INTEGRAL FIELD SPECTROSCOPY OF SUPERNova EXPLOSION SITES: CONSTRAINING THE MASS AND METALLICITY OF THE PROGENITORS. II. TYPE II-P AND II-L SUPERNOVAE

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Received 2012 October 4; accepted 2013 June 9; published 2013 July 12

ABSTRACT

Thirteen explosion sites of Type II-P and II-L supernovae (SNe) in nearby galaxies have been observed using integral field spectroscopy, enabling both spatial and spectral study of the explosion sites. We used the properties of the parent stellar population of the coeval SN progenitor star to derive its metallicity and initial mass. The spectrum of the parent stellar population yields estimates of metallicity via the strong-line method and age via a comparison with simple stellar population models. These metallicity and age parameters are adopted for the progenitor star. Age, or lifetime of the star, was used to derive the initial (zero-age main sequence) mass of the star using comparisons with stellar evolution models. With this technique, we were able to determine the metallicities and initial masses of the SN progenitors in our sample. Our results indicate that some Type II SN progenitors may have been stars with masses comparable to those of SN Ib/c progenitors.

Key words: stars: massive – supernovae: general

Online-only material: color figures

1. INTRODUCTION

Recent efforts to study supernova (SN) progenitors have been greatly strengthened by the availability of high-resolution archival images of the explosion site; these images enable direct identification of the progenitor star before the explosion. However, among core-collapse SNe, only the progenitors of Type II SNe have been directly detected and well characterized (see Smartt 2009 for a review). On the other hand, theoretical predictions for SN progenitor stars have been proposed (e.g., Heger et al. 2003; Eldridge & Tout 2004; Georgy et al. 2009), but these predictions are not very well tested with observational data.

Smartt et al. (2009) presented a comprehensive study of nearby Type II-P SNe with pre-explosion imaging. By comparing progenitor luminosity and colors in several passbands with theoretical stellar evolution models, the properties of the SN progenitor star were derived. Despite the fact that only a handful of SN II-P progenitors have good detections in several passbands, and the majority are only detected in a few bands or not even detected at all, these authors were able to derive the mass range of SN II-P progenitors to be within $8.5^{+1.1}_{-1.5}$ and $16.5 \pm 1.5 \, M_\odot$.

SNe II-L are thought to have lost more of their hydrogen envelopes compared to Type II-P. There are fewer successful detections of II-L progenitors (SN 2009kr; Elias-Rosa et al. 2010; Fraser et al. 2010, SN 2009hd; Elias-Rosa et al. 2011), but already these provide indications that SNe II-L are produced by stars more massive than II-P progenitors. However, the position of the SN II-L progenitors in the Hertzsprung–Russell (H-R) diagram implies that they were yellow supergiant stars shortly prior to exploding. This introduces a problem since stellar evolution predictions are not consistent with a star exploding as an SN in this yellow supergiant stage. Considering the low number of progenitor detections, it is necessary to study this issue further, either with the same method or other methods.

While pre-explosion progenitor detection offers the most direct method of constraining progenitor properties, it is greatly limited by the availability of usable pre-explosion data of the explosion site. It is therefore difficult to improve the statistics on progenitor properties. Metallicity is usually assumed since it is not possible to derive metallicity from imaging data alone. The use of proxies for determining metallicity is not uncommon. The determination of progenitor properties depends very much on the location of the purported star on the H-R diagram—which is sensitive to uncertainties in luminosity and the final stages of stellar evolution. Furthermore, the detected progenitor could be confused with other nearby stars, a binary companion, or a small compact star cluster until post-explosion observations confirm that it has already disappeared after the explosion. Up to this point, other than the very nearby SN 1987A, only a few confirmed SN progenitor disappearances have been reported in the literature: SN Ib 1993J and SN II-P 2003gd (Maund & Smartt 2009), SN Ib 1993J and SN II-P 2003gd (Maund & Smartt 2009), SN II-P 2008bk (Mattila et al. 2010), and SN Ib 2011dh (Van Dyk et al. 2013). Alternative strategies in constraining progenitor properties from the local environment have frequently been implemented (e.g., Leloudas et al. 2011; Anderson et al. 2012; Sanders et al. 2012), providing more insight into the nature of SN progenitors. The basic reasoning of this study is similar to that of Gogarten et al. (2009), who estimated the initial progenitor mass of NGC 300 OT2008-1 to be 12–25 $M_\odot$ from an analysis of the stellar population within 50 pc of the transient.
In this paper and also the preceding paper in this series (Kuncarayakti et al. 2013, Paper I), we report the results of our investigation of nearby SN explosion sites using integral field spectroscopy (IFS). Taking advantage of IFS, the SN explosion sites could be studied spatially and spectrally to reveal the nature of the stellar populations present there. The parent stellar population of the SN progenitor star provides metallicity and age estimates of the SN progenitor, assuming it was coeval with the parent cluster.

Stars are born in clusters (Lada & Lada 2003; also see Bressert et al. 2010) for a discussion on how the adopted cluster definition may change the fraction of stars born in clusters, between \( \sim 45\% \sim 90\% \)). therefore is possible to derive the age and metallicity of a star based on its parent star cluster. Furthermore, all massive stars may have been born within clustered environments (Portegies Zwart et al. 2010). As the velocity dispersion inside a star cluster is typically a few km s\(^{-1}\) (Bastian & Goodwin 2006; Portegies Zwart et al. 2010), or a few pc Myr\(^{-1}\), the short-lived progenitor star is expected to be still in the vicinity of the parent cluster if it is unbound. In both this paper and our preceding paper, we use the terms star cluster, H\(\alpha\) region, and OB association interchangeably to refer to a stellar population. The age, or lifetime, of the progenitor corresponds to the initial (zero-age main sequence; ZAMS) mass of the star, since the evolution of a single star is mainly governed by its mass at birth. With this method, we are able to put constraints on the metallicity and initial mass of several core-collapse SN progenitors.

The paper is organized as follows. We present the observations and data analysis in Section 2, followed by the description and results for each explosion site in Section 3. We discuss the estimate of contamination in Section 4 and the overall results are discussed in Section 5. Finally, the paper is summarized in Section 6.

### 2. DATA ACQUISITION AND ANALYSIS METHOD

The method of our data acquisition and analysis is the same as described in Kuncarayakti et al. (2013, Paper I). Here, we repeat the description of the data acquisition and analysis. We used the Asiago Supernova Database (Barbon et al. 1999) to select our samples. Broadband images of SN host galaxies with radial velocities of 3000 km s\(^{-1}\) or less were inspected visually using ALADIN\(^9\) to find SNe associated with bright stellar populations. We used DSS and SDSS images for this purpose, and also additionally the published SN environment images from Boffi et al. (1999). The study of Boffi et al. (1999) was initially meant to observe SN light echoes but detected star clusters instead.

In this visual inspection, we selected SNe closely associated with a bright knot at the explosion site. The knots are interpreted as the parent stellar populations of the SN progenitor stars. We do not expect to have any bias toward very young stellar populations, since the selection was based on broadband images rather than, for example, H\(\alpha\) or U-band images that are dominated by light from very young stellar populations. With this selection method, we prevent the inclusion of an age bias in our sample of SN explosion sites. Table 1 lists our SN site targets and observations. The fifth column of Table 1 shows the positional uncertainty of each SN. The reasons for each estimate are given in the description of each explosion site. Typically, a Hubble Space Telescope (HST) observation of an SN has subarcsecond pointing accuracy.

| SN   | Type | R.A. (2000) | Decl. (2000) | \(\sigma_{\text{IFU}}\) | Galaxy (NGS) | \(d^a\) (Mpc) | Obs. Date\(^b\) | Exposure | Seeing |
|------|------|-------------|--------------|----------------|--------------|-------------|-------------|-----------|--------|
| 1970G | II-L | 14:03:00.83 | +54:14:32.8  | \(\pm 0.7\)  | NGC 5457 (3) | 6.9         | 2011 Mar 10 | 1800 s    | 1.73   |
| 2009hd | II-L | 11:20:16.39 | +12:58:46.3  | \(\pm 0.01\) | NGC 3627 (4) | 10.0        | 2011 Mar 15 | 1800 s    | 0.6    |
| 2009te | II-L | 05:12:03.30 | −15:41:52.2  | \(\pm 0.02\) | NGC 1832 (2) | 26.2        | 2011 Mar 11 | 1800 s    | 1.73   |
| 1961I | II   | 12:22:00.44 | +64:28:13.3  | \(\pm 2\)    | NGC 4303 (6) | 16.4        | 2011 Mar 15 | 1800 s    | 1.70   |
| 1994L | II   | 09:20:08.8  | −16:32:28    | \(\pm 1\)    | NGC 2848 (1) | 27.7        | 2011 Mar 11 | 1800 s    | 1.73   |
| 1999gi | II-P | 10:18:16.66 | +41:26:28.2  | \(\pm 0.02\) | NGC 3184 (6) | 11.9        | 2011 Mar 11 | 1800 s    | 1.70   |
| 1999gn | II-P | 12:21:57.04 | +40:27:45.7  | \(\pm 0.1\)  | NGC 4303 (6) | 16.4        | 2011 Mar 15 | 1800 s    | 0.8    |
| 2002hh | II-P | 20:34:44.29 | +60:07:19.0  | \(\pm 0.1\)  | NGC 6946 (9) | 5.9         | 2010 Aug 1  | 1800 s    | 0.8    |
| 2003ic | II-P | 03:18:15.0  | +44:31:34.6  | \(\pm 0.17\) | NGC 4051 (3) | 14.5        | 2011 Mar 13 | 1800 s    | 0.8    |
| 2004am | II-P | 09:55:46.61 | +69:40:38.1  | \(\pm 0.1\)  | NGC 3034 (3) | 3.7         | 2011 Mar 10 | 1800 s    | 1.70   |
| 2004dj | II-P | 07:37:17.02 | +65:35:57.8  | \(\pm 0.1\)  | NGC 2403 (3) | 3.5         | 2011 Mar 10 | 1800 s    | 1.73   |
| 2005ay | II-P | 11:52:48.07 | +44:06:18.4  | \(\pm 0.1\)  | NGC 3938 (3) | 17.4        | 2011 Mar 15 | 1800 s    | 1.74   |
| 2008bk | II-P | 23:57:50.42 | −32:33:21.5  | \(\pm 0.05\) | NGC 7793 (1) | 4.1         | 2010 Aug 1  | 1800 s    | 0.8    |

Notes.
\(^a\) Mean redshift-independent distance from NED (http://ned.ipac.caltech.edu).
\(^b\) Hawaiian Standard Time (UTC – 10).

\(^9\) http://aladin.u-strasbg.fr/aladin.gml
indicated on the IFU fields in the figures were estimated using ALADIN from the SN position–cluster center offset and orientation on the broadband images. SNIFS is controlled by a remote operation and a fully dedicated pipeline processes the raw data to produce final wavelength- and flux-calibrated \((x, y, \lambda)\) data cubes. Aldering et al. (2006) present an outline of the data reduction process that is similar to the description in Section 4 of Bacon et al. (2001). During the observing run, we obtained integral field spectroscopy of 16 nearby Type II-P and II-L SN sites. However, in this paper only those with reliable SN positional uncertainties are presented (13 SN sites).

The final data cubes were measured and analyzed using IRAF.\(^{10}\) The data cubes can be thought of as stacks of images taken at different wavelengths. For each wavelength “slice,” the flux density was measured by performing aperture photometry on objects in the field using the task `apphot` in IRAF. The seeing FWHM was used as the aperture radius, or in case where the object was too close to another object or to the field edge, a smaller radius was used. Sky subtraction was done using annular apertures around the object; in most cases the annulus was larger than the field, thus in effect only a small part of it was used to measure the sky. The position of the object in the wavelength direction was traced, thus eliminating the effect of differential atmospheric refraction (DAR; Filippenko 1982).

Arranging each photometric measurement by wavelength, a spectrum of each object was obtained. Subsequent spectral analysis was done using IRAF/splot. The nebular emission lines and stellar absorption lines were measured by fitting a Gaussian curve. Prior to making line measurements for determining metallicity, the stellar continuum was removed from the spectrum by fitting a polynomial function. For the equivalent width (EW) measurement, a polynomial function was also used to fit and normalize the continuum.

We use oxygen abundance as a measure of metallicity. This was done using the O3N2 and N2 indices of Pettini & Pagel (2004, hereafter PP04), which require the observation of the line ratios \([\text{N II}] \lambda 6584/\text{H} \alpha\) (for the N2 index determination) and \([\text{O III}] \lambda 5007/\text{H} \beta\) (for the O3N2 index determination). We adopt the value of the solar oxygen abundance as 12+log(O/H) = 8.66 (Asplund et al. 2004, following PP04). In the cases where only the N2 determination is possible, the resulting metallicity is adopted; otherwise, metallicity is averaged from the O3N2 and N2 determinations. PP04 mentioned that the 1\(\sigma\) error in metallicity from the N2 determination is \(\pm 0.18\) dex. When the metallicity is determined from both N2 and O3N2, the quoted errors represent the upper and lower bounds of the metallicity in units of Z\(_{\odot}\).

The age of the stellar population was determined by comparing age indicators in the spectrum with simple stellar population (SSP) models from Starburst99 (Leitherer et al. 1999). We assume an instantaneous-burst population with a standard Salpeter initial mass function (IMF; \(\alpha = 2.35\)). For the age indicator, we primarily use the EW of H\(\alpha\) emission; we also use the EW of the near-infrared Ca II triplet (CaT) at \(\lambda \lambda 8489, 8542, 8662\) as a secondary indicator. The evolution of these lines with SSP age is presented in Figure 1. While H\(\alpha\) shows an almost linear behavior with age, CaT is quite degenerate and only EW values around 6 \(\AA\) or larger are useful for age determination. As the age solutions in that range are not single-valued, again H\(\alpha\) is needed to constrain the solution. For example, at CaT EW = 6 \(\AA\), the possible age solutions are 7 and 14.5 Myr. Despite this degeneracy, CaT is very useful since it is a good indicator of the presence of red supergiant stars.

The error on the EW measurements was estimated from the signal-to-noise ratio of the continuum part of the spectrum. The age of the stellar population is equal to the age of the SN progenitor. Padova stellar evolution models of Bressan et al. (1993) for solar metallicity (\(Z = 0.02\)) and Fagotto et al. (1994) for 0.4 solar metallicity (\(Z = 0.008\)) were used to estimate the initial mass of the star from its lifetime, for each respective metallicity. The dividing line between the two models is \(Z = 0.02\) and \(Z = 0.008\) is an observed oxygen abundance of 0.7 \(\odot\)\(\text{H}\)\(\odot\) corresponding to 12 + log(O/H) = 8.50. In Paper I, we demonstrated that the selection of SSP models for age determination does not affect the estimate of the progenitor initial mass significantly; consistencies are generally better than 20%–30%.

3. THE EXPLOSION SITES

3.1. SN II-L Sites

3.1.1. SN 1970G Site

Fesen (1993) reported the optical rediscovery of the SN almost 22 yr after maximum light. The reported SN position was accurate to within 0\('\).2 SN–circumstellar matter interactions were suggested as the energy source of the late-time emission. SN 1970G has also been detected in late times in other wavelengths including radio (Stockdale et al. 2001) and X-ray (Immler & Kuntz 2005).

\(^{10}\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Figure 2. Left panel: the SN 1970G site reconstructed from the IFU FoV. The SN position within a 1 arcsec error radius is indicated by the circle. The approximate linear scale corresponding to 2 arcsec is also indicated; this scale is calculated from the host galaxy distance only, and thus does not take into account the projection effect and host galaxy inclination. “SC” indicates the host star cluster. Right panel: extracted spectrum of the star cluster. (A color version of this figure is available in the online journal.)

Figure 3. IFU FoV and extracted host cluster spectrum for SN 2009hd. Figure annotations are the same as in Figure 2. (A color version of this figure is available in the online journal.)

Our observations show that the spectrum of the cluster is very similar in appearance to the host of SN 1961U—a blue continuum rising toward the UV region, dominated by strong emission lines of ionized gas (Figure 2). High-order Paschen emission lines are present along with helium lines. No Wolf–Rayet (WR) star signatures could be found. We determined the metallicity of the site as around half solar. At this metallicity, the age determined from H$\alpha$ is 3.4 Myr, which corresponds to the lifetime of a very massive star exceeding $\sim 100 M_\odot$.

3.1.2. SN 2009hd Site

SN 2009hd exploded in the nearby spiral galaxy M66 (NGC 3627). The study by Elias-Rosa et al. (2011) provides a comprehensive investigation of the evolution of SN 2009hd and the nature of its progenitor star. Using pre-explosion HST images, they detected a possible progenitor in F814W images but not in the F555W filter. The purported progenitor might have been a luminous red or yellow supergiant with an initial mass $\lesssim 20 M_\odot$ based on their analysis, with a positional uncertainty of the order of 0″01.

With SNIFS, we found that the explosion site appears to be clumpy with the presence of at least three distinct stellar populations. We extracted the spectrum of the H$\alpha$ region nearest to SN 2009hd, 1 arcsec west of the SN. Its continuum is rising toward blue wavelengths with strong Hz emission (Figure 3). Using the N2 calibration, we determined the metallicity of this cluster to be slightly lower than solar, $0.89 Z_\odot$, using both the O3N2 and N2 indices. The EW of the H$\alpha$ line indicates a very young age of 3.3 Myr. This corresponds to the lifetime of a very massive star with a mass on the order of $\sim 117 M_\odot$.

3.2. SN II-P Sites

3.2.1. SN 1961I Site

SN 1961I appears to be not well studied. We could not find any reference reporting the characteristics nor the exact subtype of this SN except that it is a Type II SN. We provisionally take this SN along with SN 1994L as Type II-P, simply based on the observed fact that SNe II-P are the most populous class within the Type II SN classification (Smartt et al. 2009). The SN position measured on Palomar survey plates was shown to be accurate to within 2″ by Porter (1993).
Boffi et al. (1999) suspected that the bright patch at the explosion site may be an H\textsc{ii} region or a young open cluster. We confirmed this with SNIFS, finding that the object has a very blue continuum with Balmer emission lines (Figure 5). We found that the SN host cluster is 6.4 Myr old with 0.91 solar metallicity. Translated into a stellar lifetime, at solar metallicity the age corresponds to a star with initial mass of $29.1 \, M_\odot$.

### 3.2.2. SN 1994L Site

This object is not very well studied and is only known by its Type II classification. No further study has found a secure subtype for the classification of this object. As with SN 1961I, this SN was provisionally taken as a Type II-P. The position of SN 1994L is probably accurate to 1″, as estimated by Van Dyk (1992) for SNe of that era.

The host galaxy NGC 2848 is an Sc spiral. No other SNe have been reported in this galaxy. SN 1994L exploded in a bright cluster in the southern part of the galaxy. Our SNIFS pointing missed the explosion spot but a large portion of the cluster is within the field, it is therefore possible to extract the cluster (Figure 6). Using SNIFS data, we derived a host cluster age of nearly 5.0 Myr at 0.69 solar metallicity, which corresponds to the lifetime of a 45.9 $M_\odot$ star.

#### 3.2.3. SN 1999gi Site

The progenitor of this SN has been searched for in HST pre-explosion images (positional uncertainty on the order of 0′02) but was not detected; only upper limits could be derived (Smartt et al. 2009). The upper mass limit for the progenitor star was derived to be 14 $M_\odot$.

Using SNIFS, we observed the parent stellar population of SN 1999gi and the data show that there are at least three clusters present at the explosion site within the SNIFS IFU FoV (Figure 7). For the cluster at the SN position (SC-B), we derived an age of 6.3 Myr, which corresponds to a progenitor mass of 29.4 $M_\odot$. We also measured a brighter cluster west of the SN host cluster and derived age of 5.5 Myr (corresponding to a turnoff mass of 36.7 $M_\odot$). The clusters have 0.79 and 0.72 solar metallicity, respectively. We could not measure the third cluster since it lies at the edge of the FoV and thus only a small part of it is visible.
3.2.4. SN 1999gn Site

SN 1999gn is not well studied. It is a Type II-P SN and was suspected to be a low-luminosity event (Pastorello et al. 2004). Van Dyk et al. (2000) reported that the SN was observed during the Two Micron All Sky Survey (2MASS) and that it is included in the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003). The 2MASS coordinates of SN 1999gn agree with the coordinates from Dimai & Li (1999) within about 0.1″—this value is assigned as the positional uncertainty of this SN.

SNIFS data show that there are two clusters in the SN environment (Figure 8). The brighter one, the SN host cluster (SC-A), is very young with an age of 3.3 Myr and a metallicity of 1.07 solar. This age would imply a very massive progenitor star with an initial mass on the order of \( \sim 117 M_\odot \). A neighboring cluster was found to be older, with an age of 6 Myr and a 1.02 solar metallicity. This age corresponds to the lifetime of a 30.9 \( M_\odot \) star.

3.2.5. SN 2002hh Site

This interesting SN in NGC 6946 is well studied. Pozzo et al. (2006) presented a \( \sim 1 \) yr photometric and spectroscopic monitoring campaign of the SN in the optical and infrared. They inferred a progenitor mass of 16–18 \( M_\odot \) from the luminosity of the [O I] \( \lambda \lambda 6300,6364 \) line in the SN spectra. The self-obscuring progenitor of SN 2002hh has been suspected to be a massive M supergiant or a luminous blue variable (LBV) that has undergone massive mass loss, inferred from the massive (\( \gtrsim 10 M_\odot \)) dust+gas shell surrounding the SN (Barlow et al. 2005). This shell might have been produced by episodic ejection prior to the SN explosion. However, Meikle et al. (2006) showed that the amount of circumstellar material present around the SN is likely to be smaller, \( \sim 3.6 M_\odot \). Smartt et al. (2009) derived a progenitor upper mass limit of 18 \( M_\odot \) from a nondetection in pre-explosion images. Their positional uncertainty is on the order of 0.1″.

With SNIFS, we observed the explosion site of SN 2002hh and managed to capture the H\textsc{i} region northeast of the SN position (also present in Meikle et al. 2006, Figure 2). The spectrum of the object is dominated by strong emission lines indicative of a young stellar population (Figure 9). We derived the metallicity of the host H\textsc{i} region as 1.05 solar using the O3N2 and N2 indices, and an age of 5.8 Myr. The age corresponds to the lifetime of a 33.2 \( M_\odot \) star.
3.2.6. SN 2003ie Site

There are few published studies on this particular SN. Smartt et al. (2009) suggested that SN 2003ie may not be a normal Type II-P and derived a progenitor upper mass limit of 24 $M_\odot$ from a nondetection in pre-explosion images (positional uncertainty of 0.17′). Arcavi et al. (2013) reported that this SN may have been a faint SN II-P resulting from the explosion of a rather low-mass progenitor star (<12 $M_\odot$). The position of SN 2003ie coincides with a bright cluster with extended Hα emission, but unfortunately our SNIFS pointing was inaccurate and only a small part of the host cluster fell inside the IFU FoV. We failed to extract the spectrum of this cluster (SC-A; see Figure 10). However, another faint cluster is visible at the southeast side of SC-A. This cluster appears to be associated with the extension of SC-A along the southeast direction. We managed to obtain the spectrum of this SC-B cluster and derived a metallicity of 0.93 solar metallicity and an age of 5.9 Myr. This age corresponds with a progenitor initial mass of 32 $M_\odot$. From our IFU reconstructed images, we notice that SC-A is stronger than SC-B in Hα, so probably it is younger. This implies that the mass of the progenitor star may be higher than 32 $M_\odot$.

3.2.7. SN 2004am Site

SN 2004am is not very well studied, but its position is coincident (given a positional uncertainty of the order of 0.1′) with the star cluster Sandage 96 in one of the spiral arms of the host galaxy. Several authors have attempted to characterize the progenitor star based on the study of Sandage 96. Maží-Apellániz et al. (2004) presented their study of Sandage 96 using published photometry and fit the SED with Starburst99 SSP models to derive an age of 13.6 Myr. Based on this age, these authors proposed a 15 $M_\odot$ initial mass for the SN progenitor. Solar metallicity of the cluster is assumed in this work. Another estimate by Wang et al. (2005) yields a cluster age of ∼20 Myr (∼12 $M_\odot$ SN progenitor) at 0.4 solar metallicity. Furthermore, Vinkó et al. (2009) studied Sandage 96 in detail after SN 2004dj had faded and found that the age distribution of the stellar population within the cluster is bimodal: ∼10–16 Myr and ∼32–100 Myr. While it is likely that the older population is captured field stars, the younger population gives a mass estimate for the SN 2004dj progenitor of ∼12–20 $M_\odot$. The 10 Myr lower limit is supported by the lack of Hα emission associated with Sandage 96, as revealed from narrowband Hα imaging.

Our SNIFS spectrum shows unambiguously that M82-L is a young cluster exhibiting prominent Balmer and CaT absorption lines, but is severely reddened hence the red appearance of the SED (Figure 11). Hα shows up in emission in the spectrum. We derived the N2 metallicity of the cluster as 1.35 solar. From the Hα emission EW, we determined the age of the cluster as 12.6 Myr, while the CaT EW yields an age between 9 and 15 Myr with a mean value of 12.8 Myr. These two measurements agree very well with each other and are consistent with the 18$^{+17}_{-8}$ Myr estimate of Lançon et al. (2008). The mean Hα+CaT age of 12.7 Myr corresponds to the lifetime of a 15.8 $M_\odot$ star.

3.2.8. SN 2004dj Site

SN 2004dj exploded in the nearby spiral galaxy NGC 2403. The position coincides (given a positional uncertainty of the order of 0.1′) with the star cluster Sandage 96 in one of the spiral arms of the host galaxy. Several authors have attempted to characterize the progenitor star based on the study of Sandage 96. Maží-Apellániz et al. (2004) presented their study of Sandage 96 using published photometry and fit the SED with Starburst99 SSP models to derive an age of 13.6 Myr. Based on this age, these authors proposed a 15 $M_\odot$ initial mass for the SN progenitor. Solar metallicity of the cluster is assumed in this work. Another estimate by Wang et al. (2005) yields a cluster age of ∼20 Myr (∼12 $M_\odot$ SN progenitor) at 0.4 solar metallicity. Furthermore, Vinkó et al. (2009) studied Sandage 96 in detail after SN 2004dj had faded and found that the age distribution of the stellar population within the cluster is bimodal: ∼10–16 Myr and ∼32–100 Myr. While it is likely that the older population is captured field stars, the younger population gives a mass estimate for the SN 2004dj progenitor of ∼12–20 $M_\odot$. The 10 Myr lower limit is supported by the lack of Hα emission associated with Sandage 96, as revealed from narrowband Hα imaging.
Our SNIFS observations also show that the cluster is dominated by continuum light without any detectable nebular emission throughout the instrument spectral response. The extracted spectrum confirms that the light of the cluster is mainly continuum emission produced by a young population (Figure 12). The overall spectrum is blue in color, showing prominent Balmer absorption. No emission lines are detected in the cluster spectrum. To determine metallicity, we used our observations of a nearby H II region, 35 arcsec east of Sandage 96 (corresponding to 595 pc at NGC 2403’s distance). The metallicity of the H II region is subsolar, 0.33 Z⊙; this metallicity is adopted as the metallicity of Sandage 96. We used the near-infrared CaT EW as an age indicator. Using a Starburst99 SSP model with 0.4 Z⊙, we determined the age of Sandage 96 to be 15.6 Myr, which corresponds to the lifetime of a 14.7 M⊙ star at the same metallicity. This result is consistent with previous studies that found age estimates between ∼10 and 20 Myr.

3.2.9. SN 2005ay Site

SN 2005ay was discovered to be a subluminous SN II-P by Tsvetkov et al. (2006). Based on light curve and spectral analysis, they suggested that the SN was produced by a progenitor with a mass around the low end of the SN II-P progenitor mass distribution.

Our IFU data (Figure 13) show that SN 2005ay was situated at the northeastern edge of a fuzzy cluster (SC-A). The cluster was found to have a 0.81 solar metallicity from the N2 determination and an age of 5.6 Myr. In the site, there is a neighboring cluster visible in Hα only (SC-B). This cluster turned out to be a very young H II region with an age of 2.7 Myr at nearly solar metallicity, 0.95 Z⊙. The age of SC-A corresponds to a high progenitor mass of 35.9 M⊙.

3.2.10. SN 2008bk Site

SN 2008bk exploded in the spiral galaxy NGC 7793 and is the only SN ever recorded to explode in that galaxy. Mattila et al. (2008) reported their discovery of the progenitor star in high-quality pre-explosion Very Large Telescope images. Their positional uncertainty is around 0.05′. From optical and near-infrared photometry, they derived the luminosity and colors of the star, which lead into a mass estimate of ∼8.5 M⊙.

Two years later, the disappearance of the purported progenitor star was confirmed and reported in Mattila et al. (2010) and Van Dyk (2013). This makes SN 2008bk one of the prime examples of SNe with a detected, pre-explosion progenitor star that is well-characterized with a confirmed disappearance after the explosion. Van Dyk et al. (2012) also reported their analysis of their pre-explosion detection of the progenitor star, which was consistently determined to have a mass between 8 and 8.5 M⊙.

Our SNIFS observations of the explosion site unfortunately did not manage to cover the exact location of the SN due to an inaccuracy in pointing (Figure 14). However, two sources to the southeast of the SN position were within the IFU FoV; these sources may provide additional information about the immediate environment of the progenitor star. The northern object (SC-A) shows a relatively red continuum without any noticeable emission lines. We only managed to obtain the blue part of the spectrum of SC-B due to its position at the field edge. Nevertheless, it shows a markedly different appearance than the spectrum of SC-A. The continuum, rising toward bluer wavelengths, is probably indicative of a younger age.

The absence of Hα emission in the site suggests that the environment is characterized by an age older than ∼10–15 Myr. This is consistent with the low-mass determination of the SN 2008bk progenitor, whose ∼8 M⊙ initial mass should correspond to a stellar lifetime of the order of ∼30–40 Myr.
4. CLUSTER MEMBERSHIP PROBABILITY AND AN ESTIMATE OF CONTAMINATION

To check the reliability of our results, we estimate the membership probability of the SN progenitor star to its host stellar population based on its projected position relative to the host cluster light profile. We also address the possibility of contamination from other clusters in the field. These clusters are supposedly fainter, hence invisible within our detection limit, and may have been the real parent cluster of the SN progenitor instead of the brightest visible clusters in the environment.

The light profile of the host cluster was determined using the IRAF task `imexamine`, and the FWHM was normalized by the seeing size at the time of observation. The separation, i.e., the radial distance of the SN position from the cluster center, was then compared with the radial light profile of the cluster to see where the SN position falls within the cluster light profile. The radial membership probability curve of each cluster was derived as the number of stars in the cluster at each radius; this is obtained by multiplying the light profile with the area of rings at different radii. The number density of stars is assumed to be proportional to the light from the cluster. If the SN progenitors are located randomly within the host cluster, they should show a concentration toward the peak probability. On the other hand, if the SN progenitors originated from the field and thus have no association with the cluster, the separation distribution would not show a preference for any particular position.

In the upper panel of Figure 15, the separation of each SN in our SNIFS sample (from Papers I and II) are plotted against the normalized host cluster light profile and the probability curve; the histogram is plotted in the lower panel. It is apparent that all SNe fall within a 1×FWHM radius from the cluster center, and the majority show a concentration toward the cluster center. On the other hand, the distribution of SN-cluster separation clearly does not follow the peak of the analytical probability curve around a radius 0.5×FWHM. This shows that the SN progenitors are concentrated toward the cluster center and do not randomly appear everywhere in the cluster, further suggesting a physical association between SN progenitors and their respective host cluster. The histogram for different types of SN shows two distribution peaks, at the cluster center and around 0.8×FWHM, except for SNe Ic which are concentrated toward the cluster center (Figure 15, upper panel). We note that the positional uncertainty of the SN coordinates may affect this measurement. While for the most recent SNe, especially those whose progenitors were isolated via direct imaging, the positions could be obtained with subarcsecond accuracy; for the older SNe (~1990s), the uncertainty is on the order of 1" and may even reach around 10" for SNe observed before the ~1980s (Van Dyk 1992).

To address the possibility of contamination by fainter clusters, we performed a Monte Carlo simulation of the SN-cluster separation by generating SNIFS FoVs and adding clusters based on the cluster luminosity function of nearby galaxies. In nearby galaxies, it was found that cluster luminosity function typically has a slope with $\alpha \sim -2$ (Larsen 2002; More et al. 2009), with a number density of about 5–20 clusters kpc$^{-2}$. We applied this luminosity function to add invisible clusters into our fields, scaled by the number of actually detected clusters and assuming a somewhat overestimated number density of 20 clusters kpc$^{-2}$. Typically, there is one dominant cluster accompanied by two fainter clusters in the simulated field of 360×360 pc, the median size of our observed fields. This represents the real observed situation where we usually detect one or two clusters in the SNIFS FoV, implying that there might be 2–4 more invisible clusters there according to the assumed cluster luminosity function. One can quickly compare the likelihood of a SN progenitor star being harbored in the dominant cluster and the fainter ones by assuming a cluster luminosity function for a population of identical star clusters in terms of IMF, age, metallicity, and other physical properties so
that the only difference is the number of stars within the cluster. With a cluster \(\sim 2\)–3 mag brighter than the detection limit—the case of the SNIFS sample—the fainter clusters should have about 6–15 times fewer stars since the cluster luminosity is proportional to the number of stars. Even though the luminosity function dictates that there should be 2–4 of these faint clusters for each bright cluster, in conclusion their combined likelihood of harboring an SN progenitor is still \(\sim 30\%\) less than that of the bright cluster. Actually, this would not even change the SN progenitor mass determination since the same cluster age was assumed. If the fainter clusters are older (which is quite likely, since clusters tend to disperse, thus becoming less luminous as they age; Fall et al., 2005), their likelihood of harboring a SN progenitor would become even smaller. Therefore, statistically it is more likely that the bright clusters are the real hosts of the SN progenitors. Bastian & Goodwin (2006) estimated that the cluster stars would still be physically associated with a cluster for 10–40 Myr.

Even if the parent cluster is dispersing, the progenitor star would still not be too far away from the host cluster, considering its relatively short lifetime. With a typical cluster velocity dispersion of few km s\(^{-1}\) (\(\approx \text{few pc Myr}^{-1}\)), the progenitor star would still be located within a few tens of pc from the host cluster if it was not a runaway star. It is true that the possible distance traversed increases with a longer lifetime (lower progenitor mass), but we can expect those distances to still be around 100–200 pc at the most. Furthermore, if the progenitor movement is mostly radial or has a significant radial component, the progenitor would appear even closer to the host cluster.

In the Monte Carlo simulation, we generated two populations of SN–cluster associations. The first population is fully random: the positions of clusters and SN are randomized within the simulated field, thus there is no association whatsoever between the SN and the clusters. In the second population, the position of the SN is randomized around 0.5 × FWHM of the brightest cluster’s light profile (peak of the membership probability curve), thus representing the association between the two. We generated distribution models by combining these two populations with different proportions and compared each one with the observed SN–cluster separation. Kolmogorov–Smirnov (KS) tests were performed to check whether the model and the observed separation could belong to the same parent population.

Our simulation shows that the observed separation distribution is best represented by a model containing 50% random SN–cluster population and 50% associated SN–cluster population. In the upper panel of Figure 16, we plot the comparison between the observed distribution and the 50:50 model, which yields a KS-test probability value of 80% that both distributions came from the same parent population. In the lower panel, we show the KS probability values from different models containing random:associated populations, from 10:90 (association-dominated) to 90:10 (random-dominated), peaking at the 50:50 composition. This shows that approximately 50% of all SN–cluster pairs might represent real physical associations, while the other 50% may be just contaminants from chance alignment. The consequence is discussed in the following section.

5. DISCUSSION

The importance of metallicity is believed to be paramount in the evolution of stripped-envelope (Ib/c) SNe. This is because a mechanism is thought to be necessary to remove the outer layers of the progenitor star to produce a hydrogen-deficient core-collapse SN. A metallicity-driven stellar wind is thought to be one viable scenario. In addition, removal of the envelope via a close binary interaction is also thought to be one viable scenario. However, in the case of SNe II, there is still a significant amount of the hydrogen envelope present at the time of explosion. Type II-L SN progenitors are presumed to have lost a large portion of their hydrogen envelopes, but still retain some part of it before the explosion.

Our measurement shows that on average SN II-L progenitors have lower metallicities compared to II-P progenitors. The results are tabulated in Tables 2 and 3. We found a metallicity value of \(0.81 \pm 0.22\) (rms; standard error of the mean/SEM = \(\sigma/\sqrt{N} = \pm 0.12\) \(Z\)) for the II-L progenitors and 0.88 ± 0.28 (SEM = ±0.09) \(Z\) for the II-P progenitors. The difference is not significant, only \(0.4\sigma\). As SNe II-L have lost more of their envelopes compared with SNe II-P, this result is somehow contradictory to the expectation that SN II-L progenitors should have higher metallicities since a higher metallicity will produce a more vigorous mass loss—assuming a similar progenitor mass range. However, we note that this result is based on only a small number of SN II-L progenitors (three).

We found that the average age of SN II-L host clusters is younger than that of II-P hosts; 4.3 ± 1.8 (SEM = ±1.0) Myr compared with 7.6 ± 4.2 (SEM = ±1.5) Myr. The difference is significant at the 1.8\(\sigma\) level. When the derived progenitor mass is compared, it is apparent that SNe II-L are produced by stars of higher mass compared to SNe II-P, as recent direct observations of progenitors suggest (e.g., Elías-Rosado et al., 2010, 2011). We found the mean initial mass for II-L progenitors to be 84.1 ± 47.8 (SEM = ±15.9) \(M\) while it is 39.3 ± 30.8 (SEM = ±3.4) \(M\) for II-P progenitors (1.5\(\sigma\) difference). The mean values are very high, even higher than the initial mass of SN Ib/c progenitors (see Paper I, but note the large errors). If progenitors with masses greater than 100 \(M\) are ignored, the mean value for the SN II-P progenitor mass would decrease to 29.5 ± 10.3 \(M\), similar with the SN 2009hd progenitor mass of 29.3 \(M\), the only SN II-L progenitor under 100 \(M\).
In Figure 17, we plot the mass and metallicity determinations for SN progenitors in our sample, including the Ib/c ones presented in Paper I, on the mass–metallicity diagram of Georgy et al.’s (2009) model. It is apparent that the Type II progenitors are scattered all over the three regions on the diagram, even reaching the high-mass regions predicted for SN Ib/c progenitors. Smith et al. (2011a) pointed out that some of the very massive stars may still retain their hydrogen envelopes at the time of the SN explosion, resulting in Type II SNe.

The average progenitor mass value decreases drastically if we only consider the best cases, i.e., SNe within 150 pc of the parent cluster center (which indicates a high association between cluster and SN) and with estimated progenitor masses not exceeding 100 $M_{\odot}$. Most of our clusters are smaller than this size (150 pc), and only a few are approximately this size.

However, if we apply this criterion, only SN 2009hd is left within the SNe II-L sample. With this criterion and excluding two cases where we could not recover the host cluster well (SNe 2003ie and 2008bk), the SN II-P progenitor mass would reduce to $24.4 \pm 8.6 M_{\odot}$, or $25.3 \pm 7.9 M_{\odot}$ if SN 2009hd is added to the SN II-P population. This average mass is rather similar to that of the SN Ib ($22.6 \pm 12.1 M_{\odot}$) and SN Ic progenitors ($27.5 \pm 6.7 M_{\odot}$) obtained in Paper I. If the combined populations of SNe Ib/c and SNe II-P/L are compared, the difference in initial mass is significant at only the 0.1$\sigma$ level, signifying the similarity of the two populations.

In our contamination analysis, it was found that half of the sample of SNe progenitors and host clusters may have been just a chance superposition. Considering the fact that all of our sample of SNe progenitors and host clusters may have been contaminated, we only consider the best cases, i.e., SNe within 150 pc of the parent cluster center (which indicates a high association between cluster and SN) and with estimated progenitor masses not exceeding 100 $M_{\odot}$. Most of our clusters are smaller than this size (150 pc), and only a few are approximately this size.

However, if we apply this criterion, only SN 2009hd is left within the SNe II-L sample. With this criterion and excluding two cases where we could not recover the host cluster well (SNe 2003ie and 2008bk), the SN II-P progenitor mass would reduce to $24.4 \pm 8.6 M_{\odot}$, or $25.3 \pm 7.9 M_{\odot}$ if SN 2009hd is added to the SN II-P population. This average mass is rather similar to that of the SN Ib ($22.6 \pm 12.1 M_{\odot}$) and SN Ic progenitors ($27.5 \pm 6.7 M_{\odot}$) obtained in Paper I. If the combined populations of SNe Ib/c and SNe II-P/L are compared, the difference in initial mass is significant at only the 0.1$\sigma$ level, signifying the similarity of the two populations.
LBV progenitor of SN II is given by Gal-Yam & Leonard (2009); the explosion site of Type II SN 2005gl was observed before and after the explosion, and it is evident that the blue source at the SN position disappeared after the explosion. This source was interpreted as the LBV progenitor of the SN, with an initial mass over $\sim 50 M_\odot$. Our result may serve to provide more evidence to support the notion that some massive stars may still retain their hydrogen envelope prior to exploding as SNe, producing a Type II event. The light curve decline of Type II SNe has been found to span a range from a rapid decline similar to stripped SNe to a plateau-like profile similar to SNe II-P (Kiewe et al. 2012). Recently, Mauerhan et al. (2013) suggested a new class of SN IIn-P, which show spectral signatures of a Type IIn SN but have plateau-type light curves like SNe II-P. The progenitors of this class of SN may have been stars of around $8-10 M_\odot$ or $>25 M_\odot$ similar to some of our derived progenitor masses. Given the diversity of Type IIn light curves, the lack of multi-epoch spectroscopic observation of Type II SNe may lead to the misidentification of the SN type, from Type IIn into II-P or II-L based on the light curves only. We note that this may be the case for some SNe in our sample, especially the historic and poorly observed ones.

Disregarding any physical interpretation, we plot the distribution of all host cluster Hα EWs for each SN type in Figure 18. It is apparent that the Hα EW distribution of SN II hosts is similar to the Hα EW distribution of SNe Ib/c. Cedrés & Cepa (2002) showed that the distributions of Hα EWs in the II regions in two nearby spiral galaxies, NGC 5457 and NGC 4395, peak around log(Hα EW) $\sim 3$. Considering this, it is possible that the objects with Hα EW $\gtrsim 900$ Å in Figure 18 are just outliers and are included in our sample as a result of random sampling.

We also compare the result of our SN progenitor mass and environment age determination with previous studies using different methods in Table 4. While our progenitor mass result is generally at odds with initial mass estimates from progenitor direct detection or nondetection, the derived environment age is generally consistent. This may indicate that the SN progenitor mass determined via environment age may not represent the true progenitor mass. It is possible that the star formation history at the explosion site is not instantaneous and that the SN progenitor emerged from an older burst compared to the younger burst that produced the dominant stellar population. We note that the method used in this work is sensitive to ages about 20 Myr or younger (see Figure 1) and is thus insensitive to stellar populations harboring stars less massive than $\sim 12 M_\odot$.

In Figure 1, we also show the Hα EW evolution from Starburst99 for continuous star formation. If this continuous star formation rate was used to derive the SSP age instead of...
the instantaneous one, the resulting age would significantly decrease. This may push very massive progenitors into the lower-mass region. Less massive progenitors would have very old ages. In line with this, Crowther (2013) pointed out that giant H ii regions (with sizes of \( \sim 100 \) pc or larger) may sustain several episodes of star formation, and that the typical duty cycle of \( \sim 20 \) Myr corresponds to the lifetime of a \( 12 \, M_{\odot} \) star. We note that this star formation history caveat is present not only in our study but also in other similar works relying on stellar populations at SN explosion sites (e.g., Sanders et al. 2012; Leloudas et al. 2011; Levesque et al. 2010). We are currently trying to resolve this issue by increasing the sensitivity of the method to older (\( \gtrsim 15 \) Myr) stellar populations and mapping the star formation history of the explosion site; these results will be published elsewhere.

### 6. SUMMARY

In this study, we investigated the mass and metallicity of Type II-P and II-L SN progenitors by studying parent stellar populations. With IFS, the explosion sites of the SNe were observed spatially and spectrally. This enabled us to obtain spectra of the stellar populations present at the site and to derive the metallicity via the strong line method. The age of each stellar population was derived from H\(_\alpha\) and/or Ca triplet EWs, compared to theoretical values from Starburst99 SSP models. We note that this kind of study is limited by the unknown star formation history of the site. Also, in several cases, the SN was not well documented or studied.

We found that on average SN II-L explosion sites are younger and less metal-rich compared to the sites of II-P progenitors. We estimate that about 50% of our SN–parent cluster samples are chance alignments, leaving the other 50% as real physical associations. This estimate implies that at least some of the SN II-P/II-L progenitors were massive stars comparable to single SN Ib/c progenitors (\( \gtrsim 25 \, M_{\odot} \)). The distribution of H\(_\alpha\) EWs of SN II host clusters also shows a similarity to that of SN Ib/c hosts. While this result may not be compatible with some of the contemporary theoretical models and observational results that point out that SN II-P and II-L progenitors are stars less than \( \sim 25 \, M_{\odot} \), it does not contradict the notion that a massive star above the WR mass limit could explode while still retaining its hydrogen envelope, in agreement with Smith et al. (2011a).

We acknowledge the anonymous referee for helpful comments and suggestions. H.K. acknowledges generous support from the Japanese government MEXT (Monbukagakusho) scholarship. Useful help from R. Pain, S. Rodney, and P. Weilbacher on working with data cubes is appreciated. We thank G. Leloudas for carefully reading the draft and providing important comments. We also thank J. Sollerman and F. Taddia for helpful comments on the draft of the manuscript. This work was supported in part by a JSPS core-to-core program “International Research Network for Dark Energy” and by JSPS research grants. This work is based on the data from the University of Hawaii 88 inch Telescope (UH88); the telescope time was afforded from funding from the National Astronomical Observatory of Japan. The work of K.M. is supported by the World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan, and Grant-in-aid for Scientific Research (23740141). G.A. was supported by the Director, Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. SNIFS on the 2.2 m telescope is part of the Nearby Supernova Factory II project, a scientific collaboration among the Centre de Recherche Astronomique de Lyon, Institut de Physique Nucléaire de Lyon, Laboratoire de Physique Nucléaire et des Hautes Energies, Lawrence Berkeley National Laboratory, Yale University, University of Bonn, Max Planck Institute for Astrophysics, Tsinghua Center for Astrophysics, and the Centre de Physique des Particules de Marseille. This research has made use of the SIMBAD database and ALADIN, operated at CDS, Strasbourg, France. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

**Facility:** UH:2.2m (SNIFS, OPTIC)

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