EARLY-TYPE HOST GALAXIES OF TYPE II AND Ib SUPERNOVAE

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ABSTRACT

Recent studies find that some early-type galaxies host Type II or Ib supernovae (SNe II, Ib). This may imply recent star formation activities in these SNe host galaxies, but a massive star origin of the SNe Ib so far observed in early-type galaxies has been questioned because of their intrinsic faintness and unusually strong Ca lines shown in the nebular phase. To address the issue, we investigate the properties of early-type SNe host galaxies using the data with Galaxy Evolution Explorer (GALEX) ultraviolet photometry and the Sloan Digital Sky Survey optical data. Our sample includes eight SNe II and one peculiar SN Ib (SN 2000ds) host galaxies as well as 32 SN Ia host galaxies. The host galaxy of SN 2005cz, another peculiar SN Ib, is also analyzed using the GALEX data and the NASA/IPAC Extragalactic Database optical data. We find that the NUV–optical colors of SN II/Ib host galaxies are systematically bluer than those of SN Ia host galaxies, and some SN II/Ib host galaxies with NUV − r colors markedly bluer than the others exhibit strong radio emission. We perform a stellar population synthesis analysis and find a clear signature of recent star formation activities in most of the SN II/Ib host galaxies. Our results generally support the association of the SNe II/Ib hosted in early-type galaxies with core collapse of massive stars. We briefly discuss implications for the progenitors of the peculiar SNe Ib 2000ds and 2005cz.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – supernovae: general

Online-only material: color figures

1. INTRODUCTION

There is a general consensus that most (if not all) supernovae (SNe) II, Ib, and Ic originate from the core collapse of massive stars. Observations show that they occur predominantly in late-type galaxies where active star formation takes place (e.g., Maza & van den Bergh 1976; Cappellaro et al. 1999; Hamuy 2003). However, several studies report observations of SNe II and Ib in early-type galaxies (van den Bergh et al. 2002, 2003, 2005; Hakobyan et al. 2008; Leaman et al. 2010), which are traditionally considered old stellar populations composed mainly of low-mass stars. Although Hakobyan et al. (2008) argue that many of the previously reported early-type SN II/Ib host galaxies may be misclassified spirals, it is clear that at least some of them belong to genuine early types in the morphological sense (Hakobyan et al. 2008; Leaman et al. 2010).

Perets et al. (2010) note that all of the SNe Ib observed so far in early-type galaxies belong to a subclass of Type Ib SNe; they show a typical Type-Ib-like spectrum characterized by the strong helium lines and weak silicon lines at early time, but appear to be systematically fainter than typical SNe Ib, and show strong Ca II and weak O I emission lines in late-time optical spectra. Their origin is currently a matter of debate. Their progenitors might be related to rather old stellar populations (e.g., helium-accreting white dwarfs or mergers of ONeMg and He white dwarfs; Kawabata et al. 2010; Perets et al. 2010), or their relatively frequent detection in early-type galaxies might be due to their intrinsic faintness, even if they have a core-collapse origin (Kawabata et al. 2010).

Given this intriguing finding, a careful study of the stellar population in the early-type host galaxies of SNe II/Ib is important for a better understanding of recent star formation activities that may be related to such events. The Galaxy Evolution Explorer (GALEX) ultraviolet (UV) filters are particularly useful for this purpose, since they allow us to detect even a tiny number of young massive stars in galaxies. Many recent studies with GALEX data show that a significant fraction of early-type galaxies exhibit enhanced UV light as a sign of recent star formation (Yi et al. 2005; Salim et al. 2007; Donas et al. 2007; Schawinski et al. 2007b; Kaviraj et al. 2007, 2008).

In this paper, we present the UV–optical color–magnitude relation of early-type host galaxies of some SNe II/Ib, including SN 2000ds and SN 2005cz, which belong to the faint, Ca-rich class. By comparing them to early-type host galaxies of SNe Ia, we discuss whether the properties of early-type SN II/Ib host galaxies differ systematically from those of SNe Ia, and if the faint, Ca-rich class of SN Ib can still be explained within the framework of the core-collapse scenario.

Throughout this paper, we assume a ΛCDM cosmology with Ωm = 0.3 and H0 = 70 km s⁻¹ Mpc⁻¹.

2. SAMPLE

The catalog of the Center for Astrophysics (CfA) provides all SNe³ reported since 1885. We construct a list of galaxies that have hosted SNe II or Ib in this catalog that overlaps with Data Release 7 of the Sloan Digital Sky Survey (SDSS; York et al. 2000; Stoughton et al. 2002; Abazajian et al. 2009). We cross-match the detections in the GALEX GR5/6 archive, and perform visual inspection of both SDSS optical and GALEX UV images to select early-type galaxies. We de-redden the colors with respect to Galactic extinction using Schlegel et al. (1998) maps provided by the SDSS pipeline and assuming A_{NUV} = 8.741 × E(B − V) (Wyder et al. 2005). Thus, the final sample comprises nine early-type host galaxies of SNe II/Ib.4 We also

³ http://www.cfa.harvard.edu/iau/lists/Supernovae.html
⁴ We exclude the SN 1986M, which is classified as SN Ib in the CfA catalog and SN Ia in the Asiago SN catalog (http://web.oapd.inaf.it/supern/cat/); respectively. Given its rather high luminosity, it is more likely to be an SN Ia rather than an SN Ib.
has an angular resolution of \( 20 \text{ cm} \) (FIRST survey (Becker et al. 1995), which use radio observations in the Faint Images of the Radio Sky (FIRST) survey (Becker et al. 1995), which use radio observations in the Faint Images of the Radio Sky Survey (FIRST) to identify faint radio sources. The top optical images show the positions of SNe marked by star symbols. We label the host galaxy listed in Table 1 in each panel.

(A color version of this figure is available in the online journal.)

Figure 1. Sample of early-type host galaxies of SN II/Ib. The top row is SDSS optical images, the middle row is GALEX UV images, and the bottom row is FIRST radio images. The top optical images show the positions of SNe marked by star symbols. We label the host galaxy listed in Table 1 in each panel.

(A color version of this figure is available in the online journal.)

Table 1

| List | Host Galaxy Name | \( z^a \) | \( r_{\text{arcsec}} \) | NUV - \( r \) (mag) | \( \log_{10}(f_{\text{FIRST}}) \) (W Hz\(^{-1}\)) | Supernova Name | Type | Mag\(^b\) | Dist\(^c\) (kpc) | Comment |
|------|------------------|----------|----------------|-----------------|-----------------|--------------|------|---------|-------------|---------|
| 1    | NGC 1260         | 0.019    | 7.76           | 5.62            | ...             | 2006gy       | SNII  | 15.0    | 0.53        |         |
| 2    | SDSS J160713.55−000443.6 | 0.031 | 5.61           | 5.51            | ...             | 2001ax       | SNII  | 17.5    | 2.57        |         |
| 3    | NGC 774          | 0.015    | 13.78          | 5.24            | ...             | 2006ee       | SNII  | 17.6    | 3.07        |         |
| 4    | NGC 2768         | 0.005    | 29.67          | 4.63            | 20.75           | 2000ds       | SNII  | 17.9    | 2.23        |         |
| 5    | SDSS J024606.79−073803.7 | 0.030 | 6.00           | 4.28            | ...             | 2008al       | SNII  | 17.6    | 12.89       |         |
| 6    | NGC 4001         | 0.047    | 6.55           | 4.17            | ...             | 2003ky       | SNII  | 17.4    | 4.99        |         |
| 7    | SDSS J153452.53+070047.9 | 0.070 | 3.21           | 3.35            | ...             | 2007ed       | SNII  | 19.7    | 5.73        |         |
| 8    | SDSS J164734.90+495000.7 | 0.048 | 1.85           | 3.38            | 23.90           | 2009fe       | SNII  | 18.1    | 0.65        |         |
| 9    | SDSS J003328.04−001912.9 | 0.107 | 2.79           | 2.67            | 22.41           | 2006ho       | SNII  | 19.6    | 0.05        |         |

Notes:

\(^a\) Redshift.
\(^b\) Apparent magnitude of the supernova.
\(^c\) Distance between the center of the host galaxy and the supernova position.

use radio observations in the Faint Images of the Radio Sky (FIRST) survey (Becker et al. 1995), which has an angular resolution of \( \sim 5' \) and a completeness limit of 1 mJy. There are three sample galaxies with radio detections. For comparison, we use the same procedure to construct a sample of early-type galaxies hosting an SN Ia.

We list the SNe II/Ib sample in Table 1, which includes one confirmed SN Ib and eight SNe II. All SNe II in our sample (except for SN 2006gy), seem to have luminosity typical of core-collapse SNe (see Table 1); thus, they are not likely to belong to a hybrid class of SN IIa. Figure 1 shows a sample of early-type host galaxies of SNe II/Ib with optical, UV, and radio images. The SDSS optical images are shown in the top row, where the positions of SNe are marked by star symbols. The GALEX UV images and the FIRST radio images are shown in the second and third rows, respectively. Most of the SNe II/Ib reside close to the center of the host galaxy, except for SN 2008al. Their locations are similar to those indicated by UV and radio emission.

Regarding morphology of host galaxies, NGC 1260 (label 1) and NGC 774 (label 3) are classified as S0 in the NASA/IPAC Extragalactic Database (NED). NGC 2768 (label 4) is classified as elliptical. Labels 5, 7, 8, and 9 have FracDev = 1, which is the weight of de Vaucouleurs profile in the best composite (de Vaucouleurs + exponential) fit to the image in the \( r \) band. Labels 2 and 6 have FracDev = 0.89. All nine galaxies have concentration indices greater than 2.5. All galaxies are fairly bright, and all but one are close (\( z < 0.05 \)); thus, morphology determination based on visual inspection and pipeline parameters is deemed reliable.

3. UV–OPTICAL COLOR–MAGNITUDE RELATION

The UV–optical color–magnitude relation (see, e.g., Yi et al. 2005; Kaviraj et al. 2007; Schawinski et al. 2007b) is a particularly efficient tool for studying recent star formation in early-type galaxies because of its high sensitivity to young stellar populations. Figure 2 shows the NUV – \( r \) color–magnitude relation for the SN II host galaxies (blue circles with label), the SN Ib (2000ds) host galaxy (star symbol), and the SN Ia host galaxies (small red circles). We also show the host galaxy of SN 2005cz (NGC 4589; cf. Kawabata et al. 2010), with a star symbol. We do not have SDSS photometry of this galaxy, so we convert its Johnson magnitudes (from NED) to SDSS magnitudes using the equations given by Jester et al. (2005). We also show typical early-type galaxies (gray dots) for comparison. The empirical threshold of NUV – \( r \) < 5.4 (dashed line) is a criterion that is used to find old galaxies with recent star formation. Yi et al. (2005) derived this value from the nearby prominent UV-upturn galaxy NGC 4552; hence, it should be
considered a lower bound in the NUV − r color of purely old stellar populations.

A cursory inspection of this diagram shows that most of the early-type host galaxies of SNe II and SNe Ia reside below NUV − r ∼ 5.4, implying that they have undergone recent star formation, while the SN Ia host galaxies show relatively redder UV−optical colors. We also find that SNe II/Ib preferentially occur in relatively small host galaxies (M_r ≤ −22) compared to the case of SNe Ia (cf. Arcavi et al. 2010). This is not surprising considering that SN rates correlate with star formation rates. It should be noted that less massive early-type galaxies are more likely to have experienced recent star formation (Schawinski et al. 2007b; Jeong et al. 2009). Li et al. (2010) find that SNe II preferentially occur in relatively smaller host galaxies. But direct comparison is difficult because interpretation on galaxy size can be tricky when dealing with a heterogeneous sample of galaxy morphologies.

The host galaxy of SN 2000ds (NGC 2768, label 4) shows an NUV − r color that is significantly bluer than those of most SN Ia hosts, strongly implying the presence of young stars. On the other hand, NGC 4589 (star symbol), which is the host galaxy of another peculiar SN Ib (SN 2005cz), shows a marginal NUV − r color. Note that NGC 4589 is a strong 21 cm H_i source (Theureau et al. 2007) and shows large opaque dust patches (Michard & Marchal 1994; Carollo et al. 1997; Lauer et al. 2005). Also note that NUV colors are more sensitive to dust than optical colors by a factor of four, so the presence of a small amount of dust can have a proportionally greater effect in the NUV than in the optical colors. After all, the intrinsic colors of this galaxy might be substantially bluer than the observed colors.

Our sample includes the host galaxy of SN 2006gy (NGC 1260, label 1), which is one of the most luminous SNe ever discovered. Even though the progenitor of this highly luminous SN IIn is generally believed to be a very massive star (e.g., Smith et al. 2010), the NUV − r color of the host galaxy is not particularly blue compared to the other SN II/Ib host galaxies. Like NGC 4589, this galaxy has also been found to be fairly dusty (Ofek et al. 2007).

We find that the host galaxy of SN 2000ds and two of the eight SN II host galaxies that show a markedly bluer NUV − r color (labels 8 and 9) are strong radio sources (see Table 1 and Figure 1). Recently, some authors argued that radio loudness in early-type galaxies may be related to a recent merger event that enhanced the SN Ia rate from young stellar populations (Della Valle et al. 2005; Mannucci et al. 2006; Graham et al. 2010). If this is the case, the strong radio emission in these galaxies would serve as more evidence of recent star formation in these host galaxies. However, not all SN II host galaxies in our sample have significant radio emission. The issue of the correlation between radio emission and the presence of young stellar populations should be addressed carefully in future work.

4. STELLAR POPULATION ANALYSIS

The use of NUV − r color to find galaxies with recent star formation (as discussed in the previous section) is overly simplistic, as it is based on the assumption that all early-type galaxies should have an underlying UV-upturn component from old stars at a level similar to that of NGC 4552 (see the review of O’Connell 1999). Contrarily, it was recently found that only a small fraction of early-type galaxies show a UV upturn (Yi 2010). Hence, we hereby use a more sophisticated method to characterize the stellar populations in our SN host galaxies.

We consider a two-stage star formation history to determine the age and mass fraction of the young stellar component in the SN host galaxies. Both starbursts are assumed to be instantaneous. The base models in this study are taken from Yi (2003), and are specialized for old stellar populations. Since these models do not cover ages younger than 1 Gyr, we combine them with the models of Bruzual & Charlot (2003) for a young stellar population (Ferreras & Silk 2000; Kaviraj et al. 2007; Schawinski et al. 2007a). We assume a single uniform age of 12 Gyr for the old component. The young component is allowed to vary in age (10^−3 ≤ t_young ≤ 10 Gyr) and mass fraction (10^−6 ≤ f_young ≤ 1). More complex models, such as those based on multiple starbursts or continuous star formation, do not affect this analysis very much because UV light is insensitive to the details of the star formation history, but is highly dominated by the most recent star formation event.

To constrain these two parameters, we fit the observed UV and optical colors to models, and compute the associated χ^2 statistic to obtain a probability distribution of the age and mass fraction of the young stellar component. Internal extinction is also constrained in the χ^2 minimization. The best fit and confidence levels are shown in Figure 3. The χ^2 minimum is marked with circles along with error bars.

We first note that this analysis is heavily subject to various degeneracies. The most important one for the UV analysis is the age−mass degeneracy. A larger fraction of the young component is hardly distinguishable from a smaller fraction of the younger component.

The majority of SN Ia host galaxies have a characteristic age of 300−600 Myr for the young stellar component, which agrees with previous studies (e.g., Mannucci et al. 2005; Sullivan et al. 2006; Schawinski 2009). Our quiescent SN Ia host galaxies (filled red circles) are found to have a small number of young stars, but this is because our building-block population models do not have a significant UV flux such as that exhibited by
UV-upturn galaxies (e.g., NGC 4552). These galaxies usually have a small UV flux, with which robust estimations of the young component properties are difficult. They lie along the degeneracy area marked by the pink-shaded region. In this regard, the young component mass fraction is an upper limit of about 0.05. The SN II/ Ib host galaxies are markedly different from the quiescent SN Ia host galaxies. Most of the SN II/ Ib host galaxies are located below the degeneracy region, strongly indicating the presence of young stars.

5. IMPLICATIONS FOR THE PROGENITORS OF FAINT, Ca-RICH SNe Ib

The SNe II in our sample must have a core-collapse origin as mentioned in Section 2, and the above discussion confirms that their progenitor ages are systematically smaller than those of the SNe Ia. The host galaxy of SN 2000ds (NGC 2768) appears to have properties similar to those of the SNe II host galaxies. The relatively strong radio emission of NGC 2768 may be additional evidence to support the connection between SN 2000ds and recent star formation. The host galaxy of SN 2005cz (NGC 4552) also seems to show signatures of recent star formation. It is located below the degeneracy region in Figure 3 and known to be dusty as discussed above. Our result thus indicates that the faint, Ca-rich SNe Ib 2000ds and 2005cz originate from massive stars like the SNe II in our sample.

Our result may give some hints for their progenitor masses. Given the characteristic age of about 300–400 Myr for the young stellar component in NGC 2768 and NGC 4552 according to our stellar population model, the progenitors of SN 2000ds and SN 2005cz are not likely to have an initial mass much larger than about 10 $M_\odot$. This conclusion is very similar to that of Kawabata et al. (2010) for SN 2005cz. They argued that the high Ca to oxygen abundance ratio implied by observation in the ejecta of such peculiar SNe Ib can be best explained by explosive nucleosynthesis in a relatively small stellar core containing very thin silicon and oxygen shells. The corresponding helium core size may not significantly exceed 3 $M_\odot$. This independently points to moderately massive progenitors having initial masses of about 10 $M_\odot$.

Both being SNe Ib, the progenitors of SN 2000ds and SN 2005cz must have lost their hydrogen envelope, leaving naked helium cores of 2–3 $M_\odot$. This could only be possible in close binary systems, unless the mass-loss rate of their progenitors were unrealistically high (e.g., Kawabata et al. 2010; Yoon et al. 2010). It is important to note that the initial masses of core-collapse SNe could be lower, down to about 5–6 $M_\odot$, with binary interactions, compared to the canonical limit of 8–10 $M_\odot$ for single stars. Such binary star evolution with initial masses of 5–11 $M_\odot$ toward helium stars of about 2–3 $M_\odot$ such as SN Ib progenitors is required to explain the formation of binary pulsars PSR B2303+46 and PSR J1141–6545 with old white dwarf companions (e.g., Tauris & Sennels 2000). Therefore, it is not surprising that SN Ib like 2000ds can be found in some early-type galaxies, hovering around relatively young stars with ages of $\sim$100 Myr.

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