Constraints on core-collapse supernova progenitors from correlations
with Hα emission

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ABSTRACT

We present observational constraints on the nature of the different core-collapse supernova (SN) types through an investigation of the association of their explosion sites with recent star formation (SF), as traced by Hα + [N II] line emission. We discuss results on the analysed data of the positions of 168 core-collapse SNe with respect to the Hα emission within their host galaxies.

From our analysis we find that overall the type II progenitor population does not trace the underlying SF. Our results are consistent with a significant fraction of SNII arising from progenitor stars of less than 10 M⊙. We find that the SNe of type Ib show a higher degree of association with H II regions than those of type II (without accurately tracing the emission), while the type Ic population accurately traces the Hα emission. This implies that the main core-collapse SN types form a sequence of increasing progenitor mass, from the type II, to Ib and finally Ic. We find that the type Ibn subclass display a similar degree of association with the line emission to the overall SNII population, implying that at least the majority of these SNe do not arise from the most massive stars. We also find that the small number of SN ‘impostors’ within our sample do not trace the SF of their host galaxies, a result that would not be expected if these events arise from massive luminous blue variable star progenitors.

Key words: supernovae: general – galaxies: general – galaxies: statistics.

1 INTRODUCTION

Despite years of observational and theoretical research on the nature of supernova (SN) explosions and the properties of their progenitors there remain substantial gaps in our knowledge of all SN types. Although there are many different theoretical predictions as to the nature of SN progenitors, the observational evidence to discriminate between various progenitor scenarios remains sparse. SNe can be split into two theoretical classes; SNIa which are thought to arise from the thermonuclear explosion of an accreting white dwarf, and core-collapse (CC) SNe which are believed to signal the collapse of the cores of massive stars at the end points in their stellar evolution.

Results from the first paper in this series (James & Anderson 2006, JA06 henceforth) suggested that the SNIb/c arise from higher mass progenitors than SNII (albeit with small statistics; only eight SNIb/c). We test these initial results with an increased sample size enabling us to distinguish between the various CC subtypes, and present results from a combined sample of 100 SNII (which can be further separated into 37 IIP, eight IIL, four Ibn, 12 Ifn), 62 SNIb/c (22 Ib, 34 Ic and six that only have Ib/c classification) and six SN ‘impostors’. We will present results and discussion of SNIa within the context of the methods used in this paper elsewhere. We will also present further research on the radial positions of SNe within galaxies, and on correlations between CC SN type and local metallicity in future publications. Here we concentrate on results on the progenitor masses of the different CC SNe.

1.1 Core-collapse supernovae

CC SNe are thought to be the final stage in the stellar evolution of stars with initial masses > 8–10 M⊙, when fusion ceases in the cores of their progenitors and they can no longer support themselves against gravitational collapse. The different types of CC SNe are classified according to the presence/absence of spectral lines in their early time spectra, plus the shape of their light curves. The first major classification comes from the presence of strong hydrogen (H) emission in the SNII. SN Ibn and Ic lack any detectable H emission, while the SN Ic also lack the helium lines seen in SN Ibn. SNII can
also be separated in various subtypes. SNIIP and IIL are classified in terms of the decline shape of their light curves (Barbon, Ciatti & Rosino 1979; plateau in the former and linear in the latter), thought to indicate different masses of their H envelopes prior to SN, while SNIIn show narrow emission lines within their spectra (Schlegel 1990), thought to arise from interaction of the SN ejecta with a slow-moving circumstellar medium (e.g. Chugai & Danziger 1994). SNIb are thought to be intermediate objects between the SNII and Ib as at early times their spectra are similar to SNII (prominent H lines), while at later times they appear similar to SNIb (Filippenko, Matheson & Ho 1993).

Strong evidence has been presented to support the belief that SNII and SNIb/c arise from massive progenitors, through their absence in early-type galaxies (van den Bergh, Li & Filippenko 2002), and the direct detection of a small sample of progenitors on pre-explosion images (Smartt et al. 2004; Maund, Smartt & Danziger 2005; Hendry et al. 2006; Li et al. 2006; Gal-Yam et al. 2007; Lie et al. 2007; Crockett et al. 2008). However, it is unclear how differences in the nature of their progenitors produce the different SNe we see. It is clear that there must be some process by which the progenitors of the different SNe lose part (or almost all in the case of SNIb and Ic) of their envelopes prior to explosion. The differences in efficiency of this mass-loss process could be dependent primarily on progenitor mass, with higher mass progenitors having higher mass-loss rates due to stronger stellar winds, and losing more of their envelopes. In this picture a sequence of SNe types emerges from SNIIP and IIL to SNIb, SNIb and finally Ic having successively higher initial masses. There are also other factors that probably play an important role. Initial chemical abundance will also affect the progenitor mass-loss, with higher metallicity producing stronger radiatively driven winds (e.g. Puls et al. 1996; Kudritzki & Puls 2000; Mokiem et al. 2007). It has also been proposed (Podsiadlowski, Joss & Hsu 1992) that massive binaries could produce a significant fraction of CC SNe, with mass transfer ejecting matter and leading to some of the various CC subtypes.

Since the theoretical separation of SNe into two distinct explosion classes by Hoyle & Fowler (1960), there have been many predictions as to how the different CC SN types emerge from different progenitors. There are two main theoretical routes to achieving the observed different SN types. The first attempts to describe the full range of SNe from a single star progenitor scenario. Heger et al. (2003) and Eldridge & Tout (2004) produced SN progenitor maps showing how variations in initial mass and metallicity produced the different CC SN types. These models both predict that single stars of up to ∼25–30 M⊙ will produce SNIb, with stars of slightly higher mass producing SNIIL and Ib, and those of >30 M⊙ ending their lives as SNIb/c (both authors also predict that these initial mass ranges will shift to higher values with decreasing metallicity). In both of these models no attempt was made to differentiate between the SNb and the SNc, but one would presume that within this single star scenario SNc would arise from higher mass progenitors than the SNb as they have lost even more of their stellar envelopes. Alternatively it could be that massive binaries produce the majority of CC SNe other than SNIIP (with these SNe still arising from single star progenitors). The initial mass of the stars producing SNIb/c, SNIIL and IIB would then be similar to those of SNIIP (12–20 M⊙, e.g. Shigeyama et al. 1990) but would arise from binary evolutionary processes. There is also a growing number of SNe that show evidence of binary (e.g. SN 1987A; Podsiadlowski, Joss & Rappaport 1990 and SN 1993J; Nomoto et al. 1993; Podsiadlowski et al. 1993; Maund et al. 2004). Recent comparisons of the observed ratio of SNIb/c rates to those of SNI also argue that binaries are playing the dominant role in producing SNIb/c (Kobulnicky & Fryer 2007), while Eldridge, Izzard & Tout (2008) predict an SNIb/c rate produced by a combination of single and binary progenitors that best produces the observed SN rate. Again one should note that these binary models group SNIb and Ic together and do not attempt to predict what differences in progenitor produce these two types.

Given the different predictions for the origin of the CC SN types described above, observations are needed to discriminate between these models and thus firmly tie down the progenitors of the different SN types. However, apart from a small number of direct detections of progenitors (Smartt et al. 2004; Maund et al. 2005; Hendry et al. 2006; Li et al. 2006; Gal-Yam et al. 2007; Li et al. 2007; Crockett et al. 2008) this observational evidence remains sparse. Therefore here we present results to test the above predictions and constrain differences in progenitor mass of the different CC SN subtypes by investigating the nature of their parent stellar populations within host galaxies.

1.2 Progenitor constraints from parent stellar populations

The most obvious way to determine the nature of SN progenitors is to investigate the properties of their stars on pre-explosion images. This has had some success although it is only possible for events in very nearby galaxies and therefore the statistics remain low. Another way is to investigate how the rates of the various SN types vary with different parameters, such as redshift or host galaxy properties. Our approach is intermediate to these methods as we attempt to constrain the nature of SN progenitors through investigating the environments and stellar populations at the positions of historical SNe. Here we concentrate on the association of the different CC SNe types with recent star formation (SF) as traced by Hα emission.

Kennicutt (1998) states in a review paper on Hα imaging techniques that ‘only stars with masses >10 M⊙ and lifetimes of <20 Myr contribute significantly to the ionizing flux’. Thus, if our understanding of this line emission is correct, we can use this assumption as a starting point to constrain the relative stellar lifetimes and therefore the relative masses of the various SN progenitors, through investigating how accurately the different SN types trace the emission. In JA06 we presented a statistic to quantitatively measure the association of individual SNe with the Hα emission of their host galaxies, and presented results from an initial galaxy sample (Ho/GS, discussed in Section 2). It was found that overall the SNII progenitor population did not trace the underlying SF of their host galaxies, with a significant fraction lying on regions of low or zero emission-line flux which were ascribed to a ‘runaway’ fraction of progenitor stars (however, this assumed that SNII arise from progenitors of >10 M⊙). The SNIb/c did appear to follow the emission implying that these progenitors come from higher mass stars than the SNII, although the statistics on this class were small (only eight SNe for SNIIb and Ic combined). This SN/galaxy sample has now been significantly increased, enabling the full parameter space of CC SN progenitors to be investigated and results from this increased sample are presented here.

The paper is arranged as follows. In the next section we present the data and discuss the reduction techniques employed, in Section 3 we summarize the statistic introduced in JA06 and used throughout this paper, in Section 4 we present the results for the different CC SN types, in Section 5 we discuss possible explanations for these results and their implications for the relative masses of the SN progenitors, and finally in Section 6 we draw our conclusions.
2 DATA

The initial galaxy sample that formed the data set for JA06 was the Hα Galaxy Survey (HαGS). This survey was a study of the SF properties of the local universe using Hα imaging of a representative sample of nearby galaxies, details of which can be found in James et al. (2004). 63 SNe (of all types, including SNIa) were found to have occurred in the 327 Hα GS galaxies through searching the International Astronomical Union (IAU) data base.1

Through three observing runs on the Isaac Newton Telescope (INT) and an ongoing time allocation with the Liverpool Telescope (LT) we have now obtained Hα imaging for the host galaxies of 133 additional CC SNe, the analysis of which is presented here. The LT is a fully robotic 2-m telescope operated remotely by Liverpool John Moores University. To obtain our imaging we used RATcam together with the narrow Hα and the broad-band Sloan r' filters. Images were binned 2 × 2 to give us 0.278 arcsec size pixels, and the width of the Hα filter enabled us to image target galaxies out to ∼2400 km s⁻¹. The INT observations used the Wide Field Camera (WFC) together with the Harris R-band filter, plus the rest-frame narrow Hα (filter 197) and the redshifted Hα (227) filters enabling us to image host galaxies out to ∼6000 km s⁻¹. During our 2005 INT observing run we also used the S filter (212) as a redshifted Hα filter and imaged 12 SN hosting galaxies at distances of ∼7500 km s⁻¹. The pixel scale on all INT images is 0.333 arcsec pixel⁻¹ and with both the LT and INT our exposure times were ∼800 s in Hα and ∼300 s in R.

These additional SNe/galaxies were chosen from the Padova–Asiago SN catalogue,2 as specific CC SN types were more complete for the listed SNe. At a later date all SN type classifications taken from the Padova–Asiago catalogue were checked through a thorough search of the literature and IAU circulars, as classifications can often change after the initial discovery and therefore those in the catalogue may not be completely accurate. The full list of SN types is given in Appendix B, where references are given if classifications were changed from those in the above catalogue. The main discrepancies were the classification of the so-called SN ‘impostors’ as SNII in the Padova–Asiago catalogue. These are transient objects that are believed to be the outbursts from very massive luminous blue variable (LBV) stars, which do not fully destroy the progenitor star and are therefore not classed as true SNe (e.g. van Dyk et al. 2000; Maund et al. 2006). Six such objects were found in our sample, and the results on these ‘impostors’ are presented and discussed separately in the following sections.

The distance limit for our sample (mainly set from the available Hα filters during observing runs) enables us to resolve the stellar population close to the SN position, and we also exclude edge on galaxies because of extinction effects and increased projection uncertainties. We do not include results on SNe where images were obtained within 18 months for SNII and a year for SNB/c after the catalogue explosion epoch. This is to ensure that our images are not contaminated with residual SN light and that the Hα emission that we detect is due to the underlying H II regions and not associated with the SNe themselves. Through the above telescope time allocations we have therefore obtained data on host galaxies of almost all discovered CC SNe (that have been classified IIP, IIL, Ib, IIn, Ib and Ic) that meet our selection criteria and were observable within the Hα filters of the two telescopes.

1 http://cfa-www.harvard.edu/iau/lists/Supernovae.html.
2 http://web.pd.astro.it/supern.

There are obvious biases within a set of data chosen in the above way. As we use any discovered SNe for our sample, the various different biases in the different SN surveys that discovered them mean that the galaxy/SN sample is by no means representative of the overall SN populations. Bright, well-studied galaxies will be over represented, as will brighter SNe events that are more easily detectable. However, firstly we are not analysing the overall host galaxy properties (as we will show when discussing the statistics we use in Section 3), but are analysing where within the distribution of stellar populations of the host galaxy the SNe are occurring. Secondly, the small number of CC subtypes that are discovered means that no individual survey can currently manage to analyse the properties of their host galaxies or parent stellar populations in any statistically significant way (most statistical observational studies do not even attempt to separate the Ib and Ic SN types). Taking our approach enables us to make statistical constraints on all the major CC SN subtypes. The results that are presented in this paper are on the analysis of the parent stellar populations of 100 SNII, of which 37 are IIP, eight IIL, four Ib and 12 IIn, six SN ‘impostors’, plus 22 Ib, 34 Ic and six that only have Ib/c as their classification, from both the initial Hα GS sample and our additional data described above.

2.1 Data reduction and astrometric methods

For each SN host galaxy we obtained Hα + [N ii] narrow-band imaging, plus R- and r'-band imaging used for continuum subtraction. Standard data reduction (flat-fields, bias subtraction, etc.) were achieved through the automated pipeline of the LT (Steele et al. 2004), and the INT data were processed through the INT WFC, Cambridge Astronomical Survey Unit (CASU) reduction pipeline. Continuum subtraction was then achieved by scaling the broad-band image fluxes to those of the Hα images using stars matched on each image, and subtracting the broad-band image from the Hα images. Our reduction made use of various Starlink packages.

The next process was to obtain accurate positions for the sites of our SNe on their host galaxy images. This astrometric calibration was achieved by transferring the accurate astrometry of XDSS second-generation Palomar Sky Survey images,3 on to matching galaxy images in our sample (the full process is described in JA06). In nearly all cases astrometric calibration was achieved with fit residuals of <0.2 arcsec. With accurate positions obtained for the SNe sites we could now analyse to what degree the different SNe were associated with the distribution of Hα emission within their host galaxies.

In Figs 1 and 2 we show two examples of Hα images of the host galaxies of SNe from our sample, with SN positions derived from the above astrometric calibration. We intend to present all our Hα and R-band imaging of SN host galaxies in a future publication (Ivory et al., in preparation), where we will release all of our data for public use along with host galaxy derived characteristics such as SF rates and Hα equivalent widths.

3 PIXEL STATISTICS

Previous works investigating the association of SNe with H II regions within host galaxies (e.g. Bartunov, Tsvetkov & Filimonova 1994; van Dyk, Hamuy & Filippenko 1996) have generally used some

3 Downloaded from http://cadcwww.dao.nrc.ca/cadcbin/getdss.
Another example negative continuum subtracted Hα emission in Fig. 1 and therefore having an NCR value of 0.000, whereas in Fig. 2 the SNII 2004bm falls on a bright H II region and therefore has a high NCR value of 0.704.

When we form the NCR it is found that the majority of values lying above the sky level within this distribution are small and individually contribute little to the overall flux, but by force of numbers they do contribute a significant amount to the underlying SF. Alongside this, there will be relatively few NCR values close to 1, but those that are will individually make a significant contribution to the overall flux. Thus the distribution is formed so that if an SN progenitor population is drawn from the same stellar population that produces the Hα flux, one would expect a mean NCR value for that SN type of 0.5 and a flat distribution. This is therefore the initial hypothesis that we work from, that if the progenitors of CC SNe trace the same high-mass SF as does Hα emission, we expect their NCR values to form a flat distribution. We can then investigate whether there are any differences in the mean NCR values and distributions of the different CC SN subtypes and what this may imply for differences in the relative lifetimes and masses of their progenitors.

A full discussion of the errors associated with this statistic was presented in JA06, therefore here we will summarize the main errors; those presented with the results are the statistical errors found on the various distributions. The most obvious error is that associated with the determination of the SN containing pixel. This was investigated by determining the NCR value of each SN for a 3 × 3 pixel box centred on the SN pixel (meaning that after already binning 3 × 3 we sample regions ∼2.5 and 3 arcsec on the LT and INT images, respectively). A comparison was then made of the median NCR value of the box with the SN pixel. This was repeated for the new sample where we find the size of the errors to be consistent with those from JA06, and there are in general no significant differences between the SN pixel NCR values and those of the median value of the surrounding pixels. For the overall SNII NCR distribution we find a mean difference of 0.027 between the NCR value of the SN pixel and the median pixel. The rms difference in NCR value is 0.163 where, as in JA06 this is dominated by around five cases where there is a significant difference between the values. However, overall the NCR analysis seems to give results which are robust to positional errors of 1–2 arcsec. In JA06 possible errors due to the adopted sky level were investigated but these were found to be insignificant. Finally, a Monte Carlo analysis was performed on the effects of pixel-to-pixel noise on the NCR value. Again this effect was found to be small, with errors appearing to be random and producing no tendency to bias the results in any particular direction. We will now present the results formed from using the above described statistic on the various CC SN types.
4 RESULTS

4.1 SNII

Fig. 3 shows the overall distribution of NCR values for the 100 SNII in our sample. It is immediately clear that the positions of SNII do not follow the overall distribution of SF as traced by the Hα line emission, confirming the result of JA06. In fact there is an excess of \( \sim 35 \) per cent of SNII that fall on sites of little or zero Hα flux compared to what would be expected if these SNe followed the distribution of Hα emission. The probability of the SNII progenitor population being drawn from a flat distribution (i.e. following the line emission), calculated using a Kolmogorov–Smirnov (KS) test is \(< 1\) per cent. Overall the mean NCR value for SNII is 0.252 with a standard error on the mean of 0.027. We will now present the results obtained when separating the SNII into their various subtypes. It should be noted here that \( \sim 40 \) per cent of our type II SNe do not have designated subtypes and are only classified as SNII.

4.1.1 SNIIP

SNIIP are the most abundant SNII subtype observed and therefore it is not surprising that these are the most abundant of those with subtype classification in our sample. It is also to be expected that their distribution of NCR values follows that of the overall SNII population as can be seen when comparing Figs 3 and 4, with a KS test showing that the two distributions (SNe classified as IIP removed from the overall II distribution) are formally consistent with each other. Again, if one assumes that the majority of those unclassified SNII will be of type IIP (i.e. if sufficient data were available on their light curves etc.), this is to be expected. The mean NCR value for the SNIIP population is 0.263 (0.048).

4.1.2 SNIIL

The eight SNIIL population have a mean NCR value of 0.255 (0.112) and seem to follow the same distribution as the overall SNII population.

4.1.3 SNIIb

The four SNIIb have a mean NCR value of 0.460 (0.162), higher than that of the overall SNII population. To measure the significance of this difference we used a Monte Carlo analysis. Removing the SNIIb from the distribution of SNII NCR values we calculated the fraction of times that a mean NCR value of \( \geq 0.460 \) (SNIIb mean value) was produced when four values were drawn at random from the overall SNII distribution. We found that there is only a \( \sim 6 \) per cent chance that the SNIIb parent population is drawn from the same distribution as that of the rest of the SNII.

4.1.4 SNIIn

Fig. 5 shows the distribution of the NCR values for the 12 SNIIn. The mean NCR value for this SN type is 0.256 (0.088), and these SNe seem to follow the same stellar population as that of the overall SNII population. Using a KS test we find that there is only a \( \sim 1 \) per cent chance that these SNe are drawn from a flat distribution (i.e. following the distribution of Hα emission).

4.2 SNIIb/c

The distribution of NCR values for the 62 SNIIb/c is plotted in Fig. 6. Overall the mean NCR value of these SNe is 0.421 (0.040) and these SNe are formally consistent with being drawn from the same distribution as that traced by the Hα emission, while there is \(< 1 \) per cent chance that they arise from the same parent distribution as the SNII. We have presented the results for this overall SNIIb/c group to make comparisons to the overall SNII progenitor population (as is often quoted elsewhere); however, it is clear that in fact the results for each separate group (Ib, Ic) differ as we will now discuss.
4.2.1 SNIb

Fig. 7 shows the distribution of NCR values for the SNIb population; this SN type has a mean NCR value of 0.367 (0.063). The probability of this SN class being drawn from a flat distribution is >10 per cent. We compare this population with that of the SNII and find that although the mean NCR value for the SNIb is higher than that of the SNII, using a KS test they are formally consistent with being drawn from the same progenitor population (>10 per cent chance that they arise from the same distribution).

4.2.2 SNIc

The distribution of NCR values for the SNIc is shown in Fig. 8. This is the SN type that shows the highest degree of association to the recent SF in host galaxies, as traced by Hα emission and the population has a mean NCR of 0.447 (0.057). A KS test shows that these SNe are formally consistent with being drawn from a flat distribution, but there still seems to be a slight excess at zero NCR values. When compared to the overall SNII distribution we find a <1 per cent chance that they are drawn from the same distribution. When we compare these SNe to the SNIb we find that they have a significantly higher mean value; however, there is still a >10 per cent chance that they are drawn from the same parent distribution.

4.3 SN ‘impostors’

The mean NCR value for the six SN ‘impostors’ is 0.105 (0.065), considerably lower than that of the SNII population. To measure the significance of this difference we used a Monte Carlo analysis as for the SNIib. We calculated the fraction of times that a mean NCR value of ≤0.105 (SN ‘impostors’ mean value) was produced when six values were drawn at random from the overall SNII NCR distribution. We found that there is a ~10 per cent chance that the SN ‘impostors’ are drawn from the same distribution as that of the SNII.

5 DISCUSSION

There are two main discussion points that arise from the above results. The first is that there is a real excess seen in the number of SNII that do not appear to show any association to the Hα emission, a result that was seen in JA06 and is backed up with the improved statistics presented within this paper. The second is the implications that differences in NCR values and distributions of the various CC SN types have on differences between their progenitor masses. If we assume that all stars originate within H II regions (the highest mass stars formed from an episode of SF will start to ionize the local hydrogen straight away), then the degree of association of each SN type with the overall emission can be used to constrain their relative stellar lifetimes (and therefore their relative initial masses), as with time, the stars will either move away from the host H II region due to their peculiar velocities, or the host H II region will cease to exist as the massive ionizing stars will explode as the first set of SNe. Therefore we discuss the implications of our results for the different masses of the different CC types and how these implications fit with other results on the nature of the different SN progenitors.

5.1 An excess of SNII from regions of zero Hα emission

The results presented in Section 4.1 indicate that around ~35 per cent of SNII fall on sites of little or zero Hα flux, compared to what would be expected if these SNe followed the underlying SF. For the SNIIP where we have 37 events in our sample this fractional excess remains the same. Recent research combining the results of a 10-yr survey for direct detections of SN progenitors (Smartt et al. 2008; private communication) gives additional support to the growing evidence that CC SNe (SNIIP in particular) can arise from stars with initial masses of less than 10 M⊙. One of the main results from this survey is a lower mass value for producing SNIIP of ~8.5 M⊙. Using the initial assumption for the current research that only stars with masses >10 M⊙ contribute significantly to producing Hα emission we can then compare our statistics to this mass value.
mass limit for red supergiants; Levesque et al. 2007), we can calculate the range from 10 M\(_{\odot}\) downwards (in progenitor mass) that is consistent with our statistics of \(\sim 35\) per cent of SNII falling on sites of little or zero H\(_{\alpha}\) emission. From these assumptions we calculate a lower mass value for producing SNII (and also the IIP subtype) of 7.8 M\(_{\odot}\), consistent with that suggested by direct detections. Our results therefore seem to suggest that a significant fraction of SNII are produced by progenitor stars of less than 10 M\(_{\odot}\).

JA06 discussed alternative explanations to the fact that we find a significant fraction of SNII falling on sites of zero H\(_{\alpha}\) flux. These assumed that CC SNe arise from stars of initial mass \(> 10 M_{\odot}\). Although as stated above there is growing evidence for the production of CC SNe from stars below 10 M\(_{\odot}\), the number of events used to make these constraints are still reasonably small and many stellar evolution codes predict CC from stars only of 10 M\(_{\odot}\) or higher (e.g. Ritossa, Garcia-Berro & Iben 1999). Here we therefore summarize a number of other physical processes that may be at play in producing the excess of SNII that we find occurring away from sites of recent SF.

In JA06 we discussed the ‘runaway’ hypothesis, that these SNe did originally form within an H\(_{\alpha}\) region but since moved to the position of the SN between stellar birth and death, due to some peculiar velocity. Another possibility is the destruction of massive clusters before the epoch of SN. Recent observations and simulations (Bastian & Goodwin 2006; Goodwin & Bastian 2006) have shown that many massive stellar clusters will in fact be destroyed on time-scales of \(\sim 10\) Myr. Within the stellar cluster stars with the highest mass will explode as SNe first, thus exploding while the clusters are still stable and hence will be found to be associated with the H\(_{\alpha}\) emission produced from the ionization of the local gas. These initial SNe (likely to be SNIIc and Ib, see the next section) will drive the removal of gas from the cluster eventually leading to its destruction. Therefore within this scenario there are two possible processes that could lead to our result. First, with gas removal from the system it may be that there is little gas to be ionized and therefore no host H\(_{\alpha}\) region will be seen at the site of some SNII. Secondly, as the cluster is destroyed while it attempts to regain virial equilibrium, many stars will be flung away with a high peculiar velocity leaving them far from their original host H\(_{\alpha}\) region.

Another explanation that was discussed in JA06 is the possibility that these SNe are occurring in regions of dust content, through which the SNe are visible but the H\(_{\alpha}\) emission is not. However, it is unclear why this would affect the SNII much more than the SNIIc/b. It has also been found, through mid-infrared (mid-IR) observations of the SINGS survey, that highly obscured SF regions only seen in the IR make up only a small (~4 per cent) fraction of the overall SF distribution in nearby galaxies (Prescott et al. 2007), arguing against this as a significant factor.

We conclude that the dominant effect producing our results on the association of SNII to the H\(_{\alpha}\) emission of their host galaxies is that a significant fraction of SNII progenitors are stars with initial masses below 10 M\(_{\odot}\). However, we also believe that it is likely that all the processes we discuss above play some part in producing the observed NCR distribution. We have discussed the various processes that could be involved in shaping the results that we see; now we will explore how we can use these results to compare and constrain the nature of the different progenitors of the different CC SN types.

### 5.2 Relative progenitor masses

From the arguments presented at the start of this section we can use comparisons of the mean NCR values of the different SN types to compare the relative mass ranges of their progenitors. The first conclusion is that we confirm the results of JA06 that overall the SNIIc/b progenitor population arise from more massive progenitors than the SNII. When we compare the CC SN subtypes in detail we find that the different CC subtypes appear to form a sequence of increasing progenitor mass, going from SNII at the low-mass end, through SNIIb to SNIIc as the highest mass progenitors. This sequence is illustrated in Fig. 9. In this figure we plot the cumulative distributions of the NCR values of the overall SNII, the SNIIb/c and the SNIIb and Ic distributions individually. We also plot a hypothetical distribution for a population that exactly traces the line emission. The plot shows that the SNIIc accurately traces the H\(_{\alpha}\) emission, except for a slight excess of NCR values at zero. As we go to the other SN distributions we see that they show an increasingly lower association to the line emission. A distinctive pattern emerges as indicated by the arrows on the plot, going from high to lower and lower mass progenitors implied from the differences between the distributions and the hypothetical flat distribution. This sequence can be seen to fit to the paradigm where CC SNe (II, Ib, then Ic) arise from stars of increasingly higher initial mass, leading to stronger pre-SN stellar winds that strip the stars of their envelopes and produce the observed differences we see in their spectra.

With the statistics presented in Section 4 it is harder to make any firm statements as to differences within the progenitor masses of the various SNII subtypes. However, with the small number of SNII as a strong caveat, it seems that these SNe arise from similar mass progenitors to the SNIIP. This would imply that that metallicity or binarity may play a dominant role in deciding SN type, by enabling additional envelope stripping prior to explosion.

With respect to the SNIIb, although we only have four objects in our sample our results suggest that these SNe arise from more massive progenitors than the overall SNII population. They also show a higher degree of association to the H\(_{\alpha}\) emission than the SNIIb (although again we stress the low statistics involved). A recent
discovery of the progenitor of a Ib SN (Crockett et al. 2008) has suggested a possible progenitor mass of 28 M⊙, consistent with our result that these SNe arise from towards the high end of the CC SN progenitor sequence. The only other direct detection of an SNIIb progenitor is that of SN 1993J. Maund et al. (2004) estimated that this SN arose from a interacting binary with components of 14 and 15 M⊙ stars. Again our result that SNIIb arise from stars that follow the Hα emission of their host galaxies is consistent with this result.

One of the most interesting results to arise from this paper regards the SNIIb. Our results (see Section 4.1.4) suggest that these SNe arise from similar mass progenitors to the overall SNII population and do not follow the underlying Hα emission of their host galaxies. This would seem to be in conflict with recent thoughts on this SN type. Arguments have been put forward (e.g. Smith 2008, and references therein) that the observations of these SNe (strong narrow emission lines and high luminosities) require high pre-SN mass-loss rates and huge circumstellar envelopes, arising from only the most massive stars, which would presumably trace the Hα emission within galaxies. It has also been argued that two SNIIb, (2005gl and 2005gi) had LBV progenitors (Gal-Yam et al. 2007; Trundle et al. 2008, respectively), again stars of very high mass (∼25−40 M⊙ and above). Although some SNIIb probably do arise from very massive stars, our results suggest that the majority of these events arise from progenitors towards the low end of the CC progenitor mass range. A recent direct detection of the progenitor of the SNIIb 2008S on pre-explosion Spitzer mid-IR images (Prieto et al. 2008), enabled an estimate to be made of the progenitor mass of ∼10 M⊙ consistent with our results (however, there is some debate as to whether this is a true SN and it is unlike most other SNIIb; Smartt, private communication). An intriguing possibility for progenitors from this mass range would be the super-AGB stars (SAGBs), a scenario suggested by the modelling of Poelarends et al. (2008). The initial mass range for SAGB evolution is 7.5−9.25 M⊙ and it is thought that the upper mass part of this range will produce electron-capture (EC) SNe (Poelarends et al. 2008). The mass-loss rates of these systems can be extremely high due to a large number of thermal pulses, potentially producing the capacity for interaction of the SN with a large amount of circumstellar material, and hence the narrow emission lines seen in SNIIb.

SN ‘impostors’ are thought to be the outbursts of very massive unstable LBV stars (van Dyk et al. 2000; Maund et al. 2006) that go through stages of intense mass-loss, during which the luminosity of such objects can rise by more than 3 mag (see Humphreys & Davidson 1994, for a review on this subject), hence masquerading as ‘true’ SNe. Given the presumed high-mass nature of these events (and therefore their relatively short stellar lifetimes) one would expect these events to trace the distribution of high-mass SF within their host galaxies. However, our results presented in Section 4.3 would seem to be inconsistent with this picture. We find that the SN ‘impostors’ within our sample do not trace the underlying SF and in fact show the lowest degree of association of all SN types analysed in the current paper. We stress again here that there are only six such events within our sample and it is therefore hard to draw any firm conclusions before the statistics are improved. We note however that many LBVs observed in the Local Group are often more isolated than one would expect and are not always found within dense young stellar clusters (Burggraf, Weis & Bomans 2006).

6 CONCLUSIONS

We find that there is a significant fraction of the SNII population that do not show any association to the distribution of Hα line emission. This excess of ∼35 per cent of SNII falling on sites of little or zero Hα flux, compared to what would be expected if they accurately traced the underlying SF, suggests that a large fraction of SNII arise from progenitor stars of less than 10 M⊙. Our results also imply that the different CC SN types can be separated into a sequence of increasing progenitor mass running from the SNII through the Ib, with finally the SNIIc arising from the highest mass progenitors. We now summarize our findings on the possible relative mass ranges of the progenitors of the different CC SN types.

(i) Assuming that only stars of 10 M⊙ and above significantly contribute to the ionizing flux that produces Hα emission within galaxies, we calculate a lower mass limit for producing SNII of 7.8 M⊙.
(ii) We confirm the results of JA06, that the SNIIb/c trace the SF of their host galaxies more accurately than the SNII, implying that they arise from a higher mass progenitor population than the SNII.
(iii) SNIIc accurately traces the underlying SF within their host galaxies and therefore probably arise from the highest mass progenitors of all SNe.
(iv) SNIIb show a similar degree of association to Hα emission as the overall SNII population implying that they arise from stars of similar mass to those of SNIIb, with metallicity or binarity probably playing an important role in removing part of their envelopes and thus changing the shape of their light curves.
(v) Our results suggest that SNIIb arise from more massive stars than the overall SNII population.
(vi) Although some SNII may arise from very massive stars, our results suggest that the majority come from the low end of the CC mass spectrum.
(vii) SN ‘impostors’ do not seem to trace the high-mass SF within host galaxies.

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REFERENCES

Barbon R., Ciatti F., Rosino L., 1979, A&A, 72, 287
Bartunov O. S., Tsvetkov D. Y., Filimonova I. V., 1994, PASP, 106, 1276
Bastian N., Goodwin S. P., 2006, MNRAS, 369, L9
Burggraf B., Weis K., Romans D. J., 2006, in Lamers H. J. G. L. M., Langer N., Nugis T., Annuk K., eds, ASP Conf. Ser. Vol. 353, LBVs in M33: Their Environments and Ages. Stellar Evolution at Low Metallicity: Mass Loss, Explosions, Cosmology. Astron. Soc. Pac., San Francisco, p. 245
Burke J., Pugh H., Li W., Puckett T., Cox L., 2005, IAU Circ., 8504, 2
Chugai N. N., Danziger I. J., 1994, MNRAS, 268, 173
Crockett R. M. et al., 2008, ArXiv e-prints, 805
Eldridge J. J., Tout C. A., 2004, MNRAS, 353, 87
Eldridge J. J., Izzard R. G., Tout C. A., 2008, MNRAS, 384, 1109
Filippenko A. V., 1993, BAAS, 25, 819
Filippenko A. V., Matheson T., Ho L. C., 1993, ApJ, 415, L103
Gal-Yam A. et al., 2007, ApJ, 656, 372
Ganeshalingam M., Graham J., Pugh H., Li W., 2003, IAU Circ., 8134, 1
Gaskell C. M., Cappellaro E., Dinerstein H. L., Garnett D. R., Harkness R. P., Wheeler J. C., 1986, ApJ, 306, L77
Goodrich R. W., Stringfellow G. S., Penrod G. D., Filippenko A. V., 1989, ApJ, 342, 908
Goodwin S. P., Bastian N., 2006, MNRAS, 373, 752
Hamuy M., 2003, ApJ, 582, 905
Heger A., Fryer C. L., Woosley S. E., Langer N., Hartmann D. H., 2003, ApJ, 591, 288
Hendry M. A. et al., 2006, MNRAS, 369, 1303
Hoyle F., Fowler W. A., 1960, ApJ, 132, 165
Humphreys R. M., Davidson K., 1994, PASP, 106, 1025
James P. A., Anderson J. P., 2006, A&A, 453, 57 (JA06)
James P. A. et al., 2004, A&A, 414, 23
Kemmecutt R. C. J., 1998, ARA&A, 36, 189
Kobulnicky H. A., Fryer C. L., 2007, ApJ, 670, 747
Kudritzki R.-P., Puls J., 2000, ARA&A, 38, 613
Levesque E. M., Massey P., Olsen K. A. G., Plez B., 2007, ApJ, 667, 202
Li W., Van Dyk S. D., Filippenko A. V., Cuillandre J.-C., Jha S., Bloom J. S., Riess A. G., Livio M., 2006, ApJ, 641, 1060
Li W., Wang X., Van Dyk S. D., Cuillandre J.-C., Foley R. J., Filippenko A. V., 2007, ApJ, 661, 1013
Matheson T., Calkins M., 2001, IAU Circ., 7597, 3
Matheson T., Jha S., Challis P., Kirshner R., Berlind P., 2001a, IAU Circ., 7756, 4
Matheson T., Jha S., Challis P., Kirshner R., Calkins M., 2001b, IAU Circ., 7583, 2
Maund J. R., Smartt S. J., Kudritzki R. P., Podsiadlowski P., Gilmore G. F., 2004, Nat, 427, 129
Maund J. R., Smartt S. J., Danziger I. J., 2005, MNRAS, 364, L33
Maund J. R. et al., 2006, MNRAS, 369, 1303
Mazzali P. A., Deng J., Maeda K., Nomoto K., Filippenko A. V., Matheson T., 2004, ApJ, 614, 858
Mokiem M. R. et al., 2007, A&A, 473, 603
Nomoto K., Suzuki T., Shigeyama T., Kurosaki K., Yamaoka H., Saio H., Sollima A. et al., 2007, A&A, 473, 603
Nomoto K., Suntzeff N. B., Dilday B., 2006, ApJ, 641, 21
Owen D. R., Ryan J. T., 2001, AJ, 122, 2753
Pastorello A. et al., 2004, MNRAS, 347, 74
Podsiadlowski P., Joss P. C., Rappaport S., 1990, A&A, 227, L9
Podsiadlowski P., Joss P. C., Su J. J. L., 1992, ApJ, 391, 246
Podsiadlowski P., Hsu J. J. L., Joss P. C., Ross R. R., 1993, Nat, 364, 509
Poelarends A. J. T., Herwig F., Langer N., Heger A., 2008, ApJ, 675, 614
Prescott K. M. E. et al., 2007, ApJ, 668, 182
Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, Numerical Recipes in FORTRAN, The Art of Scientific Computing, 2nd edn. Cambridge Univ. Press, Cambridge, c1992
Prieto J. L. et al., 2008, ApJ, 681, L9
Puls J. et al., 1996, A&A, 305, 171
Ritossa C., García-Berro E., Iben I. J., 1999, ApJ, 515, 381
Schlegel E. M., 1990, MNRAS, 244, 269
Shigeyama T., Nomoto K., Tsujimoto T., Hashimoto M.-A., 1990, ApJ, 361, L23
Smartt S. J., Maund J. R., Hendry M. A., Tout C. A., Gilmore G. F., Mattila S., Benn C. R., 2004, Sci, 303, 499
Smartt S. J., Eldridge J. J., Crockett R. M., Maund J. R., 2008, preprint (arXiv:0809.0403)

Smith N., 2008, in IAU Symp. 250, Episodic Mass Loss and Pre-SN Circumstellar Envelopes, p. 193
Steele I. A. et al., 2004, in Ochsmann J. M. Jr, ed., Proc. SPIE, Vol. 5489, Ground-based Telescopes, p. 679
Trundle C., Kotak R., Vink J. S., Meikle W. P. S., 2008, A&A, 483, L47
Tsvetkov D. Y., 1994, Astron. Lett., 20, 374
van den Bergh S., Li W., Filippenko A. V., 2002, PASP, 114, 820
van Dyk S. D., 1992, AJ, 103, 1788
van Dyk S. D., Hamuy M., Filippenko A. V., 1996, AJ, 111, 2017
van Dyk S. D., Peng C. Y., King J. Y., Filippenko A. V., Treffers R. R., Li W., Richmond M. W., 2000, PASP, 112, 1532
van Dyk S. D., Filippenko A. V., Chornock R., Li W., Challis P. M., 2005, PASP, 117, 553

APPENDIX A: APPLICATION OF THE KOLMOGOROV–SMIRNOV TEST TO THE SN DATA

In this appendix we highlight a feature of commonly used implementations of the KS test, which caused particular problems for the analysis presented in this paper. These tests were implemented using the online statistics calculator at http://www.physics.csbsju.edu/stats/KS-test.html but identical results were found with a direct implementation of the KSTWO code from ‘Numerical Recipes’ (Press et al. 1992).

The problems were noted when we initially found apparently significant differences between distributions of NCR values that to the eye appeared quite similar. The D statistic, parametrizing the maximum difference between pairs of normalized cumulative distributions, was for some tests found to be significantly overestimated. It appears that this occurs for those distributions with significant numbers of points with identical values (which for our NCR distributions, was for some tests found to be significantly overestimated. The sceptical reader can quickly test this, using the above web site, and the following points as input:

0.01, 0.23, 0.32, 0.40, 0.40, 0.40, 0.40, 0.51, 0.59, 0.63, 0.67, 0.73.

Paste these numbers once into one of the data entry boxes, and twice into the other, to give samples with identical normalized cumulative distributions, but different overall sizes. This results in an estimated D of 0.1667, in spite of the identical cumulative distributions. The overestimate of D appears strongly dependent on the number of identical points (large ‘steps’ in the cumulative distribution), which are a particular feature of our data sets, but will certainly affect some other applications.

This does not appear to be a generally appreciated problem. We advocate careful checking of the D value produced by KS software against an accurate plot of the normalized cumulative distributions, to ensure that it is a real difference, and not an artefact caused by steps in the distributions.
Table B1. Data for all SNe and host galaxies: columns 1 and 2 give the SN and host galaxy, respectively. In columns 3 and 4 we present the morphological type and recession velocities of the host galaxies (both taken from NED). In column 5 the SN types are listed and the NCR data for each SN are given in column 6. In column 7 the telescope used for imaging of the SN host galaxy is given and for SNe where type classification was changed from those given in the Asiago catalogue a reference for the new designated type is given in the final column, and these type classifications are marked with an asterisk.

| SN     | Host galaxy | Galaxy type | \(V_r\) (km s\(^{-1}\)) | SN type | NCR value | Telescope | Reference          |
|--------|-------------|-------------|--------------------------|---------|-----------|-----------|-------------------|
| 1917A  | NGC 6946    | SABcd       | 48                       | II      | 0.207     | INT       |                   |
| 1921B  | NGC 3184    | SABcd       | 592                      | II      | 0.000     | INT       |                   |
| 1926A  | NGC 4303    | SABbc       | 1566                     | II      | 0.078     | INT       |                   |
| 1937F  | NGC 3184    | SABcd       | 592                      | II      | 0.000     | INT       |                   |
| 1940B  | NGC 4725    | SABab       | 1206                     | II      | 0.000     | INT       |                   |
| 1941C  | NGC 4136    | SAbc        | 487                      | II      | 0.000     | INT       |                   |
| 1941A  | NGC 4559    | SAbc        | 816                      | II      | 0.859     | INT       |                   |
| 1948B  | NGC 6946    | SABcd       | 48                       | IIP     | 0.387     | INT       |                   |
| 1954A  | NGC 4214    | IABm        | 291                      | Ic      | 0.000     | INT       |                   |
| 1954C  | NGC 5879    | Sa          | 372                      | II      | 0.163     | JKT       |                   |
| 1954J  | NGC 2403    | SABcd       | 131                      | 'impostor*' 0.187 | INT       | van Dyk et al. (2005) |
| 1961V  | NGC 1058    | SAbc        | 518                      | II      | 0.365     | INT       | Goodrich et al. (1989) |
| 1961U  | NGC 3938    | SAbc        | 789                      | II      | 0.000     | LT        |                   |
| 1961I  | NGC 4303    | SABbc       | 1566                     | II      | 0.327     | INT       |                   |
| 1962L  | NGC 1073    | SAbc        | 1208                     | Ic      | 0.000     | JKT       |                   |
| 1964H  | NGC 7292    | IBm         | 986                      | II      | 0.059     | JKT       |                   |
| 1964A  | NGC 3631    | SAbc        | 1156                     | II      | 0.000     | INT       |                   |
| 1964F  | NGC 4303    | SABbc       | 1566                     | II      | 0.000     | INT       |                   |
| 1964L  | NGC 3938    | SAbc        | 809                      | Ic      | 0.000     | LT        |                   |
| 1965H  | NGC 4666    | SAbc        | 1529                     | IIP     | 0.597     | LT        |                   |
| 1965N  | NGC 3074    | SAbc        | 5144                     | IIP     | 0.031     | INT       |                   |
| 1965L  | NGC 3631    | SAbc        | 1156                     | IIP     | 0.001     | INT       |                   |
| 1966B  | NGC 4688    | SBCd        | 986                      | IIL     | 0.367     | LT        |                   |
| 1966J  | NGC 3198    | Sbc         | 663                      | Ib      | 0.000     | INT       |                   |
| 1967H  | NGC 4254    | Sa          | 2407                     | II      | 0.368     | INT       | van Dyk (1992)    |
| 1968V  | NGC 2276    | SAbc        | 2410                     | II      | 0.327     | JKT       |                   |
| 1968D  | NGC 6946    | SABcd       | 48                       | II      | 0.018     | INT       |                   |
| 1969L  | NGC 1058    | Sa          | 518                      | IIP     | 0.000     | JKT       |                   |
| 1969B  | NGC 3556    | SBCd        | 699                      | IIP     | 0.191     | INT       |                   |
| 1971S  | NGC 493     | SABcd       | 2338                     | IIP     | 0.174     | JKT       |                   |
| 1971K  | NGC 3811    | SBCd        | 3105                     | IIP     | 0.176     | INT       |                   |
| 1972Q  | NGC 4254    | Sa          | 2407                     | IIP     | 0.405     | INT       |                   |
| 1972R  | NGC 2841    | SAb         | 638                      | Ib      | 0.071     | INT       |                   |
| 1973R  | NGC 3627    | SAbb        | 727                      | IIP     | 0.325     | INT       |                   |
| 1975T  | NGC 3756    | SAbbc       | 1318                     | IIP     | 0.000     | INT       |                   |
| 1979C  | NGC 4321    | SABbc       | 1571                     | IIL     | 0.000     | LT        |                   |
| 1980K  | NGC 6946    | SABcd       | 48                       | IIL     | 0.007     | INT       |                   |
| 1982F  | NGC 4490    | Sbd         | 565                      | IIP     | 0.095     | INT       |                   |
| 1983I  | NGC 4051    | SAbbc       | 700                      | Ic      | 0.265     | JKT       |                   |
| 1984E  | NGC 3169    | Saa         | 1238                     | IIL     | 0.616     | INT       |                   |
| 1985L  | NGC 5033    | Sa          | 875                      | IIL     | 0.301     | INT       |                   |
| 1985G  | NGC 4451    | Sbc         | 864                      | IIP     | 0.641     | INT       |                   |
| 1985F  | NGC 4618    | Sbc         | 544                      | Ib*     | 0.854     | LT        | Gaskell et al. (1986) |
| 1986I  | NGC 4254    | Sa          | 2407                     | IIP     | 0.000     | INT       |                   |
| 1987K  | NGC 4651    | Sa          | 805                      | Ib      | 0.746     | JKT       |                   |
| 1987F  | NGC 4615    | Scd         | 4716                     | IIn     | 0.352     | INT       |                   |
| 1987M  | NGC 2715    | SAbc        | 1339                     | Ic      | 0.000     | INT       |                   |
| 1988L  | NGC 5480    | Sa          | 1856                     | Ib      | 0.425     | LT        |                   |
| 1989C  | UGC 5249    | Sbd         | 1874                     | IIP     | 0.689     | LT        |                   |
| 1990E  | NGC 1035    | Sa          | 1241                     | IIP     | 0.000     | LT        |                   |
| 1990H  | NGC 3294    | Sa          | 1586                     | IIP*    | 0.000     | INT       | Filippenko (1993)  |
| 1990U  | NGC 7479    | Sbc         | 2381                     | Ic      | 0.712     | JKT       |                   |
| 1991G  | NGC 4088    | SABBbc      | 757                      | IIP     | 0.066     | JKT       |                   |
| 1991N  | NGC 3310    | SABbc       | 993                      | Ic      | 0.759     | JKT       |                   |
Table B1 – continued

| SN     | Host galaxy | Galaxy type | $V_r$ (km s$^{-1}$) | SN type | NCR value | Telescope | Reference             |
|--------|-------------|-------------|---------------------|---------|-----------|-----------|-----------------------|
| 1991A  | IC 2973     | SBd         | 3210                | Ic      | 0.773     | INT       |                       |
| 1992C  | NGC 3367    | Sbc         | 3040                | II      | 0.021     | INT       |                       |
| 1993X  | NGC 4736    | SAbc        | 2410                | II      | 0.039     | JKT       |                       |
| 1993G  | NGC 3690    | Double system | 3121   | III*     | 0.064     | INT       | Tsvetkov (1994)       |
| 1994I  | NGC 5194    | SAbc        | 463                 | Ic      | 0.550     | INT       |                       |
| 1994Y  | NGC 5371    | SABbc       | 2558                | IIn     | 0.000     | INT       |                       |
| 1994ak | NGC 2782    | SABA        | 2543                | IIn     | 0.000     | LT        |                       |
| 1995F  | NGC 2726    | SAbc        | 2140                | Ic      | 0.548     | JKT       |                       |
| 1995N  | MCG−02−38−17| IBm         | 1481                | II      | 0.660     | JKT       |                       |
| 1996ae | NGC 5775    | Sb          | 1681                | IIn     | 0.747     | JKT       |                       |
| 1996ak | NGC 5021    | SBb         | 8487                | II      | 0.562     | INT       |                       |
| 1996aq | NGC 5584    | SABcd       | 1638                | Ic      | 0.050     | LT        |                       |
| 1996bu | NGC 3631    | SAc         | 1156                | IIn     | 0.000     | INT       |                       |
| 1997bs | NGC 3627    | SABB        | 727                 | ‘impostor’* | 0.023     | INT       | van Dyk et al. (2000) |
| 1997db | UGC 11861   | SABdm       | 1481                | II      | 0.029     | JKT       |                       |
| 1997dn | NGC 3451    | Sd          | 1334                | II      | 0.073     | JKT       |                       |
| 1997dq | NGC 3810    | SAc         | 993                 | Ic*     | 0.296     | JKT       | Mazzali et al. (2004) |
| 1997eg | NGC 5012    | SABc        | 2619                | IIn     | 0.338     | INT       |                       |
| 1997X  | NGC 4791    | SBO/a       | 1110                | Ic      | 0.323     | INT       |                       |
| 1997ci | NGC 3963    | SABbc       | 3188                | Ic      | 0.288     | INT       |                       |
| 1998C  | UGC 3825    | SABbc       | 8281                | II      | 0.000     | INT       |                       |
| 1998T  | NGC 3690    | Double system | 3121   | Ib      | 0.578     | INT       |                       |
| 1998Y  | NGC 2415    | I?          | 3784                | II      | 0.349     | INT       |                       |
| 1998cc | NGC 5172    | SABbc       | 4030                | Ib      | 0.331     | INT       |                       |
| 1999D  | NGC 3690    | Double system | 3121   | Ic*     | 0.054     | INT       |                       |
| 1999br | NGC 4900    | SBd         | 960                 | IIP**   | 0.099     | JKT       | Hamuy (2003)          |
| 1999bu | NGC 3786    | SABA        | 2678                | Ic      | 0.000     | INT       |                       |
| 1999bw | NGC 3198    | SBC         | 663                 | ‘impostor’* | 0.000     | INT       | van Dyk et al. (2005) |
| 1999dn | NGC 7714    | SBB         | 2798                | Ic      | 0.038     | JKT       |                       |
| 1999ec | NGC 2207    | SABbc       | 2741                | Ib      | 0.815     | INT       |                       |
| 1999ed | UGC 3555    | SABbc       | 4835                | II      | 0.615     | INT       |                       |
| 1999em | NGC 1637    | SABc        | 717                 | IIP     | 0.394     | LT        |                       |
| 1999gd | NGC 2532    | SABc        | 5260                | IIn     | 0.676     | INT       |                       |
| 1999gi | NGC 3184    | SABcd       | 592                 | IIP     | 0.637     | INT       |                       |
| 2000C  | NGC 2415    | Im?         | 3784                | Ic      | 0.494     | INT       |                       |
| 2000cr | NGC 5395    | SAb         | 3491                | Ic      | 0.000     | INT       |                       |
| 2000de | NGC 4384    | S            | 2513                | Ib      | 0.554     | INT       |                       |
| 2000ew | NGC 3810    | SAc         | 993                 | Ic      | 0.907     | JKT       |                       |
| 2001B  | IC 391      | SAc         | 1556                | Ib      | 0.201     | INT       |                       |
| 2001M  | NGC 3240    | SABb        | 3550                | Ic      | 0.142     | INT       |                       |
| 2001R  | NGC 5172    | SABbc       | 4030                | IIP**   | 0.000     | INT       | Matheson et al. (2001b) |
| 2001aa | UGC 10888   | SBB         | 6149                | Ic      | 0.000     | INT       |                       |
| 2001ac | NGC 3504    | SABab       | 1534                | ‘impostor’*             | 0.000     | INT       | Matheson & Calkins (2001) |
| 2001ai | NGC 5278    | SAb         | 7541                | Ic      | 0.878     | INT       |                       |
| 2001co | NGC 5559    | SBB         | 5166                | Ibb/c   | 0.313     | INT       |                       |
| 2001ef | IC 381      | SABbc       | 2476                | Ic      | 0.944     | INT       |                       |
| 2001ej | UGC 3829    | Sb          | 4031                | Ib      | 0.314     | INT       |                       |
| 2001fv | NGC 3512    | SABc        | 1376                | IIP**   | 0.169     | INT       | Matheson et al. (2001a) |
| 2001gd | NGC 5033    | SAc         | 875                 | Ibb     | 0.459     | INT       |                       |
| 2001is | NGC 1961    | SAbc        | 3934                | Ibb     | 0.449     | INT       |                       |
| 2002A  | UGC 3804    | SABbc       | 2887                | IIn     | 0.401     | JKT       |                       |
| 2002bm | MCG−01−32−19| SBbc        | 5462                | Ic      | 0.565     | INT       |                       |
| 2002bu | NGC 4242    | SABdm       | 506                 | IIn     | 0.000     | JKT       |                       |
| 2002cc | NGC 2604    | SBCd        | 2078                | Ic      | 0.108     | JKT       |                       |
| 2002cg | UGC 10415   | SABb        | 9574                | Ic      | 0.955     | INT       |                       |
| 2002cp | NGC 3074    | SABc        | 5144                | Ibb/c   | 0.131     | INT       |                       |
| 2002cw | NGC 6700    | SBc         | 4588                | Ic      | 0.370     | INT       |                       |
| 2002dw | UGC 11376   | S           | 6528                | Ic      | 0.475     | INT       |                       |
| 2002ed | NGC 5468    | SABcd       | 2842                | IIP     | 0.395     | INT       |                       |
| 2002ei | MCG−01−09−24| Sab         | 2319                | IIP     | 0.909     | LT        |                       |
| SN    | Host galaxy | Galaxy type | $V_r$ (km s$^{-1}$) | SN type | NCR value | Telescope | Reference |
|-------|-------------|-------------|---------------------|---------|-----------|-----------|-----------|
| 2002cl | NGC 5000    | SBbc        | 5608                | Ic      | 0.728     | INT       |           |
| 2003bp | NGC 2596    | SB          | 5938                | Ic      | 0.075     | INT       |           |
| 2003n  | UGC 10862   | Sbc         | 1691                | Ic      | 0.420     | INT       |           |
| 2004m  | NGC 3437    | SAbc        | 1283                | Ic      | 0.704     | INT       |           |
| 2005k  | NGC 3323    | SBm         | 5164                | Ic      | 0.200     | INT       |           |
| 2006gi | NGC 4303    | SAbc        | 1569                | Ic      | 0.116     | INT       |           |
| 2006ir | NGC 4303    | SAbc        | 5164                | Ic      | 0.116     | INT       |           |
| 2007mi | NGC 4303    | SAbc        | 5164                | Ic      | 0.116     | INT       |           |
| 2007nu | NGC 4303    | SAbc        | 5164                | Ic      | 0.116     | INT       |           |
| 2007tp | NGC 4303    | SAbc        | 5164                | Ic      | 0.116     | INT       |           |
| 2008ix | NGC 4303    | SAbc        | 5164                | Ic      | 0.116     | INT       |           |

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