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

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ABSTRACT

We present a study of the properties of the host galaxies of unusual transient objects of two types, both being sub-luminous 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 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 Myrs.

Key words: Supernovae: general - Supernovae: SN 1991bj, SN 2000ds, SN 2001co, SN 2003H, SN 2003dg, SN 2003dr, SN 2004gw, SN 2005E, SN 2005P, SN 2005cc, SN 2005cz, SN 2005hk, SN 2006hn, SN 2007J, SN 2007ke, SN 2008A, SN 2008ha, SN 2009J, PTF09dav, SN 2010et, PTF11bij, SN 2012Z, SN 2012hn

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 lightcurves, 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 the present 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 class (SNeIa), 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 supernova; 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 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 survey (Law et al. 2009; Rau et al. 2009, henceforth PTF). Kasliwal et al. (2012) combined these three new objects (PTF09dv, PTF10iuw (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 characterise 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 type Ic supernova (Benitez-Herrera et al. 2012), but Valenti et al. (2013) conclude from 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 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 ($\sim$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 (Valenti et al. 2009, Foley et al. 2009, 2010a), 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 a SN type Ia event) and has extremely low photospheric velocity ($\sim$2000 km s$^{-1}$ cf. 6000-11000 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, that they term ‘lax’. These differ from normal type Ia SNe 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 $\sim$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 a He-star, and therefore consider some possible connections between SN2002cx-like and Ca-rich transients, where both type of events arise from a 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 for 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 a 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,
2 METHODS

The methods we employ are explained in detail in Crowther (2013); these have been previously applied to large samples of supernovae 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 normalised 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 star formation 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 WCS forms the centre of a 3 × 3 ‘super-pixel’. A pixel in our binned images represents ~0.9 arcsecond 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 normalised 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 star-formation 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 star formation, 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 association of SNe with ongoing star formation, 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 hard 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 a star formation tracer since there already exists large samples of NCR values for the more common SN types which can be compared to. The typical duration of Hα emission from HII regions is comparable to that of the ages of the middle-to-lower mass end of CCSN. 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⊙ star). This, however, is a lower limit since a typical star formation 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 normalised to its own host, we are not sensitive to absolute calibration issues of Hα as a star-formation 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 (Vrec) provide a problem of filter choice, especially when Vrec cannot be determined for the transient itself. In the present 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...
Table 1. Hα narrow-band filter properties.

| Filter name | Telescope | Wavelength limits Å | $V_{rec}$ limits km/s |
|-------------|-----------|---------------------|-----------------------|
| ‘Halpha’    | INT       | 6522–6614           | −1865–2357            |
| ‘Ha 6657′   | INT       | 6618–6697           | 2400–6100             |
| ‘H-alpha-100’ | LT:RATCam | 6517–6617           | −2093–2478            |
| ‘Ha_6566’   | LT:JO     | 6522–6610           | −1865–2164            |
| ‘Ha_634′    | LT:JO     | 6608–6662           | 2080–4520             |
| ‘Ha_6705’   | LT:JO     | 6680–6733           | 5349–7764             |
| ‘Ha_6755’   | LT:JO     | 6729–6783           | 7595–10047            |
| ‘Ha_6822’   | LT:JO     | 6796–6849           | 10717–13097           |
| ‘665/12’    | MPI-2.2   | 6508–6713           | 1016–6857             |

1 No scanned transmission profile is available for this filter so the limits are based on manufactured specifications.

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 origin or potential for diversity within the 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 ESO. For each transient, exposures were taken in the R band, to characterise the continuum light, and a narrowband Hα filter. Details of the Hα filters used are given in Table 1 where wavelength and corresponding $V_{rec}$ limits are defined as the 50 per cent transmission limits of the filter. Exposure times were 300 seconds for R band and 900 seconds for Hα, this 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 star formation limits using this method). Images taken with the LT were reduced using the automated pipeline; standard bias and overscan subtraction and flat fielding was performed for other data. Typical seeing was 1–2 arcseconds (see Tables 1 and 5). 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 the present study are given in Tables 2 and 5 respectively. These list the International Astronomical Union (IAU) supernova name for all transients except PTF09dav and PTF11bij, which are not on 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 Catalog2, using distance modulus values for the host taken from NED); and the classification of the supernovae from the IAU database.

Details of the observations and NCR values are given in Table 3 for the Ca-rich transients and 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 star formation (i.e. Hα emission) in our observations is also noted.

Images of the twelve Ca-rich hosts are shown in Figure 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 star formation. Indeed, we find no star formation 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 artefacts 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 star formation.

Figure 2 shows the corresponding images for the SN2002cx-like sample. All these hosts are late type, and all display strong ongoing star formation with prominent HII regions.

Further discussion of the hosts of the two samples is given in Sect. 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′′) of two of the host galaxies in our samples (Fig. 3). The observations

1 http://ned.ipac.caltech.edu/
2 http://heasarc.gsfc.nasa.gov/W3Browse/all/asiosgn.html
were taken on the INT in January 2013 using the IDS spectrograph 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′′, the corresponding values for NGC 2207 (SN2003H) were 1.57 and 0.8′′.

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 star formation 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 [NII] in the central regions of the galaxy, far from the SN location, that is probably related to the known LINER nucleus of this galaxy.

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

SN2003H in NGC 2207. NGC 2207 is 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. 4 showing that there is clearly detectable star formation at the location of SN2003H, although it appears to lie in the outer regions of a star-formation 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 HII 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 be determined where in the disc it lies. This means the NCR value may not be accurate (see Sect. 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 star formation. The only apparent star formation 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 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$^2$ 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 seen in the continuum-subtracted image. No other detected star formation 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 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 $V_{rec} = 4967$ km s$^{-1}$. Due to the similarity of the velocities of the two galaxies, the chosen narrowband filter would have detected any Hα from both these galaxies, so we can be confident that we are not missing potential star formation 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 Sect. 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 of the transient from the host negates this problem and we detect no Hα anywhere near the transient, though there is clear star formation in the disc of the putative host galaxy $\sim 40$ kpc away. Kashwal 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 toward 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 toward 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 ongo-
### 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    | SBBc      | 5166                   | −15.69                              | Ib/c        |
| 2003H     | NGC 2207    | SABbc     | 2741                   | −14.16                              | Ib/c        |
| 2003dg    | UGC 6934    | Ssc (edge-on) | 5501             | −15.31                              | Ib/c        |
| 2003dr    | UGC 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        | Sh$^1$    | 11123                  | −14.7                               | –           |
| 2010et    | Uncertain   | –         | –         | –                                    | –           |
| PTF11bij  | IC 3956     | E         | 10406                  | −15.9$^2$                            | –           |
| 2012hn    | NGC 2272    | SAB0      | 2130                   | −16.0$^3$                            | I-p         |

1 Classified by PAJ based on our imaging
2 $M_R$ at discovery taken from Kasliwal et al. (2012)
3 $M_R$ at peak taken from Valenti et al. (2013)

### Table 3. Observations of the host galaxies of Ca-rich transients.

| SN name   | Host galaxy | V$_{rec}$ (km s$^{-1}$) | Telescope | Obs. date | Seeing (arcseconds) | Filter name | Ho range (km s$^{-1}$) | NCR index | SF detected in host? |
|-----------|-------------|------------------------|-----------|-----------|---------------------|-------------|------------------------|------------|---------------------|
| 2000ds    | NGC 2768    | 1373                   | INT       | Jan 2012  | 1.6                 | ‘Halpha’    | −1865–2357             | 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     | Sep 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    | UGC 5714    | 2237                   | INT       | Jan 2012  | 1.6                 | ‘Halpha’    | −1865–2357             | 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’    | −1865–2357             | 0.000      | No                  |
| 2007ke    | NGC 1129    | 5194                   | INT       | Jan 2012  | 1.7                 | ‘Ha 6657’   | 2400–6100              | 0.000      | No                  |
| PTF09dav  | Anon        | 11123                  | LT:IO     | Dec 2012  | 1.6                 | ‘Ha 6822’   | 10747–13097            | 0.000      | Yes                 |
| 2010et    | Uncertain   | –         | LT:IO | Mar 2013  | 2.9                 | ‘Ha 6705’   | 4900–7640              | 0.000      | –                   |
| PTF11bij  | IC 3956     | 10406                  | LT:IO     | Jan 2013  | 3.0                 | ‘Ha 6822’   | 10747–13097            | 0.000      | No                  |
| 2012hn    | NGC 2272    | 2130                   | LT:IO     | Feb 2013  | 2.4                 | ‘Ha 6566’   | −1865–2164             | 0.000      | No                  |

### Table 4. 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$^1$  | 5440                   | −15.46                              | Ia          |
| 2004gw    | CGCG 283-003 | Sab$^2$   | 5102                   | −16.33                              | Ia          |
| 2005P     | NGC 5468    | SABcd     | 2842                   | −15.14                              | ?           |
| 2005cc    | NGC 5383    | SBbpec    | 2270                   | −15.18                              | ?           |
| 2005hk    | UGC 272     | SABd      | 3895                   | −17.0$^3$                            | 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         |
| 2008ba    | UGC 12682   | Im        | 1393                   | −12.75                              | Ia?         |
| 2009J     | IC 2160     | SBpec     | 4739                   | −16.17                              | Ia-p        |
| 2012Z     | NGC 1309    | SABc      | 2136                   | −14.62                              | Ia-p        |

1 Classified by PAJ based on our imaging
2 $M_R$ at discovery taken from Phillips et al. (2007)
3 Puckett et al. (2008)
ing star formation, 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 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.

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 have transmissions of about half of their peak values. The filter with the slightly better transmission at the V_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 make an underlying dwarf galaxy is estimated as M_B ~ −12 by Kasliwal et al. (2012).

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

| SN name | Host galaxy | V_rec (km s⁻¹) | Telescope | Obs. date | Seeing (arcseconds) | Filter name | Ho 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’| −2093–2478        | 0.621     | Yes                 |
| 2006hk  | 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’   | −1865–2164        | 0.407     | Yes                 |
| 2009J   | IC 2160     | 4739           | MP12.2     | Feb 2010  | 1.9                 | ‘665/12’    | 1616–6857         | 0.000     | Yes                 |
| 2012Z   | NGC 1309    | 2136           | LT:RATCam  | Aug 2009  | 1.5                 | ‘H-alpha-100’| −2093–2478        | 0.000     | Yes                 |

4.2 SN2002cx-like transients

SN1991bj in IC 344. IC 344 is a spiral galaxy showing clumpy star formation in strong HII regions. SN1991bj lies on a region of weak Hα emission within the disc.

SN2004gw in CGCG 283-003. Weak star formation 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 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 star formation are seen in this face-on spiral. SN2005P is located on the edge of a fairly bright HII 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 star burst region. Lower-level, diffuse emission occurs near the ends of the bar and the base of the spiral arms. SN2005cc is located on 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. Star formation 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 HII region.

SN2007J in UGC 1778. Star formation 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 HII 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 star formation. 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 star formation. SN2008ha is located directly on top of a region of moderate Hα emission.

SN2009J in IC 2160. A strongly barred spiral showing some clumpy star formation. The transient, SN2009J is near very low level star formation 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, on a region devoid of Hα emission.

### 5 STRENGTH OF ASSOCIATION OF TRANSIENTS WITH ONGOING STAR FORMATION

#### 5.1 Host galaxy classifications

The first indications of the association of these transients with ongoing star formation 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 star formation 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 star-formation 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, Driver et al.

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

(2007a) gives 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; 3 per cent other. 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 star formation 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 star-formation 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 star formation in the local Universe. The differences between the distribution of Ca-rich host types...
and those contributing to the star-formation 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 star formation 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 eleven objects and a probability $P$ of 0.01; the observed maximum $D$ between the Ca-rich hosts and the star-formation 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 star formation. 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.

It is useful, in the interests of increasing sample
size, to look at the host types of other SN20002cx-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), SN2011av (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 SN20002cx-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 star formation at the transient’s location and conclude that the progenitor is likely to be a WD. SN2008ge is further discussed in Sect. 6.

5.2 Transient locations and ongoing star formation

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

For the five Ca-rich transients in galaxies with detectable star formation, the mean NCR value is 0.259 (standard error on mean 0.119), range 0.000-0.626. Including the seven for which we have Hα imaging which reveals no star formation anywhere in the galaxy (including SN2010et which has no obvious host), and which all thus have NCR values of 0.000, this value falls to 0.108 (0.060).

The Ca-rich transient with the strongest apparent association with an HII 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 2008; 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 eleven SN2002cx-like transients, the mean NCR value is 0.222 (0.092), range 0.000 - 0.904. Remov-
Ca-rich and SN2002cx-like transients

Figure 4. The star-formation 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 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.

Figure 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 star formation. 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 \( \sim 27 \) per cent. With no star formation, any location in the host will have NCR = 0, so by adding 27 per cent to the SNeIa sample as NCR = 0 events, this will give an expected SNeIa distribution across all galaxy types. The number of CCSNe that have been observed in non-star-forming early type hosts is \( \sim 0 \), 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 star-formation 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 SNe of type II (including all sub-types 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 \( \sim 5 \) 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 eleven transients could have been drawn from any of the other distributions shown in Fig. 5. However, the distribution most closely approximates that of the type II-P SNe, and indeed, again considering the small number statistics, reproduces it well. The distribution of SN2002cx-like transients shows a stronger association to star formation 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).
6 DISCUSSION

Though the total rate of Ca-rich and SN2002cx-like transients might be significant compared to type Ia SNe, 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 difference come from the host galaxy populations analysis. All SN2002cx-like transients have host galaxies that display strong, recent star formation 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 star formation, 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 the SN2002cx-like transients are found in hosts that display ongoing star formation, we quantitatively find a good match between SN2002cx-like events and SNeII-P with respect to association with recent star formation 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 Myrs). From the NCR analysis we confirm that Ca-rich transients do not appear to follow recent star formation in their hosts and closely resemble the distribution of ‘normal’ SNeIa, whose progenitors are expected to have significant life times (∼ Gyrs).

The samples are, as mentioned previously, inherently eclectic and suffer many biases relative a volume-limited sample. Their fainter magnitudes compared to SNe in general would suggest that they will be difficult to detect on 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 on 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 star-formation, given it is plausible to miss some of these events if they are coincident with the brightest HII regions. The discovery magnitudes quoted in Tables 2 and 4 show there is no statistically significant difference between distribution of brightnesses in each sample, suggesting 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 a He-WD, was first suggested by Perets et al. (2010) and gained additional support from the theoretical analysis by Shen & Bildsten (2004) 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 Kashiwal et al.) would require a young, star-forming environment. Our Ho-based analysis of the hosts of the Ca-rich transients makes clear that the majority of these are occurring a very long way from any detectable star formation. This also strengthens the arguments of Perets et al. (2010) and Kashiwal et al. (2012) that even extremely high-velocity,

| SN Type        | No. | Mean  | Std. err. |
|----------------|-----|-------|-----------|
| Ca-rich        | 9   | 0.0741| 0.049     |
| Ca-rich        | 12  | 0.108 | 0.060     |
| Ia             | 98  | 0.1142| 0.019     |
| SN2002cx-like  | 11  | 0.222 | 0.092     |
| SN2002cx-like  | 10  | 0.2443| 0.099     |
| II-P           | 58  | 0.264 | 0.039     |
| Ib             | 39  | 0.318 | 0.045     |
| Ic             | 52  | 0.469 | 0.040     |

1 All edge-on hosts excluded.
2 Corrected for an assumed early-type fraction of 27 per cent; mean in star-forming hosts is 0.157.
3 Edge-on host excluded.
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 they originate from the deflagration of a Chandrasekhar mass C/O WD. This model encounters difficulties explaining the diversity of such events and in particular the extremely low-mass and sub-luminous SN2008ha event. A more recent and detailed model by Jordan et al. (2012; see also Calder et al. 2004; Livne et al. 2004; 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 type Ia SNe. 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☉ 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 type II-P SNe. The environmental constraints we find therefore do not exclude, but are less favorable 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 SN2002cx-like transients arise from a variant of CCSNe with low ejecta velocity, although currently no detailed theoretical modeling 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 star formation, a substantial fraction appear to outlive their natal HII 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☉ (with typical lifetimes of 30 – 50 Myrs) 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 star-formation/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 et al. 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 star formation (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 Myrs lifetime) through an association to star-formation that is similar to that displayed by type II-P SNe. Such young progenitors are less favorable to failed detonations of Chandrasekhar mass C/O WDs, and more consistent with either the core-collapse of a 7–9 M☉ star, or a WD explosion following the accretion of 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 can not yet be adequately compared with observations, beyond the generally consistent aspects of their expected environments as studied here.

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