Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRASL **437,** L51–L55 (2014) doi:10.1093/mnrasl/slt138
Advance Access publication 2013 October 29

SN2012ca: a stripped envelope core-collapse SN interacting with dense circumstellar medium*

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Accepted 2013 October 1. Received 2013 September 23; in original form 2013 July 5

ABSTRACT

We report optical and near-infrared observations of SN2012ca with the Public ESO Spectroscopy Survey of Transient Objects (PESSTO), spread over one year since discovery. The supernova (SN) bears many similarities to SN1997cy and to other events classified as Type IIn but which have been suggested to have a thermonuclear origin with narrow hydrogen lines produced when the ejecta impact a hydrogen-rich circumstellar medium (CSM). Our analysis, especially in the nebular phase, reveals the presence of oxygen, magnesium and carbon features. This suggests a core-collapse explanation for SN2012ca, in contrast to the thermonuclear interpretation proposed for some members of this group. We suggest that the data can be explained with a hydrogen- and helium-deficient SN ejecta (Type I) interacting with a hydrogen-rich CSM, but that the explosion was more likely a Type Ic core-collapse explosion than a Type Ia thermonuclear one. This suggests that two channels (both thermonuclear and stripped envelope core-collapse) may be responsible for these SN 1997cy-like events.

Key words: supernovae: general – supernovae: individual: SN2012ca.

1 INTRODUCTION

Supernovae (SNe) are produced by two physical mechanisms: thermonuclear SNe (SN Ia) which completely destroy the degenerate progenitor star (Hillebrandt & Niemeyer 2000), and core-collapse SNe (CC-SNe) which leave a compact remnant (Janka 2012). Thermonuclear SNe can be produced through a single-degenerate channel when a white dwarf (WD) accretes hydrogen and helium from a companion or through the merger of two WDs (Hillebrandt & Niemeyer 2000). CC-SNe are produced by the explosion following the gravitational collapse of the cores of massive stars and classified according to the presence (SNe II) or absence (SN I) of H and/or He in their spectra (Filippenko 1997). Theoretical stellar evolution calculations have long attempted to link evolved model stars (Heger et al. 2003; Langer 2012) to the types of CC-SNe observed and in some cases the directly identified progenitors (Smartt 2009). The two physical mechanisms are rather different, but a number of SNe have been discovered for which the underlying origin of the explosion is unclear.

Events such as SN 2002ic (Hamuy et al. 2003; Deng et al. 2004; Wood-Vasey, Wang & Aldering 2004) and PTF11kx (Dilday et al.

*Based on observations collected at the European Organization for Astronomical Research in the Southern hemisphere, Chile, as part of programme 188.D-3003 (PESSTO).
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Published by Oxford University Press on behalf of the Royal Astronomical Society

2012; Silverman et al. 2013b) exhibit unambiguous signs of the ejecta interacting with circumstellar material (CSM). They have been classified as interacting Type Ia SNe (SNe Ia) and are thought to be of thermonuclear origin. Their spectra appear to be a 'diluted' spectrum of a bright SN Ia (e.g. SNe 1991T and 1999aa) along with superimposed H emission lines. PTF11kx shows the strongest evidence for being a thermonuclear event interacting with CSM expelled by a companion red giant star (Dilday et al. 2012). However, the physical origin of other SNe are still uncertain and this debate dates back to the peculiar Type IIn SN1997cy (Germany et al. 2000; Turatto et al. 2000). The growing arguments that many such events with narrow hydrogen (classified as SNe IIn) could be thermonuclear has resulted in SN2008J (Taddia et al. 2012) being labelled as an interacting SN Ia, while new data for SN2005gj (Aldering et al. 2006; Prieto et al. 2007) have been used to suggest a thermonuclear origin rather than a CC-SN (Silverman et al. 2013a). But this is not the unanimous view, with Benetti et al. (2006) and Trundle et al. (2008) arguing for a core-collapse origin for SNe 2002ic and 2005gj, respectively.

These ambiguous and interacting events are important for determining the possible progenitor channels for SNe Ia in particular, but are rare. During the first run of the Public ESO Spectroscopy Survey of Transient Objects (PESSTO)[1] in 2012 April, SN2012ca was classified as an unusual Type IIn, with an early spectral resemblance to SN 1997cy. Its distance and brightness have allowed an extensive follow-up until late epochs providing another object to better understand whether these events are all interacting SNe Ia or some are in fact CC-SNe. This Letter presents most of the first season of PESSTO optical and NIR data, which are publicly available in the ESO[2] and WISeREP[3] (Yaron & Gal-Yam 2012) archives.

2 OBSERVATIONS AND DATA ANALYSIS

SN2012ca was discovered in the late-type spiral galaxy ESO 336-G009 by Drescher, Parker & Brimacombe (2012), with a first detection on 2012 April 25.6 UT ($m_r \sim 14.8$ mag). A spectrum was obtained at the New Technology Telescope (NTT) + EFOSC2 (Inserra et al. 2012; Valenti et al. 2012) on April 29.4 as part of PESSTO. The initial spectrum of SN2012ca showed a resemblance to a few SNe 1997cy-like explosions at $\sim$60 d post-maximum. Because of the lack of early data, we cross-correlated the first spectrum with a library of SN 1997cy-like events at multiple epochs and found a best match adopting a peak light epoch at MJD 559 88.0 $\pm$ 9.0 (March 2). From the emission component of the Balmer lines, a redshift $z = 0.019$ was measured, consistent with that of the host galaxy. Adopting a standard cosmology with $H_0 = 72\,\mathrm{km\,s^{-1}}$, $\Omega_\mathrm{M} = 0.27$ and $\Omega_\lambda = 0.73$, NED[4] provides $\mu = 34.54 \pm 0.15$ mag from the heliocentric radial velocity of $v_\mathrm{host} = 5834 \pm 37\,\mathrm{km\,s^{-1}}$, which will be used throughout the Letter. There is no detection of Na I interstellar medium features from the host galaxy, nor do we have any evidence of significant extinction inside the host from the SN spectra itself. This suggests that the internal absorption is low, and we assume it to be negligible. Moreover, SN2012ca is 3.5 kpc far from the centre of the host galaxy; this is consistent with the absence of significant extinction. The Galactic reddening towards the SN line of sight is $E(B - V) = 0.06$ mag (Schlafly & Finkbeiner 2011), which we correct for in the following. Spectro-photometric follow-up was obtained by PESSTO with NTT+EFOSC2, Panchromatic Robotic Optical Monitoring and Polarimetry Telescope (Reichart et al. 2005), *Swift*+UVOT and ANU+WiFeS in optical, while in near-infrared (NIR) with NTT+SOFI. Images and spectra were reduced in the standard fashion, and the NTT data were processed within the PESSTO pipeline as in Valenti et al. (2013) and Fraser et al. (2013). The resolution of the optical spectra were checked and found to be $\sim$18 and $\sim$2 Å for the EFOSC2 and WiFeS data, respectively. The resolution in the NIR were $\sim$23 Å (blue grism) and $\sim$33 Å (red grism).

2.1 Bolometric luminosity

A pseudo-bolometric light curve (*Ugriz*) of SN2012ca (Fig. 1) was constructed using similar methods as in Inserra et al. (2013). There is certainly flux outside these bands; however, to first order we assume that these contributions are similar in each SN. This allows an approximate comparison of the pseudo-bolometric luminosities which is not as comprehensive as full bolometric measurements, but better than using single band comparisons. Although there are uncertainties in the explosion date, peak epoch and some caveats comparing pseudo-bolometric light curves determined using different optical filter systems, SN2012ca appears brighter and more slowly declining than SN2005gj. It is of comparable luminosity to SN1997cy between 60 and 250 d from peak, and also to the luminous Type IIn SN2010jl. However, it is significantly brighter and slower evolving than SNe 1991T (Ia) and 1998bw (Ic) or the interacting Ibn SN2006jc. Indeed, SN2012ca appears to be 10 times more luminous than the bright SN Ic reported in Fig. 1, and its overall evolution is much slower than that of normal Type Ic or Type Ia events. The post-peak decline rate is $\gamma = 0.5 \pm 0.1$ mag/100 d until the last epoch available, and is much slower than those of the interacting SNe Ia PTF11kx, SN2005gj and the Type Ibn 2006jc, with $\gamma \sim 3.1$, $\gamma \sim 1.1$ and $\gamma \sim 7.4$ mag/100d, respectively. The decrease is slower than the ^{56}Co decay even at 250 d, suggesting that the interaction is still the main energy source. One striking feature

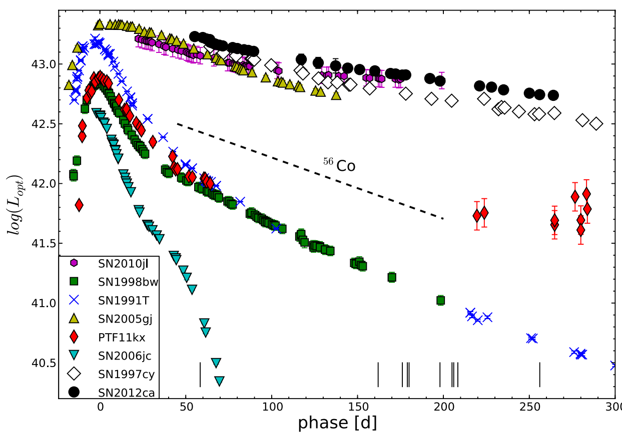

Figure 1. *Ugriz* (optical) bolometric light curves of SN2012ca, the Type Ic SN1998bw (*UBVRI*; Galama et al. 1998), the bright Type Ia 1991T (*UBVRI*; Lira et al. 1998), the Type Ia interacting PTF11kx (*gri*; Dilday et al. 2012; Silverman et al. 2013b) and SN2005gj (*ugriz*; Prieto et al. 2007), the Type IIn 2010jl (*UBVRI*; Zhang et al. 2012), the Type Ibn SN2006jc (*UBVRI*; Pastorello et al. 2007) and the peculiar Type IIn SN1997cy (*BVRI*; Germany et al. 2000; Turatto et al. 2000). Phase is with respect to maximum light at rest frame. The epochs of the SN2012ca spectra reported are marked with vertical lines.

[1] www.pessto.org
[2] as part of the Spectroscopic Survey Data Release 1 (SSDR1).
[3] http://www.weizmann.ac.il/astrophysics/wiserep/
[4] NASA/IPAC Extragalactic Database

in Fig. 1 is the self-similarity of SN2012ca, SN1997cy, SN2005gj and how different they appear compared to the initial decline of PTF11kx. While the PTF11kx decline $\gamma \sim 0.5$ after 200 d is similar to that of SN2012ca, the late-time values of the former are determined solely from *r*-band observations (assuming constant colours from neighbouring epochs) and show considerable scatter; thus, we suggest to treat this result with caution.

2.2 Spectroscopy

Optical spectra of SN2012ca are shown in Fig. 2 to illustrate the evolution during the first year. The somewhat blue continuum does not show significant evolution, suggesting an origin due to multiple, narrow lines of iron-group elements creating a pseudo-continuum (Smith et al. 2009; Silverman et al. 2013a). After about 180 d the pseudo-continuum seems visible only at wavelength shorter than 5500 Å, whereas the features redward look nebular. Most notable in SN2012ca is the presence of Balmer and He I emission lines through its entire evolution. The high resolution of WiFeS allows us to resolve narrow components in H lines. We see narrow P-Cygni absorption in Hα from a wind, as shown in Fig. 3 (right). The expansion velocity of the absorption minimum is $200 \pm 90\,\mathrm{km\,s^{-1}}$, a factor 3 greater than that measured for PTF11kx ($65\,\mathrm{km\,s^{-1}}$; Dilday et al. 2012). This is also a factor 2 or 3 greater than that observed in probable diffuse CSM from the companion of an exploding WD in some SNe Ia ($50\text{–}100\,\mathrm{km\,s^{-1}}$; Patat et al. 2011). However, Sternberg et al. (2011) noted that some higher velocities ($150\text{–}200\,\mathrm{km\,s^{-1}}$) can be reached in the CSM of a small fraction of SNe Ia. A broader emission component is also identified for H and He I. No P-Cygni profiles linked to this component are seen. The He I broader component shows a full width at half-maximum (FWHM) velocity $\sim 1800\,\mathrm{km\,s^{-1}}$, decreasing to $\sim 1500\,\mathrm{km\,s^{-1}}$ in the last spectrum, while Hα has $v_{\mathrm{FWHM}} \sim 3000\text{–}2200\,\mathrm{km\,s^{-1}}$ in the same period. This is also confirmed by the measurement of the unblended NIR features (see below). These broad lines can be associated with the fast-moving ejecta or, in case of interaction such as in SN2012ca, viable explanations are boxy emission from interaction (Chevalier & Fransson 1994) or Thomson scattering of photons by electron in a dense CSM (Chugai 2001; Dessart et al. 2009). From deblending the Ca II NIR components, we measure a velocity of $\sim 7000\,\mathrm{km\,s^{-1}}$ (at +198 d) related to the fast-moving ejecta, higher than those of H and He, suggesting a different origin for those emission components.

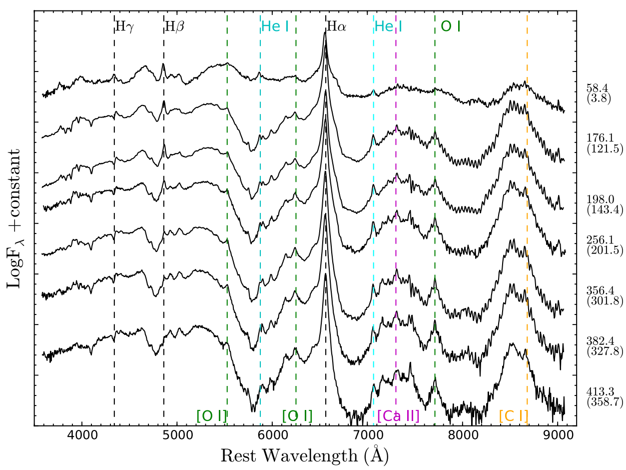

Figure 2. Rest-frame sequence of spectra of SN2012ca until one year since discovery. Phases are since the estimated maximum epoch (phases since discovery are reported in parentheses).

A combined spectrum comprised of an optical and a blue NIR grism taken on September 15, plus a red NIR grism taken on September 24 is shown in Fig. 3. As reported above, the optical region shows Balmer lines in emission, while the Paschen and Brackett series are visible at wavelengths >8500 Å with comparable velocities to the Balmer series at that phase ($v(\mathrm{Pa}\alpha)_{\mathrm{FWHM}} = v(\mathrm{H}\alpha)_{\mathrm{FWHM}} \sim 2400\,\mathrm{km\,s^{-1}}$). He I λ5876, λ7065, λ10 830 and λ20 589 emission lines are clearly detected, and also tentatively at ∼16 800 Å. Calcium has also been identified with a weak Ca II H&K line, the Ca NIR triplet and the [Ca II] $\lambda\lambda$7291, 7324 doublet, implying that at 198 d the SN is moving towards the nebular phase. Two puzzling lines at ∼6250 and ∼7710 Å are detected. They could be [O I] $\lambda\lambda$6300, 6364 and O I λ7774 ($v_{\mathrm{FWHM}} \sim 7000\,\mathrm{km\,s^{-1}}$), but blueshifted by $\sim 2500\,\mathrm{km\,s^{-1}}$. This hypothesis is strengthened by the presence of a line at ∼7170 Å identifiable as [O II] blueshifted at the same velocity. The shift could be attributed to asymmetries in the ejecta or a clump moving towards us. Moreover, [O I] λ5577 blueshifted by the same amount could be responsible for the red shoulder of the pseudo-continuum. Metal lines of various species are unambiguously detected both in the optical and the NIR. Fe II multiplet 42 is responsible for the features redder than Hβ. Mg I] λ4571 is already seen at this phase and gives plausibility to the detection of [O I] because of their mutual presence in SNe Ib/c (see Hunter et al. 2009). Other Mg lines could explain the feature at ∼4600 Å in the first spectrum and at 11 300 Å at ∼198d, whilst Mg I λ15 024, the strongest Mg line in the NIR, is detected and we measured an FWHM velocity of $\sim 7000\,\mathrm{km\,s^{-1}}$. After 256 d the Ca NIR triplet is weaker, and [C I] at ∼8700 Å is shown in emission. The [C I] profile resembles those of typical SNe Ic after five months from peak (Filippenko 1997).

Since SNe Ia and Ic have similar spectral evolution during the photospheric period and as a consequence it is not easy to detect features uniquely seen in a class before ∼60 d post-maximum (Taubenberger et al. 2006), especially if we take into account the interaction. In Fig. 4, we compare SN2012ca spectra with those of the bright SNe 1998bw (Ic) and 1991T (Ia) at similar epochs to investigate possible spectral similitudes. In the earliest spectrum of SN2012ca, the blue region ($\lesssim$5600 Å) appears more similar to SN1998bw than SN1991T both in continuum and line profiles. In the region around Hα, we cannot make a detailed comparison because of the presence of the emission lines; however, the Si II and [Fe II] lines typical of SNe Ia are not consistent with the line profiles seen in SN2012ca, even after accounting for dilution by a continuum. In the nebular phase comparison, an SN Ia spectrum at a similar phase to SN2012ca, makes it difficult to explain the region bluer than 6500 Å because of the presence of [Fe II], [Fe III] and [Co II] lines in the former. In contrast, SN2012ca bears more resemblance to SN1998bw. We suggest the emission features at 6250 and 7710 Å are indeed [O I] which would make an Ia origin unlikely. While the features are not as broad and prominent as in SN1998bw, we suggest that they are most likely to be [O I], and hence are important indications of a core-collapse origin.

In the bottom panel of Fig. 4, the difference between an interacting Type Ia and SN2012ca becomes clear, comparing the object to PTF11kx at similar epochs. They show some dissimilarities, mainly due to the presence of strong metal lines such as Fe II in PTF11kx. The 198 d spectrum is more similar to that of SN1997cy at ∼224 d (epoch defined in Turatto et al. 2000) and both show a spectral evolution in the [O I] lines regions different to that of PTF11kx. SN2012ca and SN1997cy have similar He I

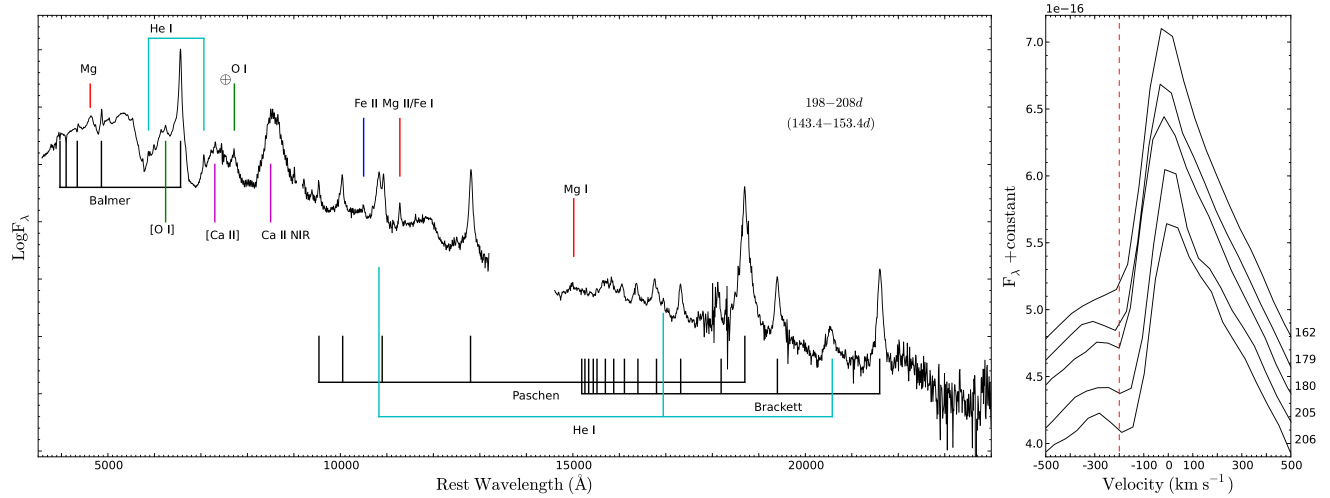

Figure 3. Right: composite spectrum of SN2012ca from optical to NIR wavelengths, at ∼198–208 d post maximum (∼143–153 d from discovery). The ⊕ symbol marks the position of the strongest telluric absorption. The most prominent features are labelled. Right: temporal evolution of Hα from 162 to 206 d post-maximum. The vertical red dashed line marks the velocity of the CSM.

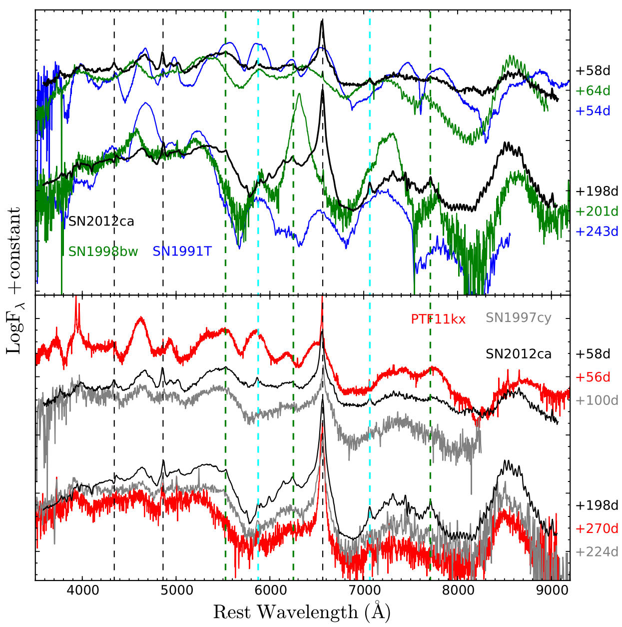

Figure 4. Top: comparison of two spectra of SN2012ca with those of SNe 1991T (Ia; Gómez & López 1998) and 1998bw (Ic; Patat et al. 2001). Bottom: comparison of the two spectra of SN2012ca with those of PTF11kx (Dilday et al. 2012) and SN1997cy (Turatto et al. 2000). Balmer, He I, O I and [O I] features are indicated by vertical black, cyan and green dashed lines, respectively. Phases with respect to maximum light.

emission lines ($EW^{\lambda 5876}_{12ca} = EW^{\lambda 5876}_{97cy} \sim 7$ Å, $EW^{\lambda 7065}_{12ca} \sim 16$ Å and $EW^{\lambda 7065}_{97cy} \sim 18$ Å), and Hα FWHM velocity ($v_{12ca} \sim 2900$ km s^{-1} and $v_{97cy} \sim 3200$ km s^{-1}).

3 IS SN2012CA AN INTERACTING CC-SNe?

The discovery of PTF11kx and its nature has changed the paradigm of these SN1997cy-like events, leading Silverman et al. (2013a) to suggest a thermonuclear origin for the majority, or even all, of these type of events. The data for SN2012ca indicate that it too is similar to SN1997cy, and we consider it more likely to have a core-collapse origin. The evidence for a core-collapse interpretation are summarized as follows.

(i) The overall spectral evolution of SN2012ca is hard to explain using diluted Type Ia spectra with superimposed emission. SNe Ia over one year are dominated by forbidden iron lines, as also shown by Filippenko et al. (1992b) for the luminous SN1991T. On the contrary, a broad-line Type Ic such as SN1998bw shows more spectral similarities.

(ii) O I, [O I] and [O II] lines were likely identified, blueshifted by ∼2500 km s^{-1}. A number of magnesium lines were identified, including Mg I λ15024 which is usually seen in spectra of SNe Ic (e.g. SNe 1998bw, 2004aw; Patat et al. 2001; Taubenberger et al. 2006). Both elements and their observed line strengths are more indicative of a massive progenitor and CC-SN origin.

(iii) We detect [C I] at 8700 Å at 413 d with $v_{\rm FWHM} \gtrsim$ 1500 km s^{-1}. This is again similar to what is typically seen in the ejecta of SNe Ic (e.g. Filippenko 1997).

(iv) The Ca II NIR triplet is usually seen during the photospheric phase of SNe Ia (Filippenko 1997). Forbidden [Ca II] has been seen only in subluminous SNe Ia (Filippenko et al. 1992a), but not in normal or bright (e.g. SN1991T) SNe Ia. The SNe Ia ejecta environment is typically more strongly ionized than in SNe Ic; thus, the absence of [Ca II] in SNe Ia is probably linked to the fact that it is at a higher ionization state (Liu, Jeffery & Schultz 1997; Mazzali et al. 2010). Any possible interaction should enhance this effect, and so the presence of [Ca II] in SN2012ca again points towards core collapse.

(v) Hα narrow P-Cygni absorption from a wind has been detected with an expansion velocity of ∼200 km s^{-1}, a factor ∼3 greater than what was seen in PTF11kx.

(vi) Broader and persistent He I emission lines have been detected in SN2012ca, in contrast to what seen in PTF11kx. Furthermore, it appears that little to no He I emission is a key attribute of members of the SN Ia-CSM class (Silverman et al. 2013a).

The data favour the interpretation of SN2012ca as a CC-SN, with a certain degree of asymmetry in the ejecta and surrounded by an H- and He-rich CSM. The interacting SN Ia scenario appears to work well for PTF11kx but the link has been extended broadly to many SNe showing interactions which are SN1997cy-like. We argue that this is almost certainly premature, and that the extensive data set for SN2012ca, including the bolometric light curve and optical to NIR spectral sequence is strongly suggestive of a core-collapse origin. The similarity to bright SNe Ic nebular spectra at phases of >150 d suggests that it could well have been a stripped envelope progenitor which impacts and interacts with an H-rich CSM. Although the presence of H in the spectra and narrow emission lines suggest a classification as an SN IIn by definition, we do not find clear evidence that the SN ejecta was H-rich. This illustrates the limitations of our currently employed SN classification nomenclature. Indeed, SN2012ca and probably SN1997cy are better referred to as interacting stripped envelope SNe. SN2012ca provides evidence of a viable alternative scenario to the thermonuclear interpretation (Ia-CSM; Silverman et al. 2013a) about interacting SNe with H- and He-rich CSM, suggesting that two different channels may be responsible for SN1997cy-like events.

ACKNOWLEDGEMENTS

Based on observations collected by PESSTO, and the Panchromatic Robotic Optical Monitoring and Polarimetry Telescope (PROMPT), Chile; the Australian National University 2.3 m Telescope and the *Swift* satellite. Funded by the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC Grant agreement no. [291222] (SJS). SB and AP acknowledge the PRIN-INAF 2011 project 'Transient Universe: from ESO Large to PESSTO'. GP acknowledges Millennium Center for Supernova Science (P10-064-F).

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