Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **434,** 527–541 (2013) doi:10.1093/mnras/stt1038
Advance Access publication 2013 July 5

Environment-derived constraints on the progenitors of low-luminosity Type I supernovae*

J. D. Lyman,[1]† P. A. James,[1] H. B. Perets,[2] J. P. Anderson,[3] A. Gal-Yam,[4] P. Mazzali[1] and S. M. Percival[1]

[1] *Astrophysics Research Institute, Liverpool John Moores University, Liverpool L3 5RF, UK*
[2] *Technion – Israel Institute of Technology, Haifa 32000, Israel*
[3] *Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile*
[4] *Benoziyo Center for Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel*

Accepted 2013 June 7. Received 2013 June 7; in original form 2013 April 30

ABSTRACT

We present a study of the properties of the host galaxies of unusual transient objects of two types, both being subluminous compared with the major classes of supernovae. Those of one type exhibit unusually strong calcium features, and have been termed 'Ca-rich'. Those of the second type, with SN2002cx as the prototype and SN2008ha as the most extreme example to date, have some properties in common with the first, but show typically lower ejecta velocities and different early spectra. We confirm important differences in the environments of the two types, with the Ca-rich transients preferentially occurring in galaxies dominated by old stellar populations. Quantitatively, the association of the Ca-rich transients with regions of ongoing star formation is well matched to that of Type Ia supernovae. The SN2002cx-like transients are very different, with none of the present sample occurring in an early-type host, and a statistical association with star-formation regions similar to that of Type II-P supernovae, and therefore a delay time of 30–50 Myr.

Key words: supernovae: general.

1 INTRODUCTION

Recent years have seen radical developments in the understanding of supernovae (SNe), driven by larger samples, higher quality and better sampled spectroscopy and light curves, and better control of selection systematics through dedicated SN searches. One result of this has been that the traditional empirically motivated classification system of SNe has faced a series of challenges, with the finding of many transients that do not fit into any of the existing classifications. Indeed, in the case of the transients that are discussed in this paper, it is not yet clear whether they lie within the broad class of core-collapse supernovae (CCSNe) or should be considered as a subset of the Type Ia SNe (SNeIa) class, with long-lived progenitors and a final explosion mechanism involving a white dwarf (WD) primary.

The aims of this paper are to constrain the progenitor systems of two of these putative new classes of SN: one termed 'Ca-rich' on the basis of the relative strength of calcium lines in spectra observed during the nebular phase (also called 'SN2005E-like' after the prototypical event; Perets et al. 2010) and another possibly related class that includes SNe 2002cx (Li et al. 2003) and 2008ha, termed 'SN2002cx-like'. In their overall spectral properties, the Ca-rich transients quite closely resemble CCSNe of Type Ib (i.e. lacking hydrogen, but showing strong helium features) which led to the claim by Kawabata et al. (2010) that one of the members of the class, SN2005cz, could indeed be a core-collapse object with a 10 $M_{\odot}$ zero-age progenitor. This would be a surprising discovery, given that the host galaxy of SN2005cz, NGC 4589, is an elliptical galaxy with a 'classical E2 morphology' (Sandage & Bedke 1994), and a corresponding expectation of a predominantly old stellar population. Simultaneously, the even more extreme environment of SN2005E, the prototypical member of the Ca-rich class that occurred far from the disc plane of an early-type S0/a galaxy, NGC 1032, led Perets et al. (2010) to conclude that these explosions are likely to arise from the accretion of helium on to an old, low-mass progenitor, probably a WD. Modelling was used to show that

---

* Based on observations made with the Isaac Newton Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias, observations made with the Liverpool Telescope operated on the island of La Palma by Liverpool John Moores University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias with financial support from the UK Science and Technology Facilities Council and observations made with the 2.2 m MPG/ESO telescope at La Silla, proposal ID: 084.D-0195.
† E-mail: jdl@astro.livjm.ac.uk

Published by Oxford University Press on behalf of the Royal Astronomical Society

such a progenitor can reproduce the observed properties, with ejecta that has high velocities but low masses, and a composition that is dominated by the products of helium burning. Perets et al. (2011) extended this analysis to SN2005cz in NGC 4589, again preferring a low-mass, long-lived progenitor, in contradiction to Kawabata et al. (2010).

The spectroscopic and environmental properties of the general class of these Ca-rich transients have been investigated by Perets et al. (2010) and Kasliwal et al. (2012). The former identified eight SNe in this group (SN2000ds, SN2001co, SN2003H, SN2003dg, SN2003dr, SN2005cz, SN2005E and SN2007ke) and the latter identified three additional objects in this class from the Palomar Transient Factory (PTF) survey (henceforth PTF; Law et al. 2009; Rau et al. 2009). Kasliwal et al. (2012) combined these three new objects [PTF09dav, PTF10iuv (SN2010et) and PTF11bij] with two of the better observed earlier events (SN2005E and SN2007ke) which share common properties of low peak luminosities, fast photometric evolution, high ejecta velocities, strong Ca emission lines and locations in the extreme outskirts of their host galaxies. They follow Perets et al. (2010, 2011) in preferring long-lived, low-mass progenitors, pointing out that the core-collapse objects with the lowest generally accepted progenitor masses, those of Type II-P, are almost never found at the extreme outlying locations that characterize these five Ca-rich events.

Valenti et al. (2013) have reported on another possible member of the Ca-rich class, SN2012hn, that was discovered by the Catalina Real-Time Transient Survey. This was initially classified as a peculiar SNIc (Benitez-Herrera et al. 2012), but Valenti et al. (2013) conclude from the analysis of later spectroscopic and light-curve data that SN2012hn much more closely resembles members of the Ca-rich class, with a low peak luminosity and rapid evolution. This is supported by its location in the outskirts of an early-type (E/S0) galaxy (discussed further in this paper). However, it should be noted that Valenti et al. (2013) find some detailed spectral differences between SN2012hn and other members of the Ca-rich class.

A very recent study by Yuan et al. (2013) has investigated the progenitors of the Ca-rich class by comparing their host galaxy locations to results from cosmological simulations. By comparison to the simulated metallicity distribution in hosts, they find that the progenitors are likely to be of low metallicity and, tied with their remote locations compared to the bulk of the host stellar mass, consequently of old age (∼10 Gyr). They conclude that a massive star origin for such events is disfavoured.

Some similarities exist between the Ca-rich events and the unusual transient SN2008ha (Foley et al. 2009, 2010b; Valenti et al. 2009), in particular the extremely low luminosity and the inferred low ejecta mass, and some similarities in the late spectra. SN2008ha, however, does not show evidence for helium (it is classified as an SNIa event) and has extremely low photospheric velocity (∼2000 km s^{-1}; cf. 6000–11 000 km s^{-1} for the Ca-rich transients). Foley et al. (2013) have recently linked SN2008ha and similar objects, including the prototypical example SN2002cx (Li et al. 2003), to a proposed new class of stellar explosion, which they term 'Iax'. These differ from normal SNeIa in having lower maximum-light ejecta velocities (2000–8000 km s^{-1}) and lower peak luminosities for a given light-curve shape. SN2008ha then appears as probably the most extreme object in this class identified to date, with the lowest peak luminosity and ejecta velocities at the bottom end of the range for this class. Foley et al. (2013) infer high rates, with ∼30 for every 100 SNeIa in the local Universe. Given the still debated/unknown origin of these events, we will generally use the term 'transients' rather than 'supernovae' throughout this paper.

Various models were suggested for the origin of these transients including complete thermonuclear deflagration of a WD (Li et al. 2003; Branch et al. 2004), failed detonation of a C/O WD (Jordan et al. 2012) or possibly a peculiar type of CCSN event (Valenti et al. 2009). Foley et al. (2013) suggested the progenitors to be C/O WDs that accrete material from an He-star, and therefore consider some possible connections between SN2002cx-like and Ca-rich transients, where both types of events arise from an He-shell detonation scenario. However, one of the major differences between the two types is their environment, as first noted by Perets et al. (2010). The Ca-rich events occur in all galaxy types (with a large fraction in early-type galaxies), and/or far from the centres of host galaxies (Kasliwal et al. 2012), whereas SN2002cx-like transients preferentially occur in late-type, star-forming galaxies, indicating a possibility of having younger progenitor systems. Foley et al. (2013) suggest that the difference might originate from a different origin of the accreted He in the two cases, i.e. SN2002cx-like events arise from accretion from an He-rich non-degenerate donor star, whereas the Ca-rich events originate from accretion from a degenerate He WD.

Valenti et al. (2009) discuss the class of SN2002cx-like events in general, and SN2008ha specifically, and conclude that these may be low-luminosity CCSNe, with progenitors that are either high-mass (25–30 $M_{\odot}$) Wolf–Rayet stars or stars from the low-mass limit of CCSNe (7–9 $M_{\odot}$). However, Eldridge et al. (2013) have recently discussed SN2008ha in the context of a study of the rates of CCSNe, and on the balance of evidence decide in favour of a thermonuclear interpretation. They thus exclude it from their study, although they warn that the evidence is far from conclusive, and that further study of SN2008ha and other SN2002cx-like transients is clearly required.

It is clear from the above discussion that the association with different types of stellar environment is of key importance in distinguishing between these different types of luminous transients and in constraining the possible progenitor objects. However, much of the environmental information, e.g. the association of the Ca-rich transients with old populations and SN2002cx-like transients with young, lacks quantification and in many cases is little more than anecdotal. Host galaxy classifications give some useful information, but they are notoriously subjective and, even if free from actual errors, they do not give precise information on the stellar population at the location of the transient event. For example, even a late-type spiral may have a bulge, or extreme outer disc, that is entirely composed of old stars. In this paper, we will make use of both host galaxy types and quantified measures of star-formation (SF) activity, local to the sites of events within their host galaxies, applied specifically to the known samples of Ca-rich and SN2002cx-like transients, to determine whether they appear to rise from the same progenitor populations and to compare these populations with the same measures for other types of SN (including 'normal' SNeIa, and core-collapse-type SNe Ib, Ic and II-P).

2 METHODS

The methods we employ are explained in detail in James & Anderson (2006); these have been previously applied to large samples of SNe in two subsequent papers (Anderson & James 2008; Anderson et al. 2012). The last of these three papers provides the main comparison sample for the current work.

Following previous work, each transient is assigned a normalized cumulative rank (NCR), based on pixel statistics of a continuum-subtracted Hα image of the host (taken either prior to or long after the transient), as a measure of the degree of association of the transient with recent SF within its host.

The continuum-subtracted Hα images are trimmed to contain the host and transient location and then binned 3×3 such that the pixel location of the transient given by the world coordinate system forms the centre of a 3×3 'superpixel'. A pixel in our binned images represents ~0.9 arcsec across the various instruments used, or ~260 pc at the mean galaxy distance. Star residuals and artefacts arising from saturation in the subtracted images are masked using a local median. Pixel values in this binned image are sorted, cumulatively summed and then normalized by the total sum of pixel values. In this way each pixel now has an associated NCR value between 0 and 1 (any negative values are set to 0). Any pixel with NCR = 0 is considered a background pixel, i.e. there is no Hα flux at that position. Positively valued pixels are then ranked within the NCR method such that low values have an association with weak emission and high values are coincident with the brightest Hα emitting regions of the host. Specifically, the NCR value is the fraction of host galaxy flux that is below the level of flux at the location of the transient, i.e. NCR = 1 means the transient location is at the site of the most intense SF activity within its host galaxy.

Using these methods, Anderson et al. (2012) find a clear separation of the CCSN subtypes, with Types II-P, Ib and Ic forming a clear sequence of increasing strength of association with current sites of SF, and high mean NCR values. This is most simply interpreted in terms of a sequence of increasing mean progenitor mass, and hence decreasing progenitor lifetime.

Crowther (2013) has looked at the progenitor constraints that can be drawn from the association of SNe with ongoing SF, using a smaller sample than Anderson et al. (2012) with higher spatial resolution and employing rather different statistical methods based on distance to the nearest region of Hα emission. Crowther (2013) finds very similar results to Anderson & James (2008) and Anderson et al. (2012) in terms of the difference of strength association between SNeII and SNeIbc, which he interprets in terms of a large fraction of SNeII outliving their natal star-formation regions. Crowther (2013) argues that the complications involving lack of resolution of individual SF regions should obscure any differences between the correlation strengths for shorter lived, higher mass progenitors than those of the SNeII, but this argument seems difficult to reconcile with the clear statistical differences found for the populations of SNe Ib and Ic investigated by Anderson et al. (2012).

Hα was chosen as an SF tracer since there already exist large samples of NCR values for the more common SN types which can be compared. The typical duration of Hα emission from H II regions is comparable to that of the ages of the middle-to-lower mass end of CCSNe. Kuncarayakti et al. (2013) show the evolution of the Hα equivalent width for a single burst in STARBURST99, which weakens strongly after 5 Myr, falling to very low values after ~15 Myr (roughly the lifetime of a 14 $M_{\odot}$ star). This, however, is a lower limit since a typical SF region will not form stars in a delta-function manner. Hα imaging thus allows us, through the NCR method, to distinguish between transients whose progenitor ages fall entirely within, or overlap with, this limit. Since each transient's NCR value is normalized to its own host, we are not sensitive to absolute calibration issues of Hα as an SF rate tracer (Lee et al. 2009; Botticella et al. 2012)

The NCR method is particularly reliant on the Hα filter used for observations. Its transmission profile must allow for detection of Hα over a reasonable velocity range so as to detect all host galaxy emission, whilst being narrow enough to allow for accurate subtraction of the underlying continuum light. Clearly, if a filter fails to transmit Hα emission from some regions of the host, this will affect the NCR value of the transient. As such, transients that are potentially well separated from their hosts in recession velocity ($V_{\rm rec}$) provide a problem of filter choice, especially when $V_{\rm rec}$ cannot be determined for the transient itself. In this study, for all cases except PTF09dav, the filter with a central wavelength best matching the host-Hα wavelength was chosen; for PTF09dav, the redshift of the transient was used to find the best matched filter as its host is anonymous. Given the widths of the filters (typically ~2000–3000 km s^{-1}), this meant Hα over a broad range of host velocities would be detected, giving confidence that we are not missing some regions of Hα emission in the host or, importantly, at the location of the transient.

3 TRANSIENT SAMPLES AND OBSERVATIONS

The samples of transients analysed here are inevitably somewhat eclectic and subject to selection biases, and thus cannot be considered in any sense to represent a statistically complete sample of objects of either type. This is unavoidable for classes of transient objects that are both relatively rare (although the global rates are highly uncertain) and substantially fainter than the main SN types. Thus, in order to compile the samples of Ca-rich and SN2002cx-like transients presented here, we have used a variety of sources. Most of the Ca-rich transients are listed in Perets et al. (2010) and Kasliwal et al. (2012), alongside SN2012hn (Valenti et al. 2013). For a complete recent compilation of the SN2002cx-like transients, see Foley et al. (2013).

We stress here that although we are investigating two classes of transients, their unknown nature, and the lack of detailed observations for some, means that there is potential contamination in each sample by transients of different origins or potential for diversity within each sample. We will discuss progenitor constraints for each sample as a whole since we are already limited by small numbers; however, it may be true that some specific events differ from these conclusions due to their erroneous classification.

New imaging observations presented here were made using the Isaac Newton Telescope (INT) and Liverpool Telescope (LT) at La Palma and the MPI2.2 at European Southern Observatory (ESO). For each transient, exposures were taken in the *R* band, to characterize the continuum light, and a narrow-band Hα filter. Details of the Hα filters used are given in Table 1, where wavelength and corresponding $V_{\rm rec}$ limits are defined as the 50 per cent transmission limits of the filter. Exposure times were 300 s for the *R* band and

Table 1. Hα narrow-band filter properties.

Filter name	Telescope	Wavelength limits (Å)	$V_{\rm rec}$ limits (km s^{-1})
'Halpha'	INT	6522–6614	0–2357
'Ha 6657'[a]	INT	6618–6697	2400–6100
'H-alpha-100'	LT:RATCam	6517–6617	0–2478
'Ha_6566'	LT:IO	6522–6610	0–2164
'Ha_6634'	LT:IO	6608–6662	2080–4520
'Ha_6705'	LT:IO	6680–6733	5349–7764
'Ha_6755'	LT:IO	6729–6783	7595–10 047
'Ha_6822'	LT:IO	6798–6849	10 747–13 097
'665/12'	MPI-2.2	6598–6713	1616–6857

[a] No scanned transmission profile is available for this filter so the limits are based on manufactured specification.

Table 2. Properties of the Ca-rich transients and their host galaxies.

SN name	Host galaxy	Host type	V_{rec} (km s^{-1})	Discovery abs. mag (unfiltered mag)	IAU classn.
2000ds	NGC 2768	E6	1373	−13.59	Ib/c
2001co	NGC 5559	SBb	5166	−15.69	Ib/c
2003H	NGC 2207	SABbc	2741	−14.16	Ib/c
2003dg	UGC 6934	Scd (edge-on)	5501	−15.31	Ib/c
2003dr	NGC 5714	Scd (edge-on)	2237	−15.06	Ib/c
2005E	NGC 1032	S0/a (edge-on)	2694	−15.86	Ib/c
2005cz	NGC 4589	E2	1980	−16.36	Ib
2007ke	NGC 1129	E	5194	−15.71	Ib
PTF09dav	Anon	Sb[a]	11 123	−14.7	–
2010et	Uncertain	–		−13.8	–
PTF11bij	IC 3956	E	10 406	−15.9[b]	–
2012hn	NGC 2272	SAB0	2130	−16.0[c]	I-p

[a] Classified by P. A. James based on our imaging.
[b] M_R at discovery taken from Kasliwal et al. (2012).
[c] M_R at peak taken from Valenti et al. (2013).

Table 3. Properties of the SN2002cx-like transients and their host galaxies.

SN name	Host galaxy	Host type	V_{rec} (km s^{-1})	Discovery abs. mag (unfiltered mag)	IAU classn.
1991bj	IC 344	SBcd[a]	5440	−15.46	Ia
2004gw	CGCG 283-003	Sab[a]	5102	−16.33	Ia
2005P	NGC 5468	SABcd	2842	−15.14	?
2005cc	NGC 5383	SBb pec	2270	−15.18	?
2005hk	UGC 272	SABd	3895	−17.05[b]	Ia-p
2006hn	UGC 6154	SBa	5156	−18.69	Ia
2007J	UGC 1778	Sdm	5034	−15.92	Ia
2008A	NGC 634	Sa (edge-on)	4925	−16.57	Iap
2008ha	UGC 12682	Im	1393	−12.7[c]	Ia?
2009J	IC 2160	SBc pec	4739	−16.17	Ia-p
2012Z	NGC 1309	SAbc	2136	−14.62	Ia-p

[a] Classified by PAJ based on our imaging.
[b] M_R at discovery taken from Phillips et al. (2007).
[c] Taken from Pucket et al. (2008).

900 s for Hα, which corresponds to a limiting Hα flux of $\sim 3.8 \times 10^{-16}$ erg s^{-1} cm^{-2} (see Anderson et al. 2012 for a discussion of SF limits using this method). Images taken with the LT were reduced using the automated pipeline; standard bias and overscan subtraction and flat-fielding were performed for other data. Typical seeing was 1–2 arcsec. Subtraction of the *R*-band images from the Hα images was performed using a version of the ISIS code (Alard 2000).

Data for the Ca-rich and SN2002cx-like transients in this study are given in Tables 2 and 3, respectively. These list the International Astronomical Union (IAU) SN name for all transients except PTF09dav and PTF11bij, which are not in the IAU list: the host galaxy name, classification and recession velocity from the NASA Extragalactic Database (NED),[1] the absolute discovery magnitude (taken from the Asiago Supernova Catalog,[2] using distance modulus values for the host taken from NED) and the classification of the SNe from the IAU data base.

Details of the observations and NCR values are given in Table 4 for the Ca-rich transients and in Table 5 for SN2002cx-like transients. Velocity limits from Table 1 are shown for the Hα filter used – the bulk of the detected light in our continuum-subtracted images will come from emission within these velocity limits (although the filters also have non-negligible transmission for a few hundred km s^{-1} outside these limits). Whether we detect any recent SF (i.e. Hα emission) in our observations is also noted.

Images of the 12 Ca-rich hosts are shown in Fig. 1, showing the *R*-band and continuum-subtracted Hα exposures with the location of the transient marked. Of these, six (NGC 2768, NGC 1032, NGC 4589, NGC 1129, IC 3956 and NGC 2272) are early-type galaxies, and hence should have no recent SF. Indeed, we find no SF as traced by Hα at the location of the transients in these early hosts or anywhere else in the hosts. The only apparent emission in the subtracted images arises from the very centre of these galaxies; due to the difficulties in obtaining a clean subtraction on such extremely bright regions, this is most likely to be an artefact arising from the image subtraction process and saturation effects rather than real Hα flux, although we cannot rule out either conclusively. It is not clear which galaxy hosted the very isolated transient SN2010et, as we discuss below. The remaining five hosts all display varying levels of SF.

Fig. 2 shows the corresponding images for the SN2002cx-like sample. All these hosts are late type, and all display strong ongoing SF with prominent H II regions.

---

[1] http://ned.ipac.caltech.edu/
[2] http://heasarc.gsfc.nasa.gov/W3Browse/all/asiagosn.html

Table 4. Observations of the host galaxies of Ca-rich transients.

SN name	Host galaxy	V_{rec} (km s^{-1})	Telescope	Obs. date	Seeing (arcsec)	Filter name	Hα range (km s^{-1})	NCR index	SF detected in host?
2000ds	NGC 2768	1373	INT	Jan. 2012	1.6	'Halpha'	0–2357	0.000	No
2001co	NGC 5559	5166	INT	Mar. 2007	1.6	'Ha 6657'	2400–6100	0.357	Yes
2003H	NGC 2207	2741	LT:IO	Sept. 2012	1.8	'Ha_6634'	2080–4520	0.312	Yes
2003dg	UGC 6934	5501	INT	Jan. 2012	1.3	'Ha 6657'	2400–6100	0.626	Yes
2003dr	NGC 5714	2237	INT	Jan. 2012	1.6	'Halpha'	0–2357	0.000	Yes
2005E	NGC 1032	2694	LT:IO	Jan. 2013	1.3	'Ha_6634'	2080–4520	0.000	No
2005cz	NGC 4589	1980	INT	Jan. 2012	1.2	'Halpha'	0–2357	0.000	No
2007ke	NGC 1129	5194	INT	Jan. 2012	1.7	'Ha 6657'	2400–6100	0.000	No
PTF09dav	Anon	11 123	LT:IO	Dec. 2012	1.6	'Ha_6822'	10 747–13 097	0.000	Yes
2010et	Uncertain	–	LT:IO	Mar. 2013	2.9	'Ha_6705'	4900–7640	0.000	–
PTF11bij	IC 3956	10 406	LT:IO	Jan. 2013	3.0	'Ha_6822	10 747–13 097	0.000	No
2012hn	NGC 2272	2130	LT:IO	Feb. 2013	2.4	'Ha_6566'	0–2164	0.000	No

Table 5. Observations of the host galaxies of SN2002cx-like transients.

SN name	Host galaxy	V_{rec} (km s^{-1})	Telescope	Obs. date	Seeing (arcsec)	Filter name	Hα range (km s^{-1})	NCR index	SF detected in host?
1991bj	IC 344	5440	INT	Jan. 2012	1.9	'Ha 6657'	2400–6100	0.163	Yes
2004gw	CGCG 283-003	5102	INT	Jan. 2012	1.7	'Ha 6657'	2400–6100	0.000	Yes
2005P	NGC 5468	2842	INT	Feb. 2008	1.4	'Ha 6657'	2400–6100	0.055	Yes
2005cc	NGC 5383	2270	LT:RATCam	Dec. 2005	1.8	'H-alpha-100'	0–2478	0.621	Yes
2005hk	UGC 272	3895	LT:IO	Oct. 2012	1.1	'Ha 6634'	2080–4520	0.000	Yes
2006hn	UGC 6154	5156	INT	Jan. 2012	1.3	'Ha 6657'	2400–6100	0.289	Yes
2007J	UGC 1778	5034	INT	Jan. 2012	1.1	'Ha 6657'	2400–6100	0.904	Yes
2008A	NGC 634	4925	INT	Jan. 2012	0.9	'Ha 6657'	2400–6100	0.000	Yes
2008ha	UGC 12682	1393	LT:IO	Oct. 2012	1.9	'Ha_6566'	0–2164	0.407	Yes
2009J	IC 2160	4739	MPI2.2	Feb. 2010	1.9	'665/12'	1616–6857	0.000	Yes
2012Z	NGC 1309	2136	LT:RATCam	Aug. 2009	1.5	'H-alpha-100'	0–2478	0.000	Yes

Further discussion of the hosts of the two samples is given in Section 5.1.

As a check on the presence and nature of emission lines at the locations of these events, we also obtained long-slit optical spectroscopy (with a slit width of 1.5 arcsec) of two of the host galaxies in our samples (Fig. 3). The observations were taken on the INT in 2013 January using the Intermediate Dispersion Spectrograph (IDS) with the R632V grating. The slit was positioned to include both the galaxy nucleus, as a positional reference, and the location of the transient. The spectral range covered included the location of any potential Hα emission. NGC 2768 (SN2000ds) was observed at an airmass of 1.3 in seeing of 1.8 arcsec; the corresponding values for NGC 2207 (SN2003H) were 1.57 and 0.8 arcsec.

4 INDIVIDUAL PROPERTIES OF THE TRANSIENTS AND THEIR ENVIRONMENTS

4.1 Ca-rich transients

SN2000ds in NGC 2768. NGC 2768 is classified as an E6 galaxy in NED and in the Third Reference Catalog (de Vaucouleurs et al. 1991). This classification is discussed by Hakobyan et al. (2008), who ultimately prefer a classification of S0. As expected, we find no Hα in our observations (apart from the region affected by subtraction artefacts at the very centre) indicating a lack of recent SF at the transient location, or indeed anywhere within this host galaxy. Our INT+IDS long-slit spectrum crossing the nucleus of NGC 2768 and the location of SN2000ds is shown in Fig. 3, confirming the lack of any line emission close to the location of the SN. There is weak, diffuse line emission in Hα and [N II] in the central regions of the galaxy, far from the SN location, that is probably related to the known low-ionization nuclear emission-line region nucleus of this galaxy.

SN2001co in NGC 5559. An inclined spiral galaxy, NGC 5559 displays prominent SF throughout the disc. SN2001co is located near the edge of the disc and is coincident with some diffuse SF.

SN2003H in NGC 2207. NGC 2207 has a close interaction with Sc galaxy IC 2163 at 2765 km s^{-1}; SN2003H lies immediately between the bulges of the two galaxies on an area of intermediate-level Hα. For the purposes of the NCR analysis, the pixels used included those from both galaxies since we cannot cleanly distinguish them as separate systems. As such, SN2003H's NCR value is relative to the interacting system as a whole. A long-slit spectrum crossing the nucleus of NGC 2207 and the location of SN2003H is shown in Fig. 3, showing that there is clearly detectable SF at the location of SN2003H, although it appears to lie in the outer regions of an SF complex. The interacting system of NGC 2207 and IC 2163 has also hosted SNe 1975A (Ia), 1999ec (Ib) and 2010jp (IIn).

SN2003dg in UGC 6934. The host displays strong H II regions along its highly inclined disc. SN2003dg appears to be somewhere in the plane of the disc, but due to line-of-sight effects it cannot

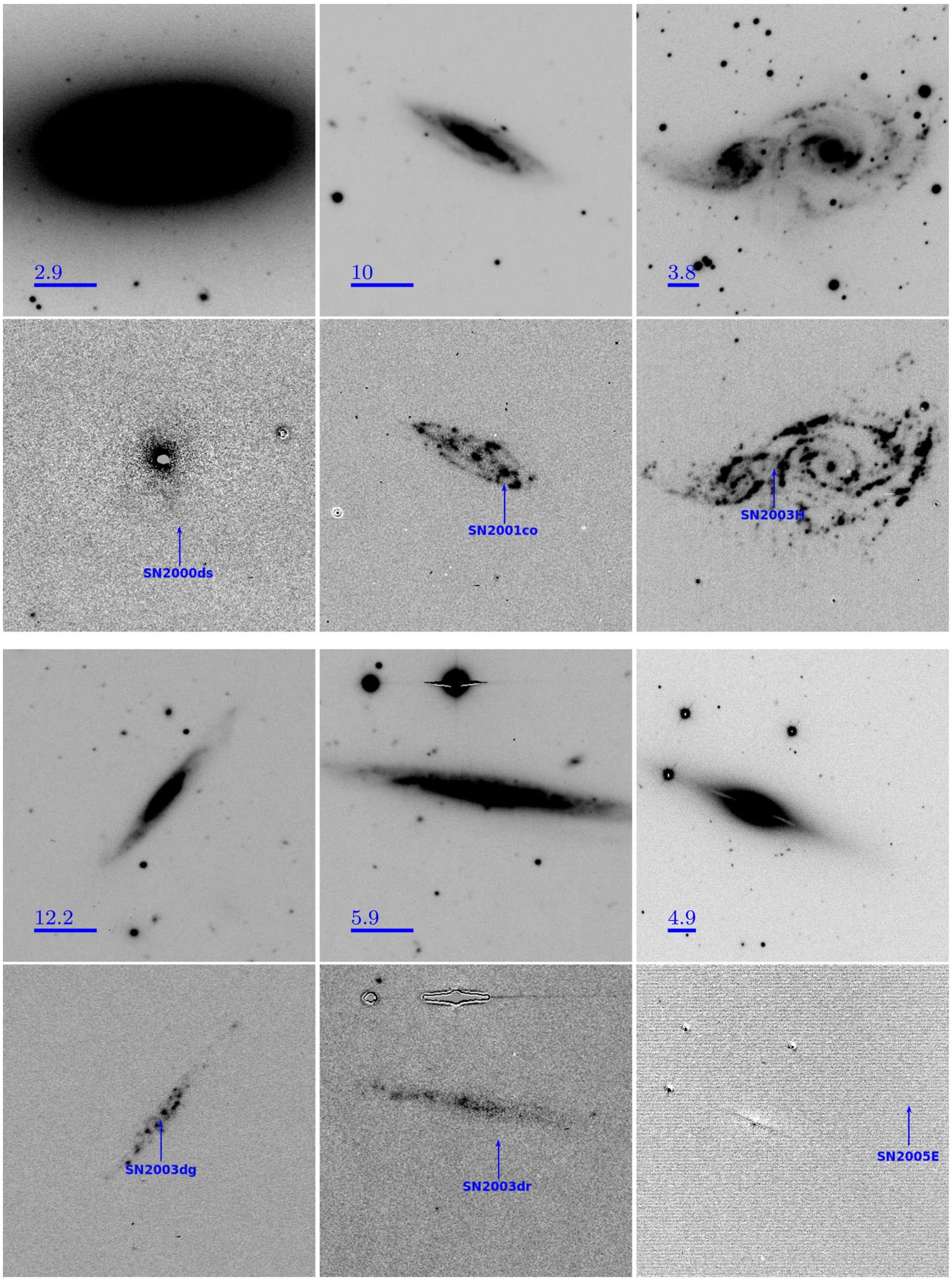

Figure 1. *R*-band (top) and continuum-subtracted Hα (bottom) images of Ca-rich transients. The location of the transient is marked in each case on the continuum-subtracted Hα image. The bars in each *R*-band image indicate 30 arcsec and are labelled with the linear size at the distance of the host in kpc. For all images, north is up and east is left.

be determined where in the disc it lies. This means the NCR value may not be accurate (see Section 5.2). From the projected view, SN2003dg is coincident with some fairly bright Hα emission.

SN2003dr in NGC 5714. SN2003dr occurred in another galaxy that is viewed almost exactly edge-on, but in this case the transient location lies well outside the plane of the disc. Thus, we can be more confident to say that it is in a region of no recent SF. The only apparent SF in NGC 5714 is diffuse and concentrated along the plane.

SN2005E in NGC 1032. NGC 1032 is an S0/a galaxy, and we find no Hα along the plane of the disc, lending weight to the argument that this is a lenticular galaxy. The host is edge-on and the transient well separated from the disc plane with no Hα evident at its location.

SN2005cz in NGC 4589. NGC 4589 is classified as an E2 elliptical galaxy in NED and in the Third Reference Catalog (de Vaucouleurs et al. 1991). Moellenhoff & Bender (1989) find unusual central kinematics, and a minor axis dust lane, which they interpret as the result of merging activity. However, they conclude from the regular shape, and a smooth light profile that follows the classic $R^{\frac{1}{4}}$ profile characteristic of elliptical galaxies (de Vaucouleurs 1948), that ‘the merging already is in an advanced state’. As with NGC 2768, in the very bright central region we observe a saturated core with subtraction residuals that accounts for the apparent Hα emission

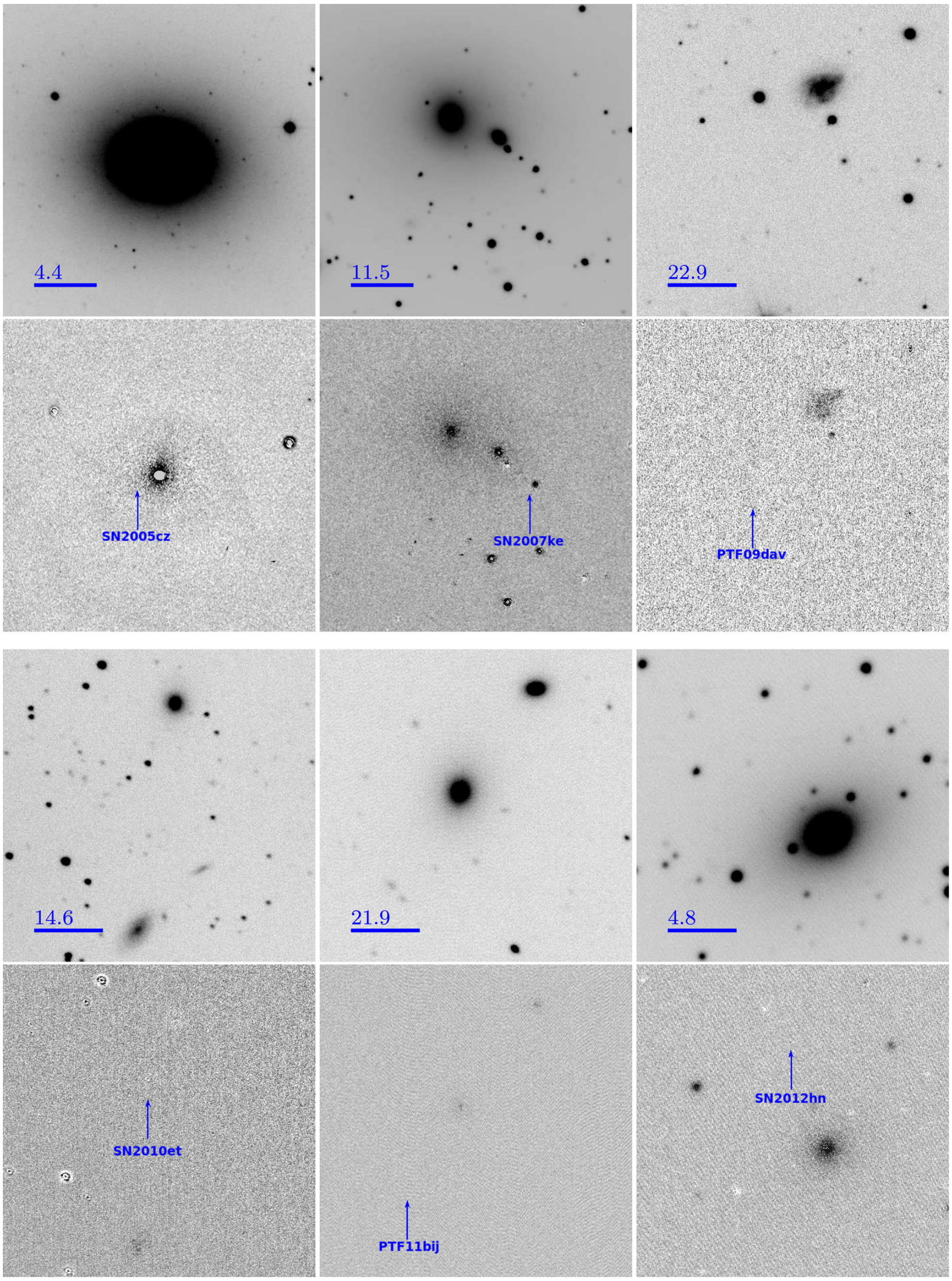

Figure 1 – *continued*

seen in the continuum-subtracted image. No other detected SF is seen from the host, as is expected if we accept its E2 morphology. The transient is located fairly close to the centre of the galaxy, although it is still outside the region of subtraction residuals.

SN2007ke in NGC 1129. The central excess in the continuum-subtracted frame may again be due to saturation effects, although it is less clear in this case. However, SN2007ke is very distant from the centre of this halo on a location of no detected Hα. (Note that the bright spot nearest to SN2007ke in the subtracted frame is a foreground star residual and was masked prior to NCR analysis.) Although NGC 1129 is the proposed host, clearly seen between this galaxy and the transient is another galaxy, MCG+07-07-003, at $V_{\rm rec} = 4967$ km s^{-1}. Due to the similarity of the velocities of the two galaxies, the chosen narrow-band filter would have detected any Hα from both these galaxies, so we can be confident that we are not missing potential SF from MCG+07-07-003 (the location of MCG+07-07-003 was included in the NCR analysis since it lies between the putative host and the transient). MCG+07-07-003 appears to be an elliptical galaxy from our imaging, possibly of the compact cE type, and so it is immaterial whether this galaxy or NGC 1129 is adopted as the host for the discussion of the statistics of host types in Section 5.2.

PTF09dav. The most distant transient in our sample, this could prove a problem for the NCR method when trying to compare consistently with the other, much nearer examples where the resolving distance at the host will be much smaller. However, the extreme separation

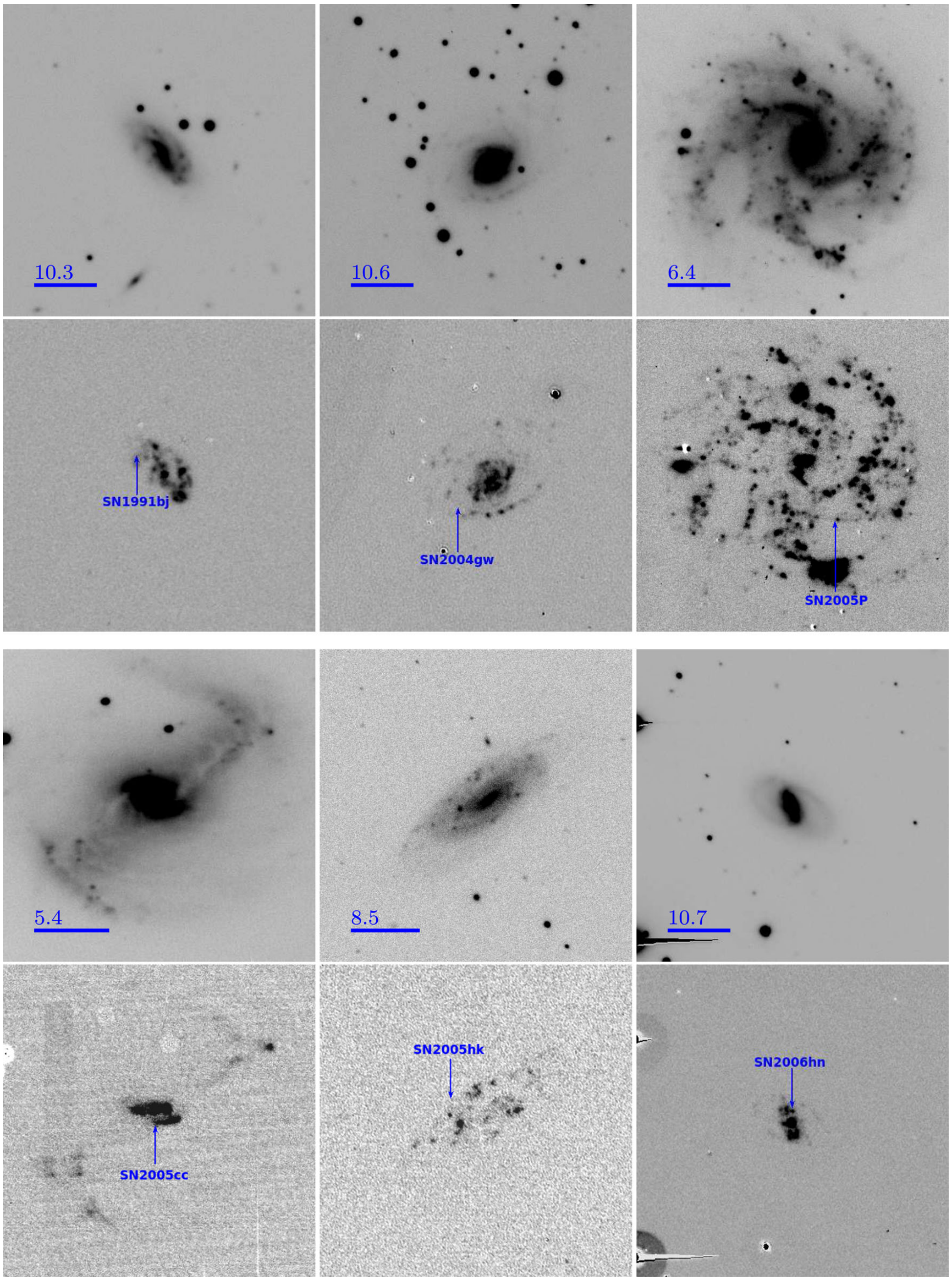

Figure 2. Same as Fig. 1 but for the SN2002cx-like transients.

of the transient from the host negates this problem and we detect no Hα anywhere near the transient, though there is clear SF in the disc of the putative host galaxy ~40 kpc away. Kasliwal et al. (2012) present a limiting magnitude of $M_R \sim -10$ for any underlying dwarf host at the location of the transient.

SN2010et. SN2010et = PTF10iuv was discovered by PTF in a very isolated location, with no obvious host galaxy. Our images, shown in Fig. 1, contain three galaxies which probably constitute a small galaxy group, since they have similar recession velocities. These are 6997 km s^{-1} for the elliptical galaxy towards the right-hand edge of the images, 7132 km s^{-1} for the faint edge-on spiral galaxy and 7407 km s^{-1} for the brighter spiral towards the left-hand edge of the images. The brighter spiral is the only galaxy in the frame to show evidence for Hα emission, and hence for ongoing SF, but this galaxy is very remote from the location of SN2010et. The elliptical galaxy is marginally the most likely host, given its luminosity and somewhat lower (but still substantial) projected distance. However, it would be very misleading to claim any strong preference for a host galaxy in this case, and so SN2010et is omitted from the analysis of host galaxy types presented later in this paper. The NCR index for the location of SN2010et is unsurprisingly 0.000, i.e. consistent with an empty 'sky' location. The limiting magnitude for an underlying dwarf galaxy is estimated as $M_R \sim -12$ by Kasliwal et al. (2012).

PTF11bij in IC 3956. Another relatively distant example, the transient is located 33 kpc from IC 3956, an elliptical galaxy that displays no definite Hα emission in the continuum-subtracted image. The recession velocity, unfortunately for this study, lies in the overlap region of the transmission curves of two Hα filters, where both

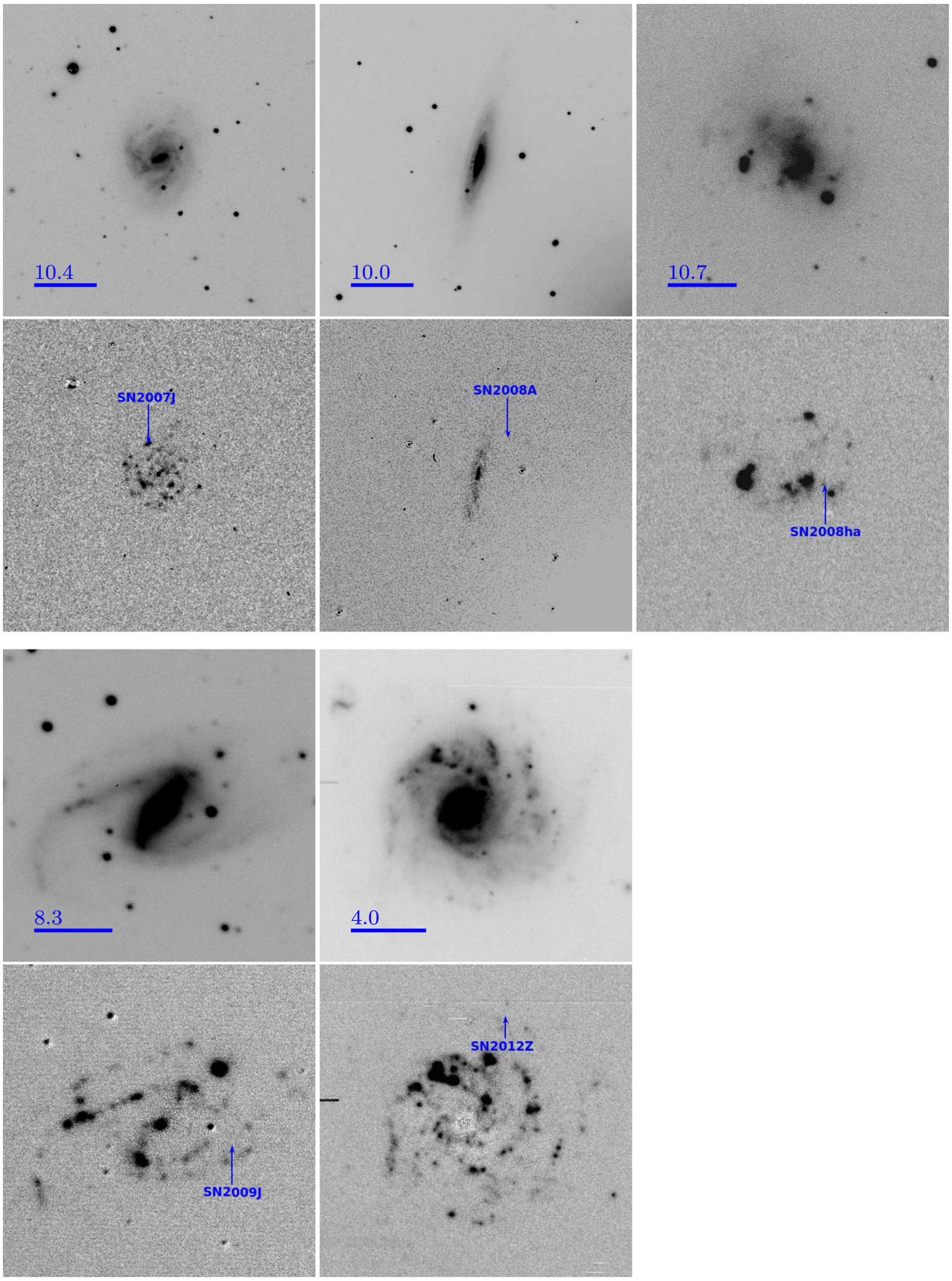

Figure 2 – *continued*

have transmissions of about half of their peak values. The filter with the slightly better transmission at the $V_{\rm rec}$ of IC 3956 was chosen; however, we must attach a strong caveat to the analysis of this transient as there is a possibility that our observations miss potential Hα emission. Regardless of this problem, the remote location around an early-type galaxy would indicate an unlikely place for significant SF and hence Hα emission. Kasliwal et al. (2012) present a limiting magnitude of $M_R \sim -12.5$ for any underlying dwarf host.

SN2012hn in NGC 2272. The host galaxy is an early-type (SAB0 in NED, E/S0 in HyperLeda[3]) with no detected SF in our imaging, although it should be noted that the recession velocity of the host galaxy would put any Hα emission only just within the half-peak transmission limit of the filter used. The transient location lies well away from the nucleus, and no emission is seen close to its location in either our broad or narrow-band imaging.

4.2 SN2002cx-like transients

SN1991bj in IC 344. IC 344 is a spiral galaxy showing clumpy SF in strong H II regions. SN1991bj lies in a region of weak Hα emission within the disc.

SN2004gw in CGCG 283-003. Weak SF is displayed throughout the disc, apart from the southerly arm, which displays several bright areas of Hα emission. The bulk of the star formation is centrally

---

[3] http://leda.univ-lyon1.fr/

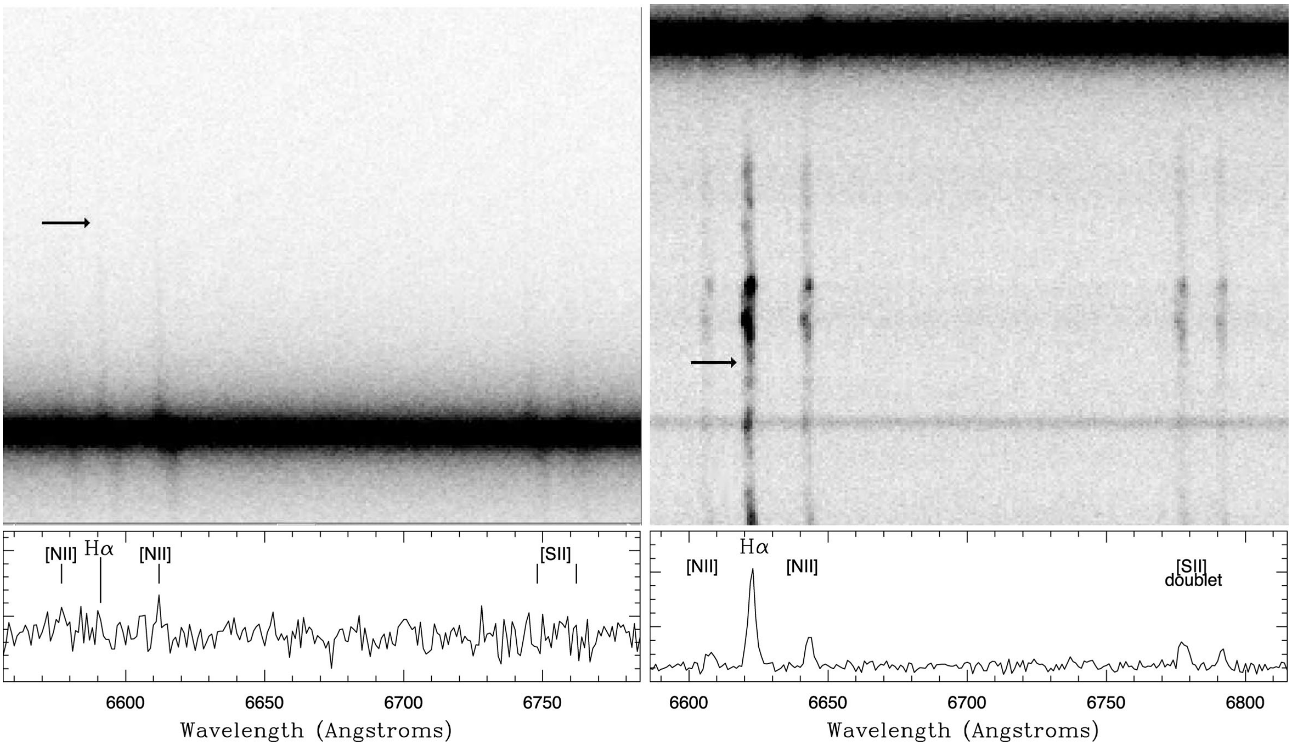

Figure 3. Spectra showing the Hα region of the long-slit spectra of SN2000ds in NGC 2768 (left) and SN2003H in NGC 2207 (right). The arrows indicate positions corresponding to Hα emission from the location where each transient occurred. A 1D spectrum is extracted for each at the position of the transient and shown in relative flux in the lower panels. SN2000ds and SN2003H are located 33.4 and 51.4 arcsec away from their respective hosts' nuclei.

located. The transient location is close to regions of very diffuse Hα emission, but is not coincident with any.

SN2005P in NGC 5468. Clumpy Hα structure with some regions of extremely intense SF is seen in this face-on spiral. SN2005P is located on the edge of a fairly bright H II region, although the low NCR value of 0.055 is warranted by the other, intensely bright regions in the host. NGC 5468 also hosted SN1999cp (Type Ia), SN2002cr (Type Ia) and SN2002ed (Type II-P).

SN2005cc in NGC 5383. A strongly barred galaxy, NGC 5383 displays strong Hα emission in the centre of the bar including an intense starburst region. Lower level, diffuse emission occurs near the ends of the bar and the base of the spiral arms. SN2005cc is located in a bright region on the southern edge of the bulge.

SN2005hk in UGC 272. The transient is located towards the outer edge of the host's disc, which displays several regions of strong Hα emission. SN2005hk is located close to some very faint emission but is coincident with an area devoid of any detected flux and thus has NCR = 0.

SN2006hn in UGC 6154. SF is concentrated around the bar region in this spiral with little elsewhere in the disc. The transient is located on the cusp of a moderately bright H II region.

SN2007J in UGC 1778. SF is clumpy, spread evenly across nearly all of the disc. SN2007J lies towards the outer edge of the disc coincident with one of the brightest H II regions.

SN2008A in NGC 634. NGC 634 is a highly inclined spiral galaxy that shows reasonably strong Hα emission in the central region with weaker emission coming from the disc plane. Line-of-sight effects mean the NCR can potentially be erroneously high, but for SN2008A, NCR = 0, meaning it is likely to indeed be in a region of no SF. NGC 634 also hosted SN2006Q (type given in the IAU list as 'II?').

SN2008ha in UGC 12682. An irregular galaxy, UGC 12682 displays several regions of strong SF. SN2008ha is located directly on top of a region of moderate Hα emission.

SN2009J in IC 2160. A strongly barred spiral showing some clumpy SF. The transient SN2009J is near very low level SF but coincident with a region of no detected Hα emission. IC 2160 also hosted SN2009iw (Type Ia).

SN2012Z in NGC 1309. Intense regions of Hα emission are observed in the arms of the face-on spiral galaxy NGC 1309. The transient is located far out in the disc of the host, in a region devoid of Hα emission.

5 STRENGTH OF ASSOCIATION OF TRANSIENTS WITH ONGOING SF

5.1 Host galaxy classifications

The first indications of the association of these transients with ongoing SF come from the Hubble types of the host galaxies. For the Ca-rich transients, the most important observation is that six of the eleven for which we have host types arise from early-type galaxies (four ellipticals and two lenticulars) which, as expected, are shown by our observations to have no detectable SF as revealed by Hα emission. The other five Ca-rich transient hosts are all nominally spiral galaxies; these are bright, star-forming galaxies with types in the range Sb–Scd, which are the types that dominate the overall

SF rate in the local Universe (James et al. 2008). One of these five is PTF09dav, which lies at a projected distance of 40.6 kpc from a bright, disturbed star-forming galaxy that was identified as the probable host by Sullivan et al. (2011), and which we have classified as being of type Sb from our imaging. However, the identification of this galaxy as the host is far from certain, given the very substantial projected offset.

The host galaxies of the eleven SN2002cx-like transients are all clearly of star-forming types, ten being spiral galaxies and one a Magellanic-type irregular. Two are classified as Sa, one as Sab, one as Sb, one as Sbc, one as Sc, two as Scd, one as Sd, one as Sdm and one as Im.

These distributions of host galaxy types can be compared with the expectations for the typical host environments of low- and high-mass stars, picked at random from across the ensemble of all galaxy types, with the important caveat that both sets of transients are likely to be subject to substantial selection biases. For low-mass stars, a reasonable comparison is with the distribution of total stellar mass across the population of galaxies in the local Universe, which has been estimated by Driver et al. (2007a,b). Driver et al. (2007b) give the following fractions of stellar mass in different galaxy components: discs = 58 ± 6 per cent, elliptical galaxies = 13 ± 4 per cent, bulges = 26 ± 4 per cent and other = 3 per cent. While the significance is far from compelling, this indicates that the Ca-rich transients are, if anything, more strongly weighted towards elliptical galaxies than would be expected if they accurately traced the low-mass stellar population. The expectation might be for one to lie in an elliptical host, whereas four are actually found. For the SN2002cx-like transients, the reverse is true; none of the hosts is an elliptical galaxy. From an inspection of Fig. 2, all occurred within the star-forming disc components of their host galaxies, with the debatable exception of SN2008A, which would be a surprising finding if they follow the distribution of old stellar mass.

To determine the expectations for high-mass stars picked at random from local galaxies, we make use of the estimates of the contributions made by galaxies of different types to the SF density of the local Universe, in James et al. (2008). This comparison is made in Fig. 4, where the filled circles in both frames represent the contributions made to the local SF rate density by galaxies of the different types. Thus, Sc galaxies (T-type = 5) make the largest single contribution, and host about 25 per cent of the current SF in the local Universe. The differences between the distribution of Ca-rich host types and those contributing to the SF rate density are striking. The lower frame of Fig. 4, where all the quantities are plotted as cumulative, normalized distributions, confirms this discrepancy for the Ca-rich transients (solid line), which show a large excess of early-type hosts. However, this cumulative distribution comparison shows that the SN2002cx-like transients (dashed line) much more closely match the expectations for a population that traces SF and hence high-mass progenitors.

The numbers of transients involved in this study are small, and the sample is potentially subject to significant selection effects. Noting these important caveats, it is still interesting to test the statistical significance of the difference between the distributions shown in Fig. 4. A one-sample Kolmogorov–Smirnov (KS) test gives a critical D value of 0.468 for a sample of 11 objects and a probability P of 0.01; the observed maximum D between the Ca-rich hosts and the SF density distribution summed over types is larger than the critical value, at 0.523. Thus, the Ca-rich hosts are significantly different from the expectations for a population that traces cosmic SF. A two-sample KS test shows that Ca-rich and SN2002cx-like host galaxies differ significantly, with a maximum D value of 0.55 and a probability of only 0.047 that the two sets of host galaxies could be drawn from the same parent distribution.

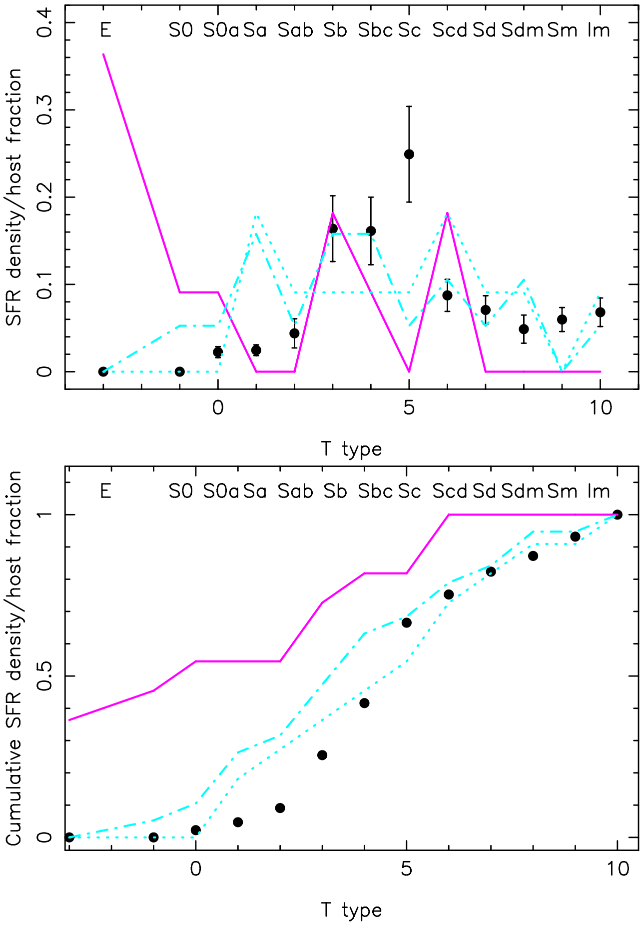

Figure 4. The SF density of the local Universe as a function of galaxy T-type (solid circles), compared with the distribution of types of the host galaxies of Ca-rich (solid lines) and SN2002cx-like (dotted lines) transients. Also shown are the host types of the full sample SN2002cx-like events for which a good host classification can be made (see the text; dot–dashed lines). Both frames show the same data, but quantities plotted in the lower frame are cumulative values along the sequence from early- to late-type galaxies.

It is useful, in the interests of increasing sample size, to look at the host types of other SN2002cx-like events, even those for which we have no Hα imaging. Some events prohibit a confident host classification to be made due to the distance to and/or a lack of high-resolution imaging of the host. Additional transients that we include are SN2002bp (UGC 6332, SBa), SN2003gq (NGC 7407, Sbc), SN2004cs (UGC 11001, Sdm), SN2008ge (NGC 1527, SAB0), SN2010ae (ESO 162-17, Sb), SN2010el (NGC 1566, SABbc), SN2011ay (NGC 2315, S0/a) and SN2011ce (NGC 6708 Sb); see Foley et al. (2013) for a discussion of each event. As can be seen in Fig. 4, this enlarged sample of 19 transients broadly follows the host distribution of our SN2002cx-like sample, as expected, although one transient has an early-type host classification – SN2008ge in NGC 1527. This may argue against a young age for the progenitor; indeed, Foley et al. (2010a) find an absence of evidence for recent SF at the transient's location and conclude that the progenitor is likely to be a WD. SN2008ge is further discussed in Section 6.

5.2 Transient locations and ongoing SF

To further quantify the apparent association of the two transient populations with current sites of SF, we make use of the NCR statistic applied to a pixel-by-pixel analysis of our continuum-subtracted Hα images, which was introduced in Section 2.

For the five Ca-rich transients in galaxies with detectable SF, the mean NCR value is 0.259 (standard error on mean 0.119), i.e. in the range 0.000–0.626. When including the other seven transients where Hα imaging reveals no SF in the galaxy (including SN2010et which has no obvious host), and the transients consequently have NCR = 0.000, the mean NCR falls to 0.108 (0.060).

The Ca-rich transient with the strongest apparent association with an H II region is SN2003dg. This occurred in the disc plane of UGC 6934, an edge-on Scd spiral galaxy. This galaxy orientation makes the interpretation of the NCR index highly ambiguous, with a greatly increased probability of line-of-sight projection effects resulting in spurious apparent correlations and large, poorly constrained extinction effects. Thus, edge-on galaxies were excluded from the NCR analysis in all of our previous papers (James & Anderson 2006; Anderson & James 2008; Anderson et al. 2012), with a limiting criterion of a major-to-minor axis ratio of 4.0. For UGC 6934, this ratio is 7.7, so it would have been excluded from our earlier studies. Removing SN2003dg from the sample, the mean NCR value falls to 0.061 (0.041).

Two more of the Ca-rich transients, SN2003dr and SN2005E, occurred in disc galaxies that are very close to being exactly edge-on. In these cases, the transient occurred far from the disc plane, so the line-of-sight projection argument does not apply. However, for the sake of consistency we recalculate the average NCR value with all three edge-on hosts removed, giving an average for the remaining nine of 0.074 (0.049).

For the 11 SN2002cx-like transients, the mean NCR value is 0.222 (0.092), i.e. in the range 0.000–0.904. Removing SN2008A, which occurred in the edge-on Sa galaxy NGC 634, the mean value is found to be 0.244 (0.099).

Fig. 5 shows the distributions of NCR values for our samples and of other well-known SN classes. The values for Ia, II-P, Ib and Ic types are taken from Anderson et al. (2012). The study of Anderson et al. (2012) was of only star-forming galaxies however, whereas we have six early-type hosts in the Ca-rich transient class that display no detected SF. In order to compensate for this fact, we use the rate of SNeIa going off in early-type galaxies from the Lick Observatory Supernova Search (Li et al. 2011), found to be ~27 per cent. With no SF, any location in the host will have NCR = 0, so by adding 27 per cent to the SNIa sample as NCR = 0 events, this will give an expected SNIa distribution across all galaxy types. The number of CCSNe that have been observed in non-star-forming early-type hosts is ~0, and as a result no correction was applied to the SN II, Ib or Ic distributions.

We have applied the KS test to the distributions of NCR values shown in Fig. 5. These confirm the extreme nature of the environments of the Ca-rich transients; even with a small sample (12 objects), the test conclusively shows that the values are not consistent with a distribution that perfectly traces the SF activity in the host galaxies (the black diagonal line in Fig. 5), with a probability of these distributions being consistent of <0.1 per cent. More importantly, the Ca-rich transient NCR values are inconsistent with the distributions for SNeII (including all subtypes and unclassified Type II; see Anderson et al. 2012) and Ib, with probabilities less than 2.5 per cent of being drawn from the distributions of either type; the consistency with the II-P sample shown in Fig. 5 is ~5 per cent. Notwithstanding the small sample size, a clear distinction exists between Ca-rich transients and SNeII/Ib.

The Ca-rich transient distribution is completely consistent with that of SNeIa, and by eye the two distributions overlay very closely, given the constraints of small number statistics. For the SN2002cx-like transients, the situation is less clear; formally the NCR values of these 11 transients could have been drawn from any of the other distributions shown in Fig. 5. However, the distribution most closely approximates that of the SNeII-P, and indeed, again considering the small number statistics, reproduces it well. The distribution of SN2002cx-like transients shows a stronger association with SF than that of SNeIa, with the mean NCR being larger even in the case of considering only star-forming hosts of SNeIa (see Table 6).

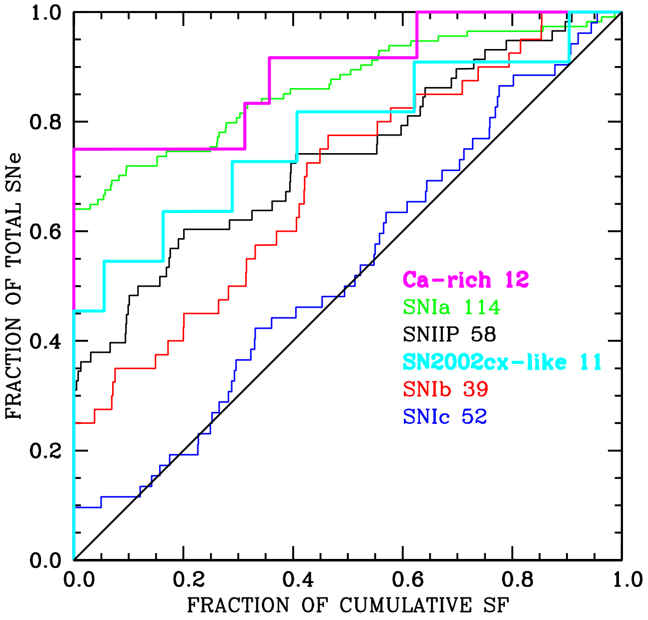

Figure 5. Cumulative distribution of the Ca-rich and SN2002cx-like samples as compared to other SN types. Data for other SNe are based on Anderson et al. (2012), with a correction factor applied to the SNIa sample to account for the fact that only star-forming galaxies were included in that study (see the text).

Table 6. Mean NCR values for the locations of different SN types.

SN type	No.	Mean	Std. err.
Ca-rich	9	0.074[a]	0.049
Ca-rich	12	0.108	0.060
Ia	98	0.114[b]	0.019
SN2002cx-like	11	0.222	0.092
SN2002cx-like	10	0.244[c]	0.099
II-P	58	0.264	0.039
Ib	39	0.318	0.045
Ic	52	0.469	0.040

[a] All edge-on hosts excluded.
[b] Corrected for an assumed early-type fraction of 27 per cent; mean in star-forming hosts is 0.157.
[c] Edge-on host excluded.

6 DISCUSSION

Though the total rate of Ca-rich and SN2002cx-like transients might be significant compared to SNeIa, the actual number of observed events is still small, mostly due to their low luminosity which limits their detection at large distances. For this reason, the sample sizes in this study are limited. Nevertheless, a clear picture emerges from our results, pointing to significant differences between the host environments of these two transient types, which, in turn, implies different types of progenitor systems. The clear distinction between the two classes is strengthened by the possible contamination from misclassified transients in each sample. Such contamination would serve to dilute any distinct behaviour between the two samples.

The first indications for such a difference come from the host galaxy population analysis. All SN2002cx-like transients have host galaxies that display strong, recent SF activity. The progenitor systems are therefore likely associated with a young stellar population, quite similar to that of CCSNe. Conversely, six of the eleven Ca-rich hosts (disregarding SN2010et, where the host is not certain) are early-type galaxies with no detected SF, and therefore point to an old stellar population lacking any young, massive stars.

Our host galaxy distributions provide strong support to the suggestion of Perets et al. (2010) of an old progenitor system for Ca-rich transients. Their original analysis of a smaller sample of events showed the host galaxy distribution of various SN types compared with the Ca-rich events. The distribution of Ca-rich transient hosts displays similarities with that of regular SNeIa, a trend strengthened by the addition of similar events identified since then presented here.

Furthermore, our NCR analysis allows the locations of the transients *within* their respective hosts to be investigated. More than simply saying that the SN2002cx-like transients are found in hosts that display ongoing SF, we quantitatively find a good match between SN2002cx-like events and SNeII-P with respect to association with recent SF in their host galaxy. Such a match would indicate a similar progenitor age for SN2002cx-like transients and SNeII-P (i.e. a typical delay time of 30–50 Myr). From the NCR analysis, we confirm that Ca-rich transients do not appear to follow recent SF in their hosts and closely resemble the distribution of 'normal' SNeIa, whose progenitors are expected to have significant lifetimes ($\sim$ Gyr).

The samples are, as mentioned previously, inherently eclectic and suffer many biases relative to a volume-limited sample. Their fainter magnitudes compared to SNe in general would suggest that they will be difficult to detect in bright galaxy regions. We note, however, that SN2003dg (Ca-rich) and SN2005cc (SN2002cx-like), both typical of the mean brightness of their sample, were discovered in the brightest central regions of their respective hosts. The preference for discovery in fainter host locations would strengthen the argument for SN2002cx-like events' association with SF, given that it is plausible to miss some of these events if they are coincident with the brightest H II regions. The discovery magnitudes quoted in Tables 2 and 3 show that there is no statistically significant difference between distribution of brightnesses in each sample, suggesting that any bias from magnitude-limited searches will affect each sample similarly (although their faintness will possibly affect the comparison to 'normal' SN types).

Our analysis provides new clues regarding the origin of these peculiar transient events, and can help constrain the suggested theoretical models. In the following, we discuss these constraints in view of the suggested theoretical models for these transients.

Ca-rich transients. Several models were suggested for the origin of the Ca-rich events. The model of He-shell detonation on a CO WD, following He accretion from an He WD, was first suggested by Perets et al. (2010) and gained additional support from the theoretical analysis by Shen & Bildsten (2009) and Waldman et al. (2011). Such a model points to a double-degenerate origin for these types of transient. In particular, Waldman et al. (2011) suggested a low-mass CO WD progenitor, which requires a long-lived stellar origin, and possibly a low-metallicity environment. An alternative model of a CC origin as suggested by Kawabata et al. (2010, see also discussion by Kasliwal et al.) would require a young, star-forming environment. Our Hα-based analysis of the hosts of the Ca-rich transients makes it clear that the majority of these are occurring a very long way from any detectable SF. This also strengthens the arguments of Perets et al. (2010) and Kasliwal et al. (2012) that even extremely high-velocity, high-mass runaway stars are implausible candidates as progenitors of the Ca-rich transients. We therefore conclude that our analysis consistently points towards old progenitor systems, and a likely thermonuclear origin, for the Ca-rich transients (see additional support through the analysis of Yuan et al. 2013).

SN2002cx-like transients. Several models were also suggested for the origin of SN2002cx-like events. Li et al. (2003) and Branch et al. (2004) suggested that they originate from the deflagration of a Chandrasekhar mass C/O WD. This model encounters difficulties in explaining the diversity of such events and in particular the extremely low-mass and subluminous SN2008ha event. A more recent and detailed model by Jordan et al. (2012, see also Calder et al. 2004; Livne, Asida & Höflich 2005; Kromer et al. 2013) discusses a failed detonation model, in which a deflagration scenario fails to explode the WD, and only burns and ejects a fraction of the WD, leaving behind an intact (but now lower mass and polluted) WD remnant. This scenario can similarly explain the low velocities observed for SN2002cx-like events due to deflagration, but in addition provides a robust explanation for the diversity of the SN2002cx-like events and the possible production of extremely low-mass and low-luminosity events. Both of these models begin with a Chandrasekhar mass WD, similar to the single-degenerate model suggested for SNeIa. WDs initially formed at high masses (which in turn form from higher mass stellar progenitors with shorter lifetimes) and require less additional accretion in order to achieve the Chandrasekhar mass. This would generally point to their association with younger environments, where more massive stars and binaries evolve and transfer mass. However, the evolution towards the Chandrasekhar mass is still expected to be generally longer, and sometimes much longer, than the typical lifetimes of CCSN stellar progenitors (>8 $M_{\odot}$ stars). Although some SN2002cx-like transients have been found in old environments (Foley et al. 2013), our finding suggest a very young environment for the progenitors of these transients, comparable with that of SNeII-P. The environmental constraints we find therefore are not excluded, but are less favourable for a Chandrasekhar mass C/O WD explosion.

Fernández & Metzger (2013) suggest neutron star-WD mergers as a possible origin for SN2002cx-like events. Some of the properties of SN2002cx-like transients are qualitatively reproduced by the model, but more detailed studies are needed. This model would suggest a mixed distribution of old and young environments, due to the distribution of the gravitational wave inspiral time leading to the merger, in contrast with the strong bias to very young environment we find here. In addition, the total rate of neutron star-WD mergers is about 3 per cent of that of SNeIa – even if all such mergers resulted in an SN2002cx-like event, the expected rates would be an order of magnitude lower than those observed (Foley et al. 2013).

Valenti et al. (2009) suggested that SN2002cx-like transients arise from a variant of CCSNe with low ejecta velocity, although currently no detailed theoretical modelling of such events has been done and shown to produce such events. Our findings of similar environments for both these transients and those of CCSNe are therefore consistent with the CC origin of SN2002cx-like transients. In particular, our detailed NCR statistics indicate that SN2002cx-like events share similar environments to those of SNeII-P, i.e. while they are evidently associated with SF, a substantial fraction appear to outlive their natal H II regions, resulting in lower values of the NCR index than would be expected for the highest mass progenitors. In the context of this scenario, our analysis would therefore point to the lower mass, 7–9 $M_\odot$ (with typical lifetimes of 30–50 Myr), progenitors discussed by Valenti et al. (2009), rather than the alternative high-mass Wolf–Rayet stars also discussed by them. It is, however, still difficult to explain the complete lack of SF/young environment for one of the SN2002cx-like events, SN2008ge (Foley et al. 2010a).

Two of the SN2002cx-like transients show spectral evidence for helium. Taken together with the young environment found for these events (beside SN2008ge), Foley et al. (2013) suggest this as possible evidence for their origin from a helium star accretion on to a WD. However, a helium layer may also form following hydrogen accretion and burning into helium on a WD (Cassisi, Iben & Tornambe 1998, and references therein). We therefore conclude that although the existence of helium in even a small fraction of these events is a potentially important clue for their origin, its interpretation is still inconclusive.

7 SUMMARY

Our investigations of the environments and host types of Ca-rich transients show a lack of association with recent SF (similar to that of SNeIa), and thus point to old progenitor systems, consistent with helium-shell detonation on low-mass C/O WDs, and inconsistent with a CCSN origin. Conversely, we find the SN2002cx-like transients to be well matched by young progenitors (likely <50 Myr lifetime) through an association with SF that is similar to that displayed by SNeII-P. Such young progenitors are less favourable to failed detonations of Chandrasekhar mass C/O WDs, and more consistent with either the core collapse of a 7–9 $M_\odot$ star or a WD explosion following the accretion of a helium star (note that one event, SN2008ge, does not seem to fit with this conclusion). While the failed detonation model for these events appears to be consistent with the observable parameters of SN2002cx-like events themselves, the latter two models currently lack an actual detailed study. Therefore, they cannot yet be adequately compared with observations, beyond the generally consistent aspects of their expected environments as studied here.

ACKNOWLEDGEMENTS

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We acknowledge the usage of the HyperLeda data base. The Liverpool Telescope is operated on the island of La Palma by Liverpool John Moores University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias with financial support from the UK Science and Technology Facilities Council. The Isaac Newton Telescope is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. This research also uses observations made with the ESO 2.2 m telescope at the La Silla Observatory (proposal ID 084.D-0195). JDL acknowledges the UK Science and Technology Facilities Council for research studentship support. JA acknowledges support from CONICYT through FONDECYT grant 3110142, and by the Millennium Center for Supernova Science (P10-064-F), with input from 'Fondo de Innovacin para La Competitividad, del Ministerio de Economa, Fomento y Turismo de Chile'. AG was supported by grants from the ISF, the EU/FP7/ERC, the Minerva and ARCHES programmes, and the Helen and Martin Kimmel Award for Innovative Investigation.

REFERENCES

Alard C., 2000, A&AS, 144, 363
Anderson J. P., James P. A., 2008, MNRAS, 390, 1527
Anderson J. P., Habergham S. M., James P. A., Hamuy M., 2012, MNRAS, 424, 1372
Benitez-Herrera S., Taubenberger S., Valenti S., Benetti S., Pastorello A., 2012, Astron. Telegram, 4047, 1
Botticella M. T., Smartt S. J., Kennicutt R. C., Cappellaro E., Sereno M., Lee J. C., 2012, A&A, 537, A132
Branch D., Baron E., Thomas R. C., Kasen D., Li W., Filippenko A. V., 2004, PASP, 116, 903
Calder A. C., Plewa T., Vladimirova N., Lamb D. Q., Truran J. W., 2004, preprint (astro-ph/0405162)
Cassisi S., Iben I., Jr, Tornambe A., 1998, ApJ, 496, 376
Crowther P. A., 2013, MNRAS, 428, 1927
de Vaucouleurs G., 1948, Ann. Astrophys., 11, 247
de Vaucouleurs G., de Vaucouleurs A., Corwin H. G., Jr, Buta R. J., Paturel G., Fouqué P., 1991, Third Reference Catalogue of Bright Galaxies. Springer, Berlin
Driver S. P., Popescu C. C., Tuffs R. J., Liske J., Graham A. W., Allen P. D., de Propris R., 2007a, MNRAS, 379, 1022
Driver S. P., Allen P. D., Liske J., Graham A. W., 2007b, ApJ, 657, L85
Eldridge J. J., Fraser M., Smartt S. J., Maund J. R., Crockett R. M., 2013, preprint (arXiv:1301.1975)
Fernández R., Metzger B. D., 2013, ApJ, 763, 108
Foley R. J. et al., 2009, AJ, 138, 376
Foley R. J. et al., 2010a, AJ, 140, 1321
Foley R. J., Brown P. J., Rest A., Challis P. J., Kirshner R. P., Wood-Vasey W. M., 2010b, ApJ, 708, L61
Foley R. J. et al., 2013, ApJ, 767, 57
Hakobyan A. A., Petrosian A. R., McLean B., Kunth D., Allen R. J., Turatto M., Barbon R., 2008, A&A, 488, 523
James P. A., Anderson J. P., 2006, A&A, 453, 57
James P. A., Knapen J. H., Shane N. S., Baldry I. K., de Jong R. S., 2008, A&A, 482, 507
Jordan G. C., IV, Perets H. B., Fisher R. T., van Rossum D. R., 2012, ApJ, 761, L23
Kasliwal M. M. et al., 2012, ApJ, 755, 161
Kawabata K. S. et al., 2010, Nat, 465, 326
Kromer M. et al., 2013, MNRAS, 429, 2287
Kuncarayakti H. et al., 2013, preprint (arXiv:1305.1105)
Law N. M. et al., 2009, PASP, 121, 1395
Lee J. C. et al., 2009, ApJ, 706, 599
Li W. et al., 2003, PASP, 115, 453
Li W. et al., 2011, MNRAS, 412, 1441
Livne E., Asida S. M., Höflich P., 2005, ApJ, 632, 443

Moellenhoff C., Bender R., 1989, A&A, 214, 61
Perets H. B. et al., 2010, Nat, 465, 322
Perets H. B., Gal-yam A., Crockett R. M., Anderson J. P., James P. A., Sullivan M., Neill J. D., Leonard D. C., 2011, ApJ, 728, L36
Phillips M. M. et al., 2007, PASP, 119, 360
Puckett T., Moore C., Newton J., Orff T., 2008, Cent. Bur. Electron. Telegrams, 1567, 1
Rau A. et al., 2009, PASP, 121, 1334
Sandage A., Bedke J., 1994, The Carnegie Atlas of Galaxies. Carnegie Institute of Washington, DC
Shen K. J., Bildsten L., 2009, ApJ, 699, 1365
Sullivan M. et al., 2011, ApJ, 732, 118
Valenti S. et al., 2009, Nat, 459, 674
Valenti S. et al., 2013, preprint (arXiv:1302.2983)
Waldman R., Sauer D., Livne E., Perets H., Glasner A., Mazzali P., Truran J. W., Gal-Yam A., 2011, ApJ, 738, 21
Yuan F., Kobayashi C., Schmidt B. P., Podsiadlowski P., Sim S. A., Scalzo R. A., 2013, MNRAS, 432, 1680

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