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CHARACTERIZING SUPERNOVA PROGENITORS VIA THE METALLICITIES OF THEIR HOST GALAXIES, FROM POOR DWARFS TO RICH SPIRALS

José L. Prieto,[1] Krzysztof Z. Stanek,[1,2] and John F. Beacom[1,2,3]

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ABSTRACT

We investigate how the different types of supernovae are relatively affected by the metallicity of their host galaxy. We match the SAI supernova catalog to the SDSS DR4 catalog of star-forming galaxies with measured metallicities. These supernova host galaxies span a range of oxygen abundance from $12 + \log(\mathrm{O/H}) = 7.9$ to 9.3 ($\sim$0.1–2.7 solar) and a range in absolute magnitude from $M_B = -15.2$ to -22.2. To reduce the various observational biases, we select a subsample of well-characterized supernovae in the redshift range from 0.01 to 0.04, which leaves us with 58 SNe II, 19 SNe Ib/c, and 38 SNe Ia. We find strong evidence that SNe Ib/c occur in higher metallicity host galaxies than SNe II, while we see no effect for SNe Ia relative to SNe II. We note some extreme and interesting supernova-host pairs, including the metal-poor ($\sim\frac{1}{4}$ solar) host of the recent SN Ia 2007bk, where the supernova was found well outside of this dwarf galaxy. To extend the luminosity range of supernova hosts to even fainter galaxies, we also match all the supernovae with $z < 0.3$ to the SDSS DR6 sky images, resulting in 1225 matches. This allows us to identify some even more extreme cases, such as the recent SN Ic 2007bg, where the likely host of this hypernova-like event has an absolute magnitude $M_B \sim -12$, making it one of the least luminous supernova hosts ever observed. This low-luminosity host is certain to be very metal-poor ($\sim\frac{1}{20}$ solar), and therefore this supernova is an excellent candidate for association with an off-axis GRB. The two catalogs that we have constructed are available online and will be updated regularly. Finally, we discuss various implications of our findings for understanding supernova progenitors and their host galaxies.

Subject headings: supernovae: general

Online material: color figures, machine-readable table

1. INTRODUCTION

On general grounds, it is thought that metallicity will affect the endpoints of stellar evolution, e.g., relative outcomes in terms of different supernova types and the observed properties of each. Metals are a source of opacity that affects supernova progenitors (e.g., Kudritzki & Puls 2000) and also the supernova explosions themselves (e.g., Heger et al. 2003). However, the hypothesized metallicity effects have been rather difficult to measure directly. The number of supernova progenitors that have been identified directly from preexplosion imaging is small and is limited to core-collapse events (e.g., Hendry et al. 2006; Li et al. 2007). Previous works have either used population studies with only observational proxies for metallicity (e.g., Prantzos & Boissier 2003) or have considered direct metallicity measurements with only relatively small numbers of events (e.g., Hamuy et al. 2000; Gallagher et al. 2005; Stanek et al. 2006; Modjaz et al. 2007).

A new approach is now possible, which we employ in this paper, that takes advantage of the large sample of well-observed and typed supernovae. Due to a fortuitous match in coverage, many of these supernovae were in host galaxies identified in the Sloan Digital Sky Survey (SDSS), which includes oxygen abundances measured from emission lines in their spectra (Tremonti et al. 2004). While these are central metallicities for the host galaxies and are not measured for each supernova site, they are much more directly connected to the latter than proxies such as the host luminosity. To further sharpen our tests, we compare the metallicity distributions of the host galaxies of SNe Ib/c and SNe Ia to those of SNe II, which are taken as a control sample.

The progenitors of core-collapse supernovae (SNe II and Ib/c) are massive stars, either single or in binaries, with initial main-sequence masses $\gtrsim 8\ M_\odot$ (e.g., Heger et al. 2003). The presence of hydrogen in the spectra of SNe II indicates that the massive envelopes are retained by the progenitors, of which red supergiants are probably the most common. However, SNe Ib/c lack hydrogen (Ib) or both hydrogen and helium (Ic) in their spectra and are therefore thought to have Wolf-Rayet (WR) stars as progenitors (see Crowther 2007 for a review). The latter originate from the most massive stars and have had their outer layers stripped off by strong winds. Thus, SN Ib/c are thought to have main-sequence masses $\gtrsim 30\ M_\odot$, which would make them $\simeq(8/30)^{1.35}$ ($\simeq$20%) of all core-collapse supernovae, assuming a Salpeter slope in the high-mass end of the initial mass function.

Based on theoretical considerations, the effects of line-driven winds are expected to introduce a metallicity dependence in the minimum mass necessary to produce WR stars (e.g., Heger et al. 2003; Eldridge & Tout 2004; Vink & de Koter 2005), which in turn can change the fractions of core-collapse supernovae that explode as SNe II and SNe Ib/c. Due to relative frequencies, SNe Ib/c will be more affected than SNe II. These metallicity effects on the progenitor winds may strongly affect the rate at which radioactive ^{26}Al is expelled into the interstellar medium before decaying (e.g., Prantzos 2004; Palacios et al. 2005), in which case the decays contribute to the observed diffuse 1.809 MeV gamma-ray line emission from the Milky Way (e.g., Diehl et al. 2006). While ^{26}Al appears to originate in massive stars, it is not yet known how much comes from the progenitors or the different core-collapse supernova types (e.g., Prantzos & Diehl 1996; Higdon et al. 2004). For the most massive stars, GRB progenitors in the collapsar model (e.g., MacFadyen & Woosley 1999; Yoon & Langer 2005), the interplay between metallicity-dependent mass loss through winds and rotation may be crucial (e.g., Hirschi et al. 2005). In all cases binary progenitors may be more complicated (e.g., Eldridge 2007).

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[1] Department of Astronomy, Ohio State University, Columbus, OH 43210.

[2] Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210.

[3] Department of Physics, Ohio State University, Columbus, OH 43210.

Prantzos & Boissier (2003) used the absolute magnitudes of galaxies as a proxy for their average metallicities, from the luminosity-metallicity relationship, and found that the number ratio of SNe Ib/c to SNe II increases with metallicity; they argued that their result is consistent with stellar evolution models of massive stars with rotation (e.g., Meynet et al. 2008). If so, then one would expect a more robust signature if the host metallicities were known directly. Ideally, in the latter approach, one would use the metallicities as measured from follow-up spectra obtained at the supernova sites, but this is difficult to accomplish in practice. This approach of using measured as opposed to estimated metallicities was adopted by Stanek et al. (2006; with compiled results from the literature) to study nearby long-duration GRBs with subsequent supernovae, with the finding that all of them had very low metallicity environments and that this appeared to be key to forming powerful GRB jets. It was also used by Modjaz et al. (2007) to study nearby broad-lined SNe Ic (without GRBs), and they found, in contrast, that the metallicities of these environments were much higher. The main caveats associated with these results are the low statistics, 5 and 12 events, respectively. We try to combine the virtues of these two studies with higher statistics and mostly direct metallicity measurements.

The likely progenitors of SNe Ia are white dwarfs, forming from stars with initial main-sequence masses $\lesssim 8\ M_\odot$, which accrete mass from a companion (single-degenerate model) until they reach the Chandrasekhar mass ($\simeq 1.4\ M_\odot$) and produce a thermonuclear explosion that completely disrupts the star (e.g., Whelan & Iben 1973). During the accretion process, white dwarfs could have strong winds when the accretion rate reaches a critical value (e.g., Hachisu et al. 1996), which would allow them to burn hydrogen steadily and grow in mass. At low metallicities ($[\mathrm{Fe/H}] \lesssim -1$), SNe Ia may be inhibited through the single-degenerate channel (Kobayashi et al. 1998), as the white dwarf wind is thought to be weak and the system passes through a common envelope phase before reaching the Chandrasekhar mass. Metallicity also affects the CNO abundances of white dwarfs, which can affect the production of ^{56}Ni in the explosion and therefore the peak luminosities of SNe Ia (e.g., Umeda et al. 1999; Höflich et al. 2000; Timmes et al. 2003; Röpke et al. 2006). Studies of the integrated metallicities of nearby SN Ia hosts (Hamuy et al. 2000; Gallagher et al. 2005) have shown that metallicity does not seem to be the main factor regulating their peak luminosities, which is consistent with some theoretical models (e.g., Podsiadlowski et al. 2006). Instead, the age of the stellar population at which SN Ia progenitors originate seems to be very important: two components—*prompt* (SNe Ia explode $\sim 10^8$ yr after star formation) and *delayed* (SNe Ia explode $>10^9$ yr after star formation)—were suggested to explain the high rates of SNe Ia in actively star-forming galaxies (late-type spirals and irregulars) compared with SNe Ia in old, elliptical galaxies (e.g., Mannucci et al. 2005; Scannapieco & Bildsten 2005; Neill et al. 2006).

In this work, to our knowledge for the first time, we compare the directly measured oxygen abundances of the hosts of SNe Ib/c and SNe Ia with SNe II. We use the Sternberg Astronomical Institute (SAI) supernova catalog and match it with the SDSS DR4 catalog of oxygen abundances of a large sample of star-forming galaxies. Using the supernova classifications presented in the literature, we can separate the sample according to different supernova types and make statistical comparisons of the metallicity distributions of their host galaxies. We also investigate some individual cases in metal-poor environments that are especially interesting and that can be used to test the strong predictions made by some theoretical models. We create a second catalog by matching the positions of all supernovae with images from SDSS DR6, independent of the host galaxy association. This allows us to investigate significantly fainter SNe hosts, and we identify some even more extreme hosts for follow-up observations. To enable their further use in other studies, we are making both catalogs available online and will update them regularly.

2. FIRST CATALOG: SUPERNOVA-HOST PAIRS WITH KNOWN HOST METALLICITIES (SAI ∩ SDSS-DR4)

We use the SAI supernova catalog[4] (Tsvetkov et al. 2004) to obtain the main properties of supernovae (name, classification, right ascension, declination, redshift) and their host information when available (galaxy name, right ascension, declination, redshift). The SAI catalog is a compilation of information about supernova discoveries obtained mainly from reports in the International Astronomical Union Circulars, which include the coordinates and classification of the supernovae from the IAU Circulars, as well as basic information about the host galaxies in cases in which the galaxies can be identified in online galaxy catalogs (e.g., HyperLEDA, NED, and SDSS). The version of the catalog we use contains 4169 entries,[5] of which we have selected 3050 supernovae discovered between 1909 and 2007 classified as SNe Ia, II, and Ib/c, including their subtypes. Supernovae in the catalog with no classification or that are only classified as Type I are not considered for further analysis, since we want to be able to distinguish between SNe Ia and the core-collapse types SNe Ib/c.

Tremonti et al. (2004) determined metallicities for a sample of star-forming galaxies in SDSS Data Release 2 (SDSS DR2; Abazajian et al. 2004) from their spectra. Here we use a larger sample of 141,317 star-forming galaxies (excluding AGNs) from the SDSS DR4 (Adelman-McCarthy et al. 2006), with metallicities derived in the same consistent fashion and which are available online.[6] The metallicities are derived by a likelihood analysis which compares multiple nebular emission lines ([O II], Hβ, [O III], Hα, [N II], [S II]) to the predictions of the hybrid stellar-population plus photoionization models of Charlot & Longhetti (2001). A particular combination of nebular emission line ratios arises from a model galaxy that is characterized by a galaxy-averaged metallicity, ionization parameter, dust-to-metal ratio, and 5500 Å dust attenuation. For each galaxy, a likelihood distribution for metallicity is constructed by comparison to a large library of model galaxies. We use the median of the oxygen abundance distributions in this paper. The metallicities derived by Tremonti et al. (2004) are essentially on the Kewley & Dopita (2002) abundance scale ($\Delta[12 + \log(\mathrm{O/H})] < 0.05$ dex; Ellison & Kewley 2005). For further reference in this paper, we call this galaxy metallicity catalog SDSS DR4.

We restrict the initial sample of galaxies to 125,958 by applying two of the cuts that Tremonti et al. (2004) used for their final cleaned sample, as follows: (1) the redshifts of the galaxies have to be reliable by SDSS standards, and (2) Hβ, Hα, and [N II] λ6584 should be detected at $>5\ \sigma$ confidence, and [S II] $\lambda\lambda$6717, 6731 and [O III] λ5007 should at least have detections. While in our analysis we directly compare nebular oxygen abundance within the SDSS DR4 catalog for the supernova hosts, when referring to "solar metallicity," we adopt the solar oxygen abundance of $12 + \log(\mathrm{O/H}) = 8.86$ (Delahaye & Pinsonneault 2006).

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[4] See http://www.sai.msu.su/sn/sncat.

[5] Version updated on 2007 June 15.

[6] At http://www.mpa-garching.mpg.de/SDSS/DR4.

TABLE 1

SUPERNOVA AND HOST GALAXY DATA

SN Name	Type[a]	R.A. (J2000.0) (deg)	Decl. (J2000.0) (deg)	Host Name	R.A. (J2000.0) (deg)	Decl. (J2000.0) (deg)	Distance[b] (arcsec)	Distance[b] (kpc)	z[c]	M_B (mag)	12 + log(O/H) (dex)
1909A..................	II:	210.5129	54.4661	NGC5457	210.8022	54.3489	738.5	. . .	0.00082	−21.03	9.12
1920A..................	II:	128.8156	28.4754	NGC2608	128.8222	28.4734	22.0	3.6	0.00727	−20.21	9.12
1936A..................	IIL	184.9830	5.3522	NGC4273	184.9836	5.3433	32.2	6.0	0.00783	−20.57	9.14
2007av.................	II	158.6798	11.1938	NGC 3279	158.6783	11.1974	13.8	. . .	0.00464	−19.35	9.02
2007be.................	IIP:	189.5277	−0.0309	UGC 07800	189.5223	−0.0270	24.1	6.7	0.01251	−19.76	9.05
2007bk.................	Ia	232.1899	58.8702	SDSS J152845.00+585200.1	232.1875	58.8667	13.4	8.7	0.03214	−18.17	8.27

NOTES.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Supernova classification in the SAI Catalog. The types followed by a colon indicate a provisional classification in the SAI Catalog.

[b] Projected SN-host distance.

[c] Redshift of the host galaxy from SDSS DR4.

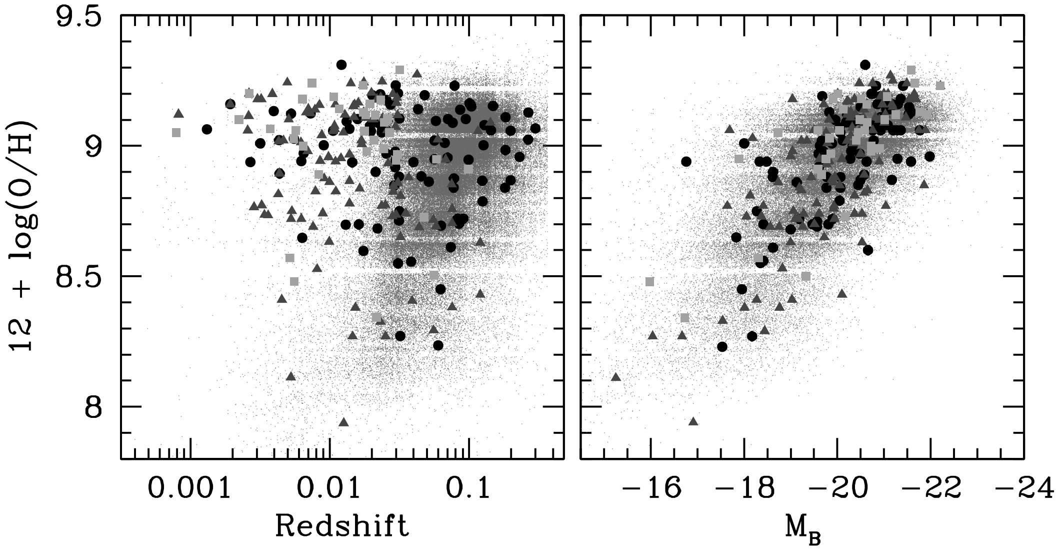

FIG. 1.—Metallicities of supernova host galaxies from SDSS DR4 as a function of redshift and absolute B magnitude. The symbols distinguish different supernova types: SNe II (*triangles*), SNe Ib/c (*squares*), and SNe Ia (*circles*). The dots in the left panel are 125,958 star-forming galaxies in SDSS DR4 with reliable metallicity and redshift measurements. The dots in the right panel are a subsample of 86,914 star-forming galaxies ($z > 0.005$) selected from the main SDSS DR4 galaxy sample. [*See the electronic edition of the Journal for a color version of this figure.*]

We cross-matched the SAI catalog with the galaxy metallicity catalog SDSS DR4 using a matching radius of 60″ (∼48 kpc at $z = 0.04$). We used the coordinates of the host galaxies in the cases in which they are known and identified in the SAI catalog, and the supernovae coordinates were used otherwise. We also required the redshifts reported in the SAI catalog, which were taken from galaxy catalogs and the IAU Circulars, to be consistent, within 20%, with the redshifts of the closest galaxy from the SDSS catalog that passed the proximity cut. After selecting the supernovae that passed the proximity and redshift criteria, we visually inspected the SDSS images around the galaxies to identify the ones that were wrongly selected as hosts (e.g., close galaxy pairs). The number of supernovae that passed all these cuts is 254 in total: 95 SNe Ia, 123 SNe II, and 36 SNe Ib/c. There were some galaxies that hosted more than one supernova: five galaxies had three supernovae each (NGC 1084, NGC 3627, NGC 3631, NGC 3938, and NGC 5457) and 15 galaxies had two supernovae (NGC 2532, NGC 2608, NGC 3627, NGC 3780, NGC 3811, NGC 3913, NGC 4012, NGC 4568, NGC 5584, NGC 5630, NGC 6962, UGC 4132, UGC 5695, IC 4229, and MCG +07-34-134).

In Table 1 we present the final matched sample of supernovae and host galaxy metallicities from SDSS DR4, as well as the absolute M_B magnitudes of the galaxies obtained from the HyperLEDA database and SDSS. The absolute magnitudes for SDSS galaxies were calculated using Petrosian gr magnitudes transformed to B magnitudes using the transformation of Lupton (2005) corrected by Galactic extinction (Schlegel et al. 1998) and internal extinction to a face-on geometry (Tully et al. 1998) and k-corrections (Blanton et al. 2003). To calculate the absolute magnitudes, we use a flat cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$. The typical 1 σ uncertainties in the oxygen abundances are 0.05 dex at $12 + \log(\mathrm{O/H}) > 8.5$, and 0.15 dex at $12 + \log(\mathrm{O/H}) < 8.5$. Our estimated uncertainty in the absolute magnitudes of the hosts is ∼0.3 mag, calculated from a subsample of galaxies in the catalog with reliable absolute magnitudes from SDSS and HyperLEDA.

Our first catalog, SAI ∩ SDSS DR4, is available online[7] and will be updated as new supernovae are discovered with host galaxy metallicities in the SDSS DR4 catalog. It includes the information presented in Table 1, as well as images around the supernovae obtained from SDSS DR6.

Figure 1 shows the distribution of metallicities as a function of redshift and M_B of the supernova host galaxies, as well as the distribution of star-forming galaxies in the SDSS DR4 catalog. The apparent "stripes" in the plots, regions with very few oxygen abundance measurements, are an effect of the grid of model parameters (metallicity, ionization parameters, attenuation, etc.) used to calculate the metallicities (see Brinchmann et al. 2004 for details). As can be seen, the redshift distribution of supernovae varies for different types, with the median redshifts of the samples at $z = 0.014$ (II), 0.018 (Ib/c), and 0.031 (Ia). This variation is a combination of several effects. First, SN Ia supernovae are, on average, ∼2 mag brighter at peak luminosity than core-collapse events (Richardson et al. 2002); therefore, they can be found at larger distances in magnitude-limited surveys. Second, the local rate of core-collapse supernovae in late-type galaxies is ∼3 times higher than the SN Ia rate (Cappellaro et al. 1999; Mannucci et al. 2005). Finally, the great interest in SN Ia as cosmological distance indicators makes most of the supernovae searches concentrate their limited spectroscopic follow-up resources on likely Type Ia supernovae (as determined by their light curves).

As shown in Figure 1, the distribution of host galaxy metallicities follows the distribution of galaxies from SDSS, with a wide range spanning ∼1.4 dex [$7.9 < 12 + \log(\mathrm{O/H}) < 9.3$]. However, there appear to be significant differences present between the hosts of different supernovae types. In particular, most of the SN Ib/c hosts are concentrated in the higher metallicity/luminosity end of the distribution [$12 + \log(\mathrm{O/H}) \gtrsim 8.7$], while the metallicities of SN II and SN Ia hosts are more evenly distributed and appear to be tracing each other fairly well.

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[7] At http://www.astronomy.ohio-state.edu/~prieto/snhosts.

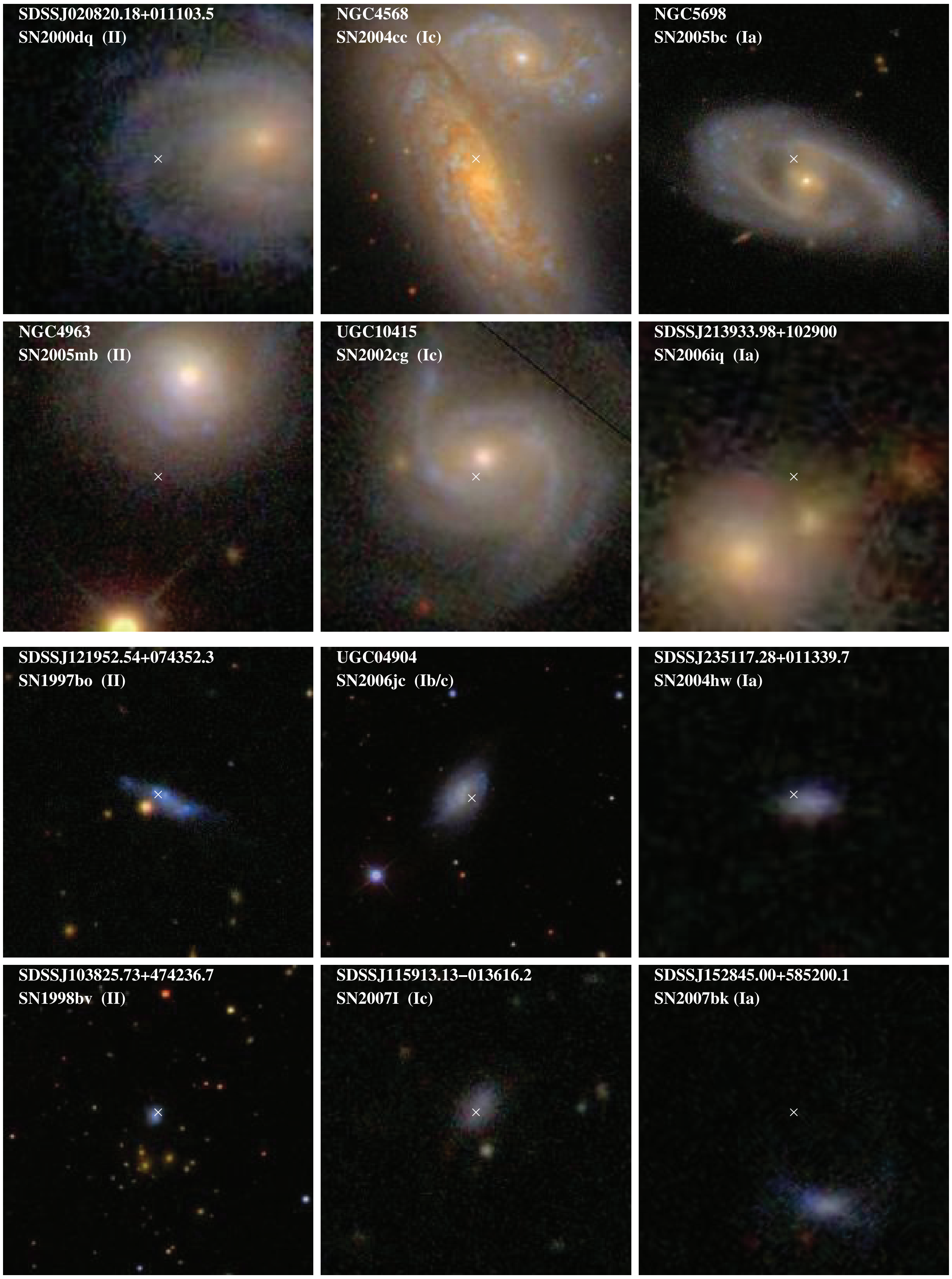

Fig. 2.—SDSS color images (*columns left to right*: SN II, SN Ib/c, SN Ia) of the most metal-rich (*top six images*) and most metal-poor (*bottom six images*) host galaxies in our sample. We show two galaxies of each supernova type. The images are centered on the position of the supernova explosion (*marked with a cross*) with north up and east to the left. They have the same physical size of 30 kpc at the distance of each galaxy.

Figure 2 shows a mosaic of SDSS DR6 (Adelman-McCarthy et al. 2008) images[8] of the host galaxies with the highest and lowest metallicities in the sample, including two supernovae of each type. This figure shows the wide range of host galaxy environments present in the sample, from big spirals (e.g., SN 2000dq, SN 2004cc, SN 2005bc, SN 2005mb, SN 2002cg, and SN 2006iq) to small dwarfs (e.g., SN 1997bo, SN 2006jc, SN 2004hw, SN 1998bv, SN 2007I, and SN 2007bk), and it shows that all types of supernovae can be found in metal-rich and metal-poor star-forming galaxies.

2.1. *Testing Supernova Trends with Metallicity*

Is the tendency of SN Ib/c hosts toward higher metallicity, compared with SNe II and SNe Ia, clearly seen in Figure 1, a real

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[8] See http://cas.sdss.org/dr6/en/tools/chart/chart.asp.

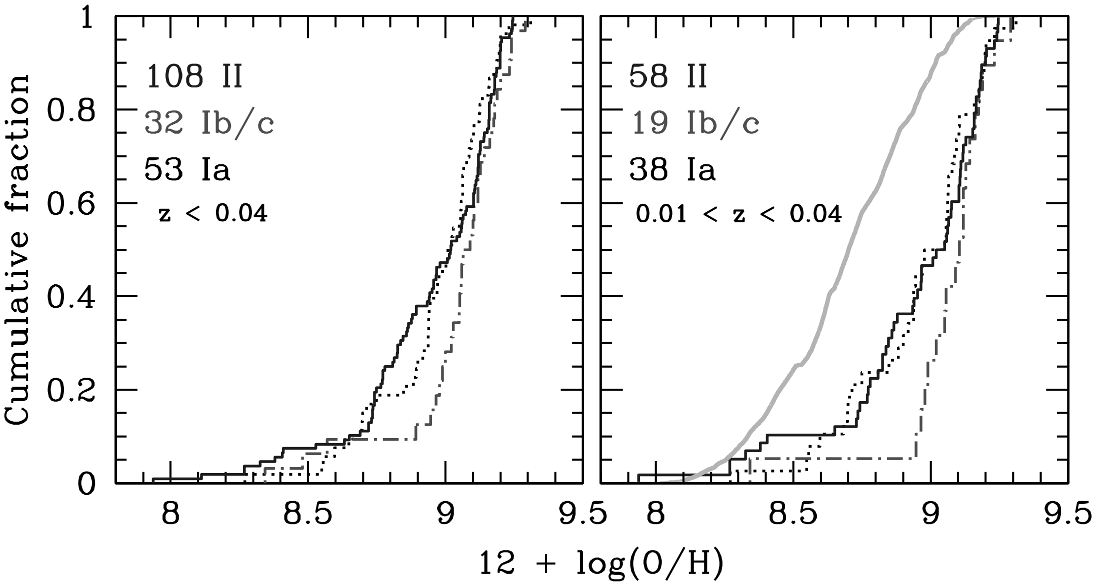

Fig. 3.—Cumulative fraction plots with the oxygen abundance of the supernova host galaxies. The number of host galaxies of each supernova type is indicated in each panel, and the lines correspond to SNe II (*solid line*), SNe Ib/c (*dot-dashed line*), and SNe Ia (*dotted line*). The left panel includes host galaxies with redshifts $z < 0.04$, while the right panel includes host galaxies with redshifts $0.01 < z < 0.04$. The thick line in the right panel shows the cumulative distribution of the 15,116 star-forming galaxies from SDSS DR4 in the same redshift range. [*See the electronic edition of the Journal for a color version of this figure.*]

physical effect? To answer this question we identify and try to reduce some of the biases present in the sample.

The supernova sample studied in this work is far from homogeneous. The supernovae have been discovered by a variety of supernova surveys, including amateur searches that look repeatedly at bright galaxies in the local universe, professional searches that look at a number of cataloged galaxies to a certain magnitude limit (e.g., LOSS), and professional searches that look at all the galaxies in a given volume (e.g., SDSS-II, Nearby Supernova Factory), among others. The host galaxies of supernovae discovered by amateur searches tend to have higher metallicities due to the luminosity-metallicity relation (see Fig. 1), while the metallicities of galaxies observed by professional searches span a wider range.

As an example of a possible bias in the supernovae in our catalog, we note that the median metallicity decreases by ~0.1 dex for the hosts of supernovae discovered between 1970 and 2007. Ideally, all the supernovae for the current study would be selected from galaxy-impartial surveys. However, the numbers of different supernova types found by such surveys in our catalog are still small (especially core-collapse events) and do not allow a statistical comparison (see the discussion in Modjaz et al. 2007).

Another bias present in the galaxy data that we use is the so-called aperture bias (Kewley et al. 2005; Ellison & Kewley 2005). The SDSS spectra are taken with a fixed fiber aperture of 3″ (2.4 kpc at $z = 0.04$). Since galaxies have radial metallicity gradients (e.g., Zaritsky et al. 1994), for nearby galaxies we are, on average, only measuring the higher central metallicity, while for more distant galaxies we are covering a larger fraction of the galaxy light with the SDSS fiber. This effect also depends on galaxy luminosity, as for dwarf galaxies the fiber will cover a larger fraction of the total light than in large spirals. Kewley et al. (2005) find a mean difference of ~0.1 dex, although with a large scatter (0.1–0.3 dex), between the central and integrated metallicities of a sample of ~100 galaxies of all types (S0–Im) in the redshift range $z = 0.005$–0.014.

In order to reduce these and other biases, we limit the comparison of supernova types to host galaxies in the redshift range $0.01 < z < 0.04$, where there are 115 supernovae. In this *pseudo* volume-limited sample, the median redshifts of the 58 SNe II (0.020), 19 SNe Ib/c (0.021), and 38 SNe Ia (0.024) hosts are consistent, while the number of galaxies in each subsample still allows us to make a meaningful statistical comparison. By using a small redshift slice we are effectively reducing the aperture biases when comparing the galaxy metallicity measurements, such that they are now comparable to or smaller than the statistical errors in the metallicity determination.

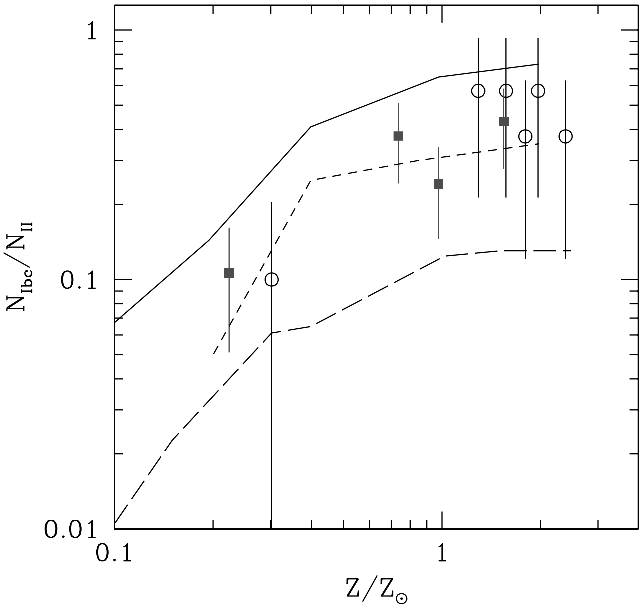

Fig. 4.—Number ratio of SNe Ib/c to SNe II as a function of metallicity of the host galaxies. The open circles are the values obtained with our sample from directly measured central metallicities, and the filled squares are the results from Prantzos & Boissier (2003) using absolute magnitudes as a proxy to host metallicities. The error bars are obtained from Poisson statistics. The solid line shows the predicted ratio from the binary models of Eldridge (2007); the dashed line is from the models of single stars with rotation of Maeder & Meynet (2004); and the dot-dashed line is from the single-star models of Eldridge (2007). [*See the electronic edition of the Journal for a color version of this figure.*]

We made additional checks of relative biases between supernova types in our redshift-limited sample. First, the ratios of the numbers of SNe Ib/c and SNe Ia to the total number of core-collapse supernovae are reasonably consistent with the ratios obtained from the local supernovae rates (e.g., Cappellaro et al. 1999; Mannucci et al. 2005). Second, the fact that the SN-host separation distributions for SNe Ia and SNe II agree, particularly at small radii (see below), suggests that our supernova samples are not biased (relatively; i.e., one supernova type to another) by obscuration effects.

We compare the metallicity distributions of the hosts of SNe Ib/c and SNe Ia to SNe II, which are taken as the control sample. Given that SNe II are the most common type of supernovae (e.g., Mannucci et al. 2005) and that they come from massive stars from a wide range of masses that explode in all environments, presumably independent of metallicity, they are effectively giving us the star formation rate–weighting of the luminosity-metallicity (or mass-metallicity) relationship for star-forming galaxies. It would be of interest to test whether indeed the SNe II rates are independent of metallicity, but this is outside the scope of the current paper.

Figure 3 shows the cumulative distribution of metallicities for hosts of different supernova types in the redshift ranges $z < 0.04$ and $0.01 < z < 0.04$. Two important results are immediately apparent:

1. The metallicities of SN Ib/c hosts tend to be higher than those of SN II hosts.
2. The SN Ia and SN II hosts have very similar metallicity distributions.

Kolmogorov-Smirnov (KS) tests between the metallicity distributions of different supernova types in the redshift range $0.01 < z < 0.04$ strengthen these findings. The KS probabilities of two host metallicity samples being drawn from the same distribution are 5% (II–Ib/c), 3% (Ia–Ib/c), and 56% (II–Ia). We obtain a similar result if we compare the mean metallicities of the host samples: 8.94 ± 0.04 (SNe II), 8.94 ± 0.04 (SNe Ia), and 9.06 ± 0.04 (SNe Ib/c), where the errors are the rms of similar-sized samples obtained using bootstrap resampling.

The metallicity distribution of the SDSS DR4 star-forming galaxies in our redshift range, weighted only by galaxy counts, is also shown in Figure 3. This should not be used in any comparisons, as it does not take into account the weighting with star formation rate or the supernova and galaxy selection criteria. We take all of these into account by only making relative comparisons between supernova types.

If we restrict the sample of SNe Ib/c to only SNe Ic and broad-lined SNe Ic in the same redshift range, leaving out supernovae classified as Ib/c and Ib, the difference in metallicity distributions of the hosts of SNe II and SNe Ic+hypernovae (13 SNe) becomes smaller, with a KS probability of 19%. If only the three supernova classified as Ib (SN 2003I, SN 2005O, and SN 2005hl) in the *pseudo* volume-limited sample are not considered, then the KS probability of SNe II and SNe Ic+hypernovae+SNe Ib/c being drawn from the same sample is 10%.

In Figure 4 we show the number ratio of SNe Ib/c to SNe II as a function of the metallicities of the host galaxies. This ratio is very important because the rates of core-collapse supernovae are expected to change as a function of the progenitor mass and metallicity, and therefore it can help to put constrains on massive stellar evolution models (e.g., Eldridge 2007). We have calculated the ratio in bins of equal number of SNe II+SNe Ib/c, with 11 supernovae per bin, to do a direct comparison with the results of Prantzos & Boissier (2003). The small statistics compared with Prantzos & Boissier (2003), who used the absolute magnitudes of the hosts as a proxy for the average metallicities through the luminosity-metallicity relationship, is reflected in the large errors of the ratio. The large error bars do not allow us to put constraints in progenitor models, although the general trend observed in the cumulative distribution (see Fig. 3) is confirmed with the number counts: SNe Ib/c are more common at higher metallicities compared with SNe II. Our results are consistent with those of Prantzos & Boissier (2003).

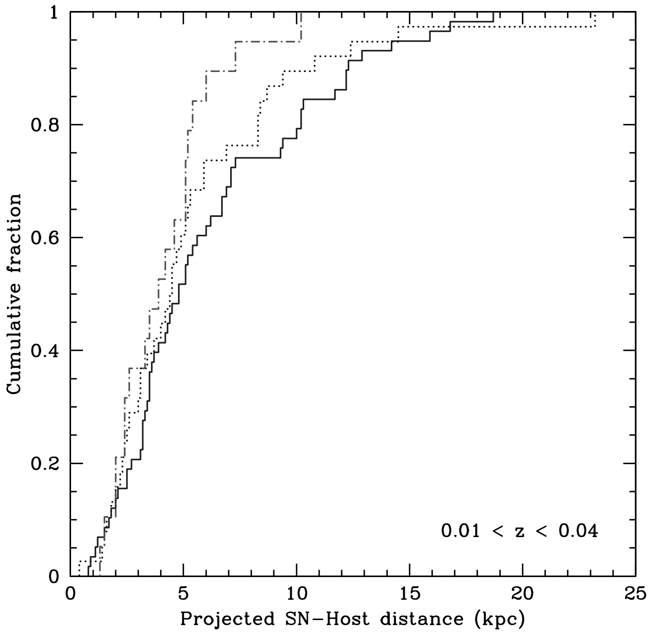

FIG. 5.—Cumulative fraction plot of the projected separation between the supernova and its host for the reduced sample in the redshift range $0.01 < z < 0.04$. The lines correspond to SNe II (*solid line*), SNe Ib/c (*dot-dashed line*), and SNe Ia (*dotted line*). [*See the electronic edition of the Journal for a color version of this figure.*]

Figure 5 shows the cumulative distributions of projected host-supernova distances for the reduced sample of 115 SNe used to compare the host metallicities ($0.01 < z < 0.04$). Clearly, the SNe Ib/c in the sample are found more toward the centers of their hosts when compared with SNe II and SNe Ia (e.g., van den Bergh 1997; Tsvetkov et al. 2004; Petrosian et al. 2005), which have similar distributions to each other (as also in Fig. 3). A galactocentric concentration of SNe Ib/c and their progenitors may be important for the angular distributions of diffuse gamma-ray line emission from the Milky Way. Besides the 1.809 MeV line from ^{26}Al, the 0.511 MeV line from positron annihilation is poorly understood in terms of its high flux and very strong central concentration (e.g., Cassé et al. 2004; Knödlseder et al. 2005; Beacom & Yüksel 2006). Since the SNe Ib/c are found at small separation, the central galaxy metallicities determined by the SDSS should be representative of the local environments of the supernovae. Taking into account the existence of negative metallicity gradients in increasing galactocentric radii, the local metallicities of the SNe II and SNe Ia, if anything, are even *lower* than deduced from the SDSS central metallicities. The tendency for SNe Ib/c to prefer higher metallicity relative to SNe II and SNe Ia is probably even stronger than shown in Figure 3.

2.2. *Supernovae in Low-Metallicity Hosts*

Even though we have shown that there is a strong preference of SNe Ib/c for high-metallicity environments, compared with

SNe II and SNe Ia, there are four SNe Ib/c with relatively metal-poor host galaxies [$12 + \log(\mathrm{O/H}) < 8.6$]. These events, and also some SNe Ia found in low-metallicity dwarfs, made us investigate more carefully a number of individual cases. We found that among the lowest metallicity host galaxies in the sample, there were supernovae that stood out because of their unusual properties (all shown in Fig. 2).

SN 2006jc.—This is a peculiar SN Ib/c supernova with strong He I lines in emission in the spectrum (Crotts et al. 2006), thought to arise from the interaction of the supernova ejecta with a He-rich circumstellar medium (Foley et al. 2007; Pastorello et al. 2007). Its host galaxy, UGC 4904 at $z = 0.006$, is a low-luminosity, blue, and relatively low-metallicity starburst [$M_B = -16.0$, $12 + \log(\mathrm{O/H}) = 8.5$]. Also present in our first catalog, interestingly, is UGC 9299 at $z = 0.005$, the host galaxy of SN 2002ao, another peculiar SN Ib/c with spectral properties very similar to SN 2006jc (Benetti et al. 2006), and it has low metallicity compared with the majority of the SN Ib/c hosts and shares similar morphological properties with the host of SN 2006jc.

SN 2007I.—A broad-lined SN Ic (or hypernova) with a spectrum similar to SN 1997ef (Blondin et al. 2007) at $z = 0.022$. Its host galaxy is a star-forming, low-metallicity dwarf [$M_B = -16.7$, $12 + \log(\mathrm{O/H}) = 8.3$], unlike other broad-lined Ic supernovae observed in higher metallicity galaxies (Modjaz et al. 2007), and somewhat similar to the host galaxies of long GRBs associated with supernovae (Stanek et al. 2006; Fruchter et al. 2006); however, see a detailed discussion in Modjaz et al. (2007). The other four broad-lined Ic supernovae in our sample that have been reported in the literature are SN 1997ef (Iwamoto et al. 2000), SN 2004ib (Sako et al. 2005), SN 2005ks (Frieman et al. 2005), and SN 2006qk (Frieman et al. 2006).

SN 2007bk.—A Type Ia supernova with a spectrum similar to the slow decliner/luminous SN 1991T (Dennefeld et al. 2007) at $z = 0.032$. The host galaxy is a low-metallicity/luminosity dwarf, with $M_B = -18.2$ and $12 + \log(\mathrm{O/H}) = 8.3$, similar to the Large Magellanic Cloud. The supernova was found very far from the center of its dwarf host, at a projected separation of $\sim$9 kpc. The magnitude of the supernova at discovery ($R = 16.7$; Mikuz 2007) and the phase obtained from the spectrum (+50 days; Dennefeld et al. [2007], although S. Blondin [private communication] finds equally good matches with templates at +30 days) imply that this was a very luminous Type Ia event. If the reported discovery magnitude and spectral phases are accurate, SN 2007bk was $\sim$0.5–1.5 mag brighter than SN 1991T at the same phase after maximum light.

3. SECOND CATALOG: SUPERNOVA-HOST PAIRS WITH UNKNOWN HOST METALLICITIES (SAI $\cap$ SDSS-DR6)

The existence of supernovae with unusual properties among the most metal-poor, low-luminosity galaxies in the first catalog prompted us to investigate a much larger sample of supernovae. We constructed a second catalog with images around the positions of supernovae using SDSS, matching the SAI catalog with SDSS DR6. We included the redshifts obtained from the SAI catalog to produce images in physical units around the supernovae. The total number of matches is 1225 for supernovae at $z < 0.3$. This catalog is also available online, with the first catalog described earlier in § 2.

This extended second catalog (SAI $\cap$ SDSS-DR6) does not have information about metallicities or luminosities of the hosts. It is a visual tool that can be used to explore the environments around supernovae found in the SDSS area, independent of the host galaxy association. Identification of the supernovae hosts and their integrated properties obtained from SDSS will be added in a future study.

Visually inspecting the images of the second catalog, we identified a number of supernovae in what appear to be very faint galaxies and which are likely to be low-luminosity, metal-poor galaxies not present in the first catalog. Some examples in the redshift range $0.01 \lesssim z \lesssim 0.05$ are (supernova types shown in parentheses): SN 1997ab (II), SN 1997az (II), SN 2001bk (II), SN 2003cv (II), SN 2004gy (II), SN 2004hx (II), SN 2005cg (Ia), SN 2005gi (II), SN 2005hm (Ib), SN 2005lb (II), SN 2006L (IIn), SN 2006bx (II), SN 2006fg (II), 2007bg (Ic), 2007bu (II), and 2007ce (Ic). In this incomplete sample, which was selected by noting some especially low luminosity galaxies, the SNe Ia/SNe II ratio is lower than expected. Similarly, in our catalog of hosts with known metallicities, SNe Ia may also be relatively underabundant at the lowest host luminosities and metallicities, as shown in Figure 1. We caution that the small statistics make these only hints, and we discuss these issues further below.

One of the most interesting supernovae in our second catalog is SN 2007bg, a recently discovered broad-lined SN Ic (Quimby et al. 2007; Harutyunyan et al. 2007) at $z = 0.03$, which has an extremely faint galaxy coincident with the position of the supernova. Using photometry and images from SDSS DR6, we estimate the luminosity of the apparent host galaxy to be $M_B \approx -12$, most likely a very metal-poor dwarf [$12 + \log(\mathrm{O/H}) \sim 7.5$, or $\sim$1/20 solar; see the metallicity-luminosity relationship extended to dwarf galaxies by Lee et al. 2006]. Due to the extremely low luminosity of that galaxy, in fact one of the lowest luminosity supernova hosts ever seen (and also fainter than most if not all GRB hosts; see, e.g., Fruchter et al. 2006), this event may represent the missing link between broad-lined SNe Ic and GRBs. This event is therefore an excellent candidate for a search for an off-axis GRB jet in radio (Soderberg et al. 2006) and possibly other wavelengths. Follow-up spectroscopic observations and deep photometry to determine the metallicity of the host and study the supernova environment are strongly encouraged in this and other cases of very low luminosity SN hosts.

4. DISCUSSION AND CONCLUSIONS

We find that SNe Ib/c tend to be in high-metallicity host galaxies, compared to SNe II, our control sample that traces the underlying star formation rates. This is the first time that such a trend has been found using the directly measured oxygen abundances of the supernova host galaxies. This finding confirms and greatly strengthens an earlier result of Prantzos & Boissier (2003), which produced a similar result using the absolute magnitudes of the host galaxies as an indirect estimate of their metallicities through the luminosity-metallicity relationship. This relation can be interpreted in relative supernova rates: the ratio of SNe Ib/c to SNe II increases with increasing metallicity and hence also with cosmic age. We also find that SNe Ib/c are consistently found toward the centers of their hosts compared with SNe II and SNe Ia, matching the results of previous studies (e.g., van den Bergh 1997; Tsvetkov et al. 2004; Petrosian et al. 2005). This suggests that direct measurements of metallicities at the explosion sites, as opposed to the central host metallicities used here, would reveal an even stronger effect, due to the radial metallicity gradients observed in spiral galaxies. The local metallicities of SNe Ib/c would be less reduced with respect to the central metallicities than those of SNe II and SNe Ia, which would widen the separation seen in Figure 3.

The tendency toward the high metallicity of SN Ib/c environments compared to those of SNe II supports, in general terms, theoretical models of the effects of metallicity in stellar evolution and the massive stars that are core-collapse supernova progenitors (e.g., Heger et al. 2003; Meynet et al. 2008; Eldridge 2007; Fryer et al. 2007). Moreover, models of stellar evolution that include rotation (from Meynet et al. 2008) predict that at high metallicity Wolf-Rayet stars will enter the WC phase earlier, when they still are rich in helium, and that these stars will explode as SNe Ib. The fact that we do see both SNe Ib and SNe Ic in hosts at high metallicity should not be taken as inconsistent with these models, mainly because the number of supernovae is small and the sample has not been homogeneously selected. There is an indication, although it is not statistically significant, that SNe Ib may be more common in higher metallicity environments than SNe Ic and broad-lined SNe Ic in our sample.

The agreement between the metallicity distributions of the hosts of SNe II and SNe Ia shows that their hosts sample a wide range of properties of star-forming galaxies, from the relatively metal-poor dwarfs to metal-rich grand design spirals. Using models of white dwarf winds in the framework of single-degenerate progenitors of SNe Ia (Hachisu et al. 1996), Kobayashi et al. (1998) made a strong prediction that SNe Ia would not be found in low-metallicity environments, such as dwarf galaxies and the outskirts of spiral galaxies. However, we do observe SNe Ia in metal-poor dwarfs (e.g., SN 2004hw, SN 2006oa, and SN 2007bk, with host metallicities between ~0.2 and 0.5 solar) and at large projected distances (>10 kpc) from their star-forming hosts (e.g., SN 1988Y, SN 1992B, SN 1993I, SN 2001bg, SN 2002gf, SN 2004ia, SN 2004ig, SN 2005ms, SN 2006fi, and SN 2006gl). There are also extreme cases that have been pointed out in previous studies, such as the low-luminosity dwarf ($M_B \approx -12.2$) host galaxy of the luminous and slow decliner SN 1999aw (Strolger et al. 2002), which is most likely very metal-poor [$12 + \log(\mathrm{O/H}) \sim 7.5$, or $\sim\frac{1}{20}$ solar; see Lee et al. 2006]. Moreover, SN 2005cg was found in a dwarf galaxy with subsolar gas metallicity (Quimby et al. 2006).

We do not find a statistically significant low-metallicity threshold in the metallicities of SNe Ia compared with SNe II hosts, as predicted from theory by Kobayashi et al. (1998) for single-degenerate progenitors of SNe Ia with winds. However, there is a preference in our second catalog for finding more SNe II in very faint galaxies compared with SNe Ia, which is suggestive of a luminosity or metallicity threshold for the main channel that produces SN Ia. This issue will have to be explored in the future with a larger sample that includes good luminosity information for the hosts and actual metallicities measured from spectra. If no metallicity threshold is found in larger samples, it means that the models and predictions of white dwarf winds will have to be revisited. This would have implications for modeling and understanding of galactic chemical evolution, which include the effects of white dwarf winds to shut down SNe Ia at low metallicities (e.g., Kobayashi et al. 2007). Interestingly, modeling the X-ray spectra of supernova remnants from probable SN Ia explosions in our Galaxy, the LMC, and M31, Badenes et al. (2007) did not find the strong effects of white dwarf winds predicted from theory.

On the other hand, independent of the existence (or not) of a mechanism that can shut down the production of SNe Ia in low-metallicity environments, we have noted examples of SNe Ia that explode in low-metallicity dwarf galaxies, such as SN 2007bk. Moreover, supernova remnants from probable SNe Ia have been identified in the LMC (e.g., Hughes et al. 1995) and SMC (e.g., van der Heyden et al. 2004). Is this SN Ia population dominated by a different kind of progenitors, such as double-degenerate mergers, compared to the main progenitor channel? Is the expected trend between progenitor metallicities and peak-luminosity starting to appear as we extend the sample to even lower metallicity hosts? It is suggestive that the small number of SNe Ia in low-metallicity hosts, such as SN 2007bk, SN 2005cg, and SN 1999aw, were all luminous events compared with normal SNe Ia. In addition, the very luminous SN Ia events that have spectral signatures of a strong ejecta–circumstellar medium interaction, such as SN 2005gj, are mostly associated with low-luminosity, and most likely low-metallicity, hosts (Prieto et al. 2007). Is low metallicity necessary to produce this extreme class of SNe Ia? Detailed comparison studies of the observational properties of supernovae in these extreme environments are encouraged.

In the course of this work we have prepared two new catalogs that should be useful for other studies. We used the SAI supernova catalog and the SDSS DR4 sample of metallicities of star-forming galaxies from Tremonti et al. (2004) to produce a catalog of supernovae hosts with metallicities derived in a consistent fashion. From this first catalog, we found several interesting core-collapse (e.g., SN 2002ao, SN 2006jc, and SN 2007I) and SN Ia events (e.g., SN 2007bk) in low-metallicity galaxies. We constructed a second catalog by matching the SAI supernova catalog with images obtained from SDSS DR6. The second catalog does not contain information on host metallicities, but it can be used to investigate the environments of supernovae independent of the host association. In that second catalog we found several examples of core-collapse supernovae in faint galaxies. One of most interesting cases is SN 2007bg, a broad-lined SN Ic in an extremely low luminosity and very likely low metallicity host. These catalogs will allow researchers to select interesting candidates for further follow-up observations. Moreover, as more homogeneous light-curve and spectroscopic data become available for supernovae in the first catalog, it will become possible to test possible correlations between supernova properties and the metallicities of their hosts, which may turn out to be crucial for improving our understanding of the nature of different supernova explosions. Another possible use of our catalogs is for systematically characterizing the morphologies of supernova hosts.

We stress the great importance of galaxy-impartial surveys for finding and studying the properties of all supernovae types. Some very interesting and potentially informative supernovae have been found in very low luminosity, low metallicity galaxies, hosts that are not included in supernova surveys based on catalogs of normal galaxies. These unusual supernovae and hosts may help probe the relationship between the SN Ib/c and SN II core-collapse supernova types, the progenitors of SNe Ia, as well as the possible correlations between observed SN Ia properties and host metallicities, the supernova-GRB connection (e.g., Stanek et al. 2003) and its possible metallicity dependence (e.g., Stanek et al. 2006; Modjaz et al. 2007), and also to test the consistency between the cosmic stellar birth and death rates (e.g., Hopkins & Beacom 2006). As we pointed out in § 2.1, at present the comparison of host metallicities using supernovae discovered by galaxy-impartial surveys is limited by their small numbers, especially for core-collapse events, since SNe Ia receive much more attention when decisions about spectroscopic follow-up are made. This is also true for the study of their observational properties (e.g., light curves and spectra). However, in order to better understand all types of cosmic explosions and put further constraints on the predictions of stellar evolution theory, a larger effort on other supernovae types is greatly needed.

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