Fig. 2**) is in a dust lane of NGC 2997 without any visibly nearby sources, either in F450W (~B), F606W (~V) or F814W (~I). Therefore, **not clear evidence of the direct detection of the progenitor has been found**.

Consequently, we input artificial stars with brightness fainter than the progenitor candidate at random positions in an area of 2"-radius circle around the progenitor candidate position, estimating an upper limit of **M_V > -8.8 mag** for the progenitor candidate of SN 2003jg. This magnitude is brighter than those we can expect for a massive WC or WO star (e.g., approximately between -3 and -6 in the LMC[8]) – thought to be the progenitor of the type Ic SN[9] -- which do not allow us to estimate the initial progenitor mass.

On the basis of its luminosity, we suggest an **undetected, compact massive star** (with initial masses up to 120 $M_\odot$[9]) hidden by a thick dust lane as progenitor of SN 2003jg.

SN 2004cc



SN 2004cc is a **highly-reddened** type Ic supernova, discovered [10] in one of the *Butterfly Galaxies*, NGC 4568.

Even from a scant coverage (using NOT+ALFOSC and *HST*+ACS/HRC), we are able to produce a relatively consistent reddening estimate and characterize this SN. Using "GELATO", our SN spectrum provides good fits with those of the type-Ic SNe 1997X[11] and 1994I at 9-10 days after maximum. SN 2004cc is also pretty similar to its mate SN 1990B[12] (which exploded in the same host galaxy) both spectroscopically and photometrically, showing, for example, the same **flattening behavior** at the late time V light curve (**Fig. 3**). Another similarity is the high extinction suffered by both SNe, which is **$A_{V,tot}$~3.20 ± 0.10 mag** in the case of SN 2004cc.

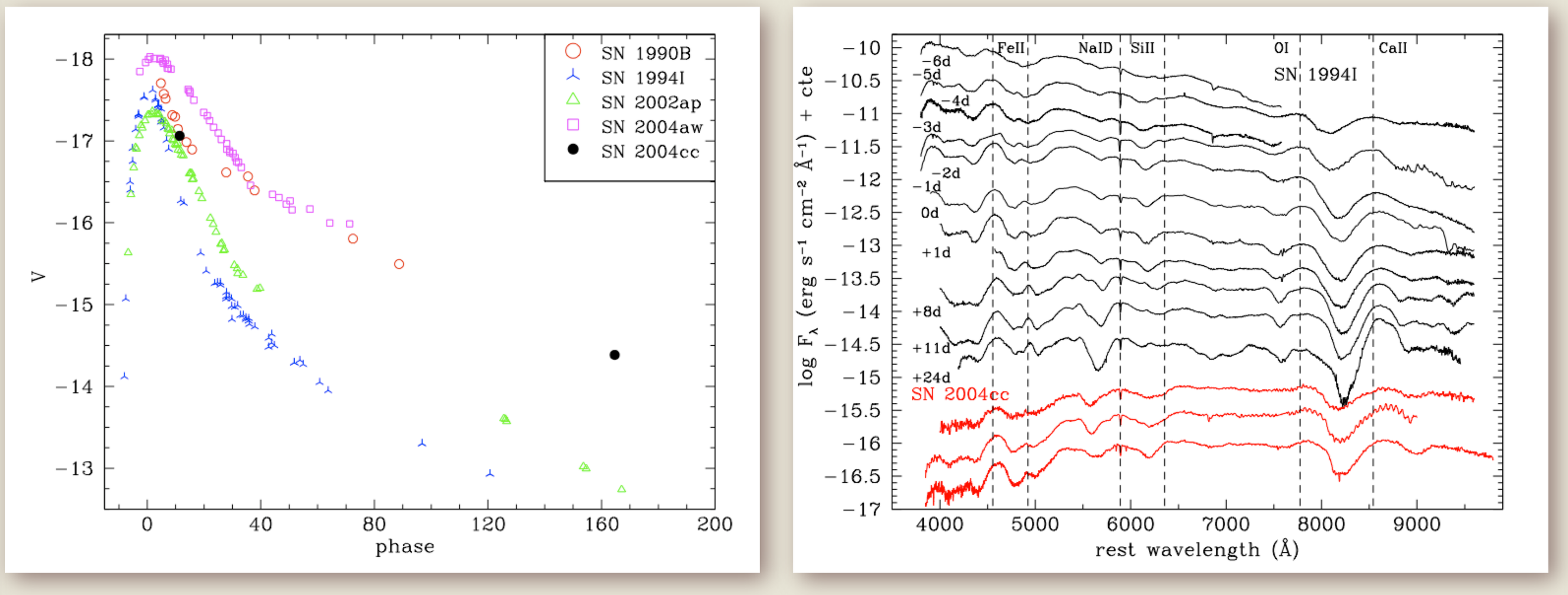


Figure 3. *Left:* Absolute V light curve of SN 2004cc along with those of the SNe Ic 1990B, 1994I, 2002ap[13] and 2004aw. Distances and extinction estimates for these SNe have been adopted from the literature. *Right:* Optical spectral evolution of SN 2004cc, along with comparison spectra of the SN Ic 1994I. All spectra have been corrected for their host-galaxy recession velocities. Ages are relative to *B maximum.*

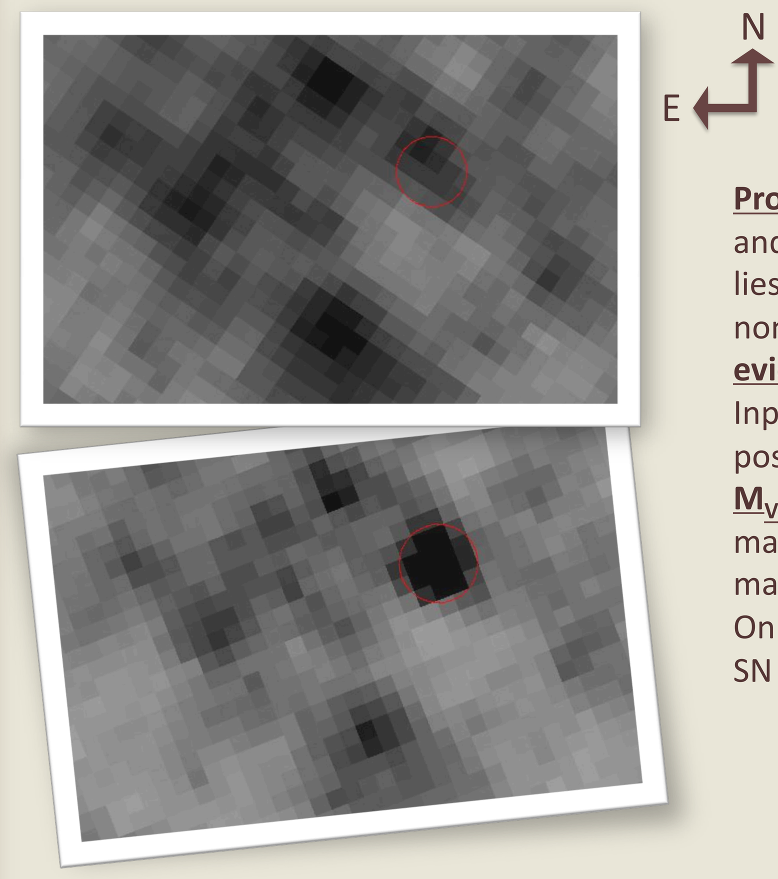


Figure 4. Subsections of NGC4568 before (*top-HST*/WFPC2) and after (*bottom-HST*/ACS-HRC) the SN2004cc explosion in F606W and F555W, respectively. The position of the SN candidate progenitor is indicated by a circle.

Progenitor: Comparing pixel-for-pixel both groups of data (pre- and post-SN explosion), we verify that the position of SN 2004cc lies on the edge of a bright source (F606W) but > 3σ from its nominal center (**Fig. 4**). **Again in this case there is not clear evidence of the direct detection of the progenitor**.

Inputting artificial stars around the progenitor candidate position as we did for SN 2003jg, we estimate an upper limit of **M_V > -9 mag** for the progenitor candidate of SN 2004cc. This magnitude is also brighter than those we can expect for a massive WC or WO star.

On the basis of its luminosity, we suggest that the progenitor of SN 2004cc is **a cluster member**.

THUS: The type Ib/c supernovae - those explosions which come from massive star populations, but lack hydrogen and helium, have been proposed to originate in the explosions of massive Wolf-Rayet stars, and we should easily be able to detect the very luminous, young progenitors if they exist. However there have been no detections of progenitors to date. This is perhaps further evidence that the most massive stars may form quenched, black-hole forming SNe and the majority of the Ib/c supernovae we see come from lower mass stars in interacting binaries[14]. Hence, **even if these results do not directly reveal the nature of the progenitors of this type of SNe, they can help to characterize the dusty environment which surrounded the progenitor of the stripped-envelope core-collapse SNe and, therefore, provides crucial constraints on the nature of the progenitors.**

(1) Dolphin, A. E. 2000, PASP, 112, 1383; (2) Martin, R. & Biggs, J. 2003, IAUC 8235; (3) Harutyunyan, A. et al. 2008, A&A, 488, 383; (4) Howell, D. A. 2003, IAUC 8241; (5) Richmond, M. W., et al. 1996, AJ, 111, 327; (6) Taubenberger, S. et al. 2006, MNRAS, 371, 1459; (7) Garnavich, P., et al. 1997, IAUC 6778; (8) Vacca, W. D. & Torres-Dodgen, A. V. 1990, ApJS, 73, 685; (9) Georgy, C. et al. 2009, A&A, 502, 611; (10) Monard, L. A. G. & Li, W. 2004, IAUC 8350; (11) Benetti, S. et al. 1997, IAUC 6554; (12) Clocchiatti, A. et al. 2001, ApJ, 553, 886; (13) Foley, R. J. et al. 2003, PASP, 115, 1220; (14) Smartt, S.J. et al. 2009, MNRAS, 395, 1409.

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