Average Spectral Properties of Type Ia Supernova Host Galaxies

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Abstract

We construct the average spectra of host galaxies of slower, faster, bluer, and redder Type Ia supernovae (SNe Ia) from the SDSS-II supernova survey. The average spectrum of slower declining (broader light curve width or higher stretch) SN Ia hosts shows stronger emission lines compared to the average spectrum of faster declining (narrower light curve width or lower stretch) SN Ia hosts. Using pPXF, we find that hosts of slower declining SNe Ia have metallicities that are, on average, 0.24 dex lower than average metallicities of faster declining SN Ia hosts. Similarly, redder SN Ia hosts have slightly higher metallicities than bluer SN Ia hosts. Lick index analysis of metallic lines and Balmer lines shows that faster declining SN Ia hosts have relatively higher metal content and have relatively older stellar populations compared with slower declining SN Ia hosts. We compute average H$_0$ star formation rate (SFR), stellar mass, and the specific SFR (sSFR) of host galaxies in these subgroups of SNe Ia. We find that slower declining SN Ia hosts have significantly higher ($>5\sigma$) sSFR than faster declining SN Ia hosts. A Kolmogorov-Smirnov test shows these two types of hosts originate from different parent distributions. Our results, when compared with the models of Childress et al., indicate that slower declining SNe Ia, being hosted in actively star-forming galaxies, are young (prompt) SNe Ia, originating from similar progenitor age groups.

Key words: galaxies: general — supernovae: general — techniques: spectroscopic

1. Introduction

Type Ia supernovae (SNe Ia) are currently the most useful distance indicators across the wider history of cosmic expansion. Empirical correlations between the properties of SNe Ia have made them standardizable candles (Phillips 1993). This eventually led to the surprising discovery that the expansion of the universe is accelerating (Perlmutter et al. 1997; Riess et al. 1998). The unknown force responsible for this acceleration, commonly known as dark energy, is poorly understood. Reducing uncertainties in determining cosmological constraints is the key to shedding light on the nature of dark energy (Betoule et al. 2014; Scolnic et al. 2017). Understanding the properties of SNe Ia and their astrophysical origin is an avenue to achieve this goal.

SNe Ia seem to show diversity in their light curve properties. Some are bluer, while some are redder. Some have faster declining light curves, while some have slower declining light curves. Why these diversities exist is not clear yet. Theory suggests that SN Ia explosions are powered by the radioactive decay of $^{56}$Ni. More $^{56}$Ni produces more luminous, slower declining SNe Ia. While directly probing SN Ia progenitors is challenging, we can study the global stellar populations of SNe Ia as a proxy for the progenitors. For example, Timmes et al. (2003) suggest a relationship between $^{56}$Ni and the host metallicity. If this prediction is true, then we expect fainter, faster declining SNe Ia to be associated with massive, metal-rich, and therefore lower star-forming galaxies and vice versa.Neill et al. (2009) have found that this trend is consistent with observed data.

A number of studies have been carried out on SNe Ia—host correlations using both global and local host properties (e.g., Lampeitl et al. 2010; Sullivan et al. 2010; Gupta et al. 2011; Johansson et al. 2013; Rigault et al. 2013; Pan et al. 2014; Hill et al. 2016; Wolf et al. 2016; Uddin et al. 2017; etc.). Some of these studies use host photometry, while others use spectra of host galaxies. The general nature of these studies are two-fold: (1) SNe Ia are grouped according to their host galaxy properties and thereafter mean SN Ia properties are computed; (2) linear regression lines are drawn between pairs of SN Ia–host property groups and the slopes are computed. From these studies it is established that SNe Ia, after standardization, are more luminous and faster declining in massive (metal-rich), older hosts and hosts with lower specific star formation rates (sSFRs).

Why the correlations discussed above exist is not clear yet. Childress et al. (2014) have made theoretical investigations on the ages of SNe Ia. Their study shows that young (prompt) SNe Ia are found in young, less massive, and actively star-forming galaxies. They originate from similar progenitor age groups and should make a uniform sample for cosmological analysis. On the other hand, old (tardy) SNe Ia are found in older galaxies with relatively lower star formation activities. These SNe Ia originate from different progenitor age groups. It is also difficult to clearly understand progenitor channels of SNe Ia. Two possible scenarios are proposed: single degenerate and double degenerate. A recent analysis from Heringer et al. (2017) favors a double-degenerate case, yet other options are possible.

A way to understand the diversity in SN Ia properties is to study average spectral signatures and average properties of their host galaxies grouped according to the properties of SNe Ia, such as color and light curve width. The advantage of such analysis is that it will give a clear picture of the properties of stellar populations of SNe Ia with different properties. Brandt et al. (2010) have constructed average spectra of faster and

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5 By more luminous we mean relatively lower Hubble residual, which is defined as $\Delta \mu = \mu_{\text{obs}} - \mu_{\text{mod}}$, the difference between the observed and the model distance modulus.
slower declining SNe Ia hosts from 101 SDSS-II SN Ia samples and showed that the average spectrum of slower declining hosts is dominated by stronger emission lines, indicating ongoing star formation. Using a sample of 84 SNe Ia, Johansson et al. (2013) split SN Ia host spectra into four bins in stretch and found that as we go from lower to higher stretch, emission line strengths of the host galaxies become increasingly prominent. While both studies mentioned above make qualitative statements, no quantitative results were shown. Their sample sizes were small, and moreover they have only studied average spectra in stretch bins, not in SN Ia color bins. In this paper, we extend such a study with 311 SNe Ia from SDSS-II—three-fold increase of sample size. Moreover, we quantify average emission line properties and derive average host properties, such as SFR and sSFR, after splitting SNe Ia according to their stretch and color.

In Section 2, we describe our sample; in Section 3, we present our analysis of average spectra, spectral properties, and properties of hosts; and we summarize in Section 4.

**Table 1**

| Subgroup | Criteria | Number |
|----------|----------|--------|
| Faster   | $x_1 < 0$ | 116    |
| Slower   | $x_1 > 0$ | 121    |
| Bluer    | $c < 0$  | 145    |
| redder   | $c > 0$  | 92     |

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**2. Data**

We use a sample of 311 SNe Ia from the Sloan Digital Sky Survey-II (SDSS-II; see Frieman et al. 2008 for the SN survey). In phase two of the survey, SDSS-II scanned a part of the sky near the celestial equator, known as Stripe 82, in order to discover supernovae. Between 2005 September and 2007 November, SDSS-II has discovered ~500 spectroscopically confirmed SNe Ia in the range $0.05 < z < 0.4$. The final data release of the SDSS-II supernova program is presented in Sako et al. (2014). We have taken SN Ia properties such as redshift ($z$), stretch ($x_1$), and color ($c$) from the Joint Light curve Analysis (JLA; Betoule et al. 2014). JLA uses SALT (Guy et al. 2010) to fit SN Ia light curves after calibrating with the CALSPEC standards. We show our sample in Figure 1. The left panel shows the distribution of SNe in the stretch–color ($x_1$–$c$) plane. The two right panels show redshift distributions of SNe Ia in stretch and color subgroups. Subgroups are defined in Table 1. We see in color distributions that there are more blue SNe Ia at higher redshifts than the redder ones. This is due to a Malmquist bias effect. The distributions in stretch subgroups seem to be similar.

The source of SN Ia host spectra is the Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013)—a survey conducted between fall of 2009 to spring of 2014. The spectrograph of BOSS has 1000 fibers, each with a diameter of 2 arcsec. The resolution is $R \sim 2000$, and the wavelength coverage is 360–1000 nm. Our goal is to study global properties...
of host galaxies, not the local properties at the explosion sites of SNe Ia. For the latter, integral field spectroscopy is promising. Figure 2 shows that some host galaxies (38%) fall within a 1 arcsec radius of the fiber. Also, 35% of the time, separations between SNe Ia and host nuclei are within 1 arcsec.

We gather FITS spectra from SDSS data release 12 (DR12) using a web-based query located at the Science Archive Server.6 The second extension of each FITS file contains a coadded calibrated spectrum of a given combination of Plate–MJD–fiber, which is a unique combination for a given object. The fourth extension contains integrated fluxes and equivalent widths of various spectral lines.

3. Analysis

The aim of this study is to compare average spectral properties and stellar populations of SN Ia hosts by splitting them according to SN Ia properties. We define various SN Ia subgroups in Table 1 and split host galaxies according to these criteria. We first combine host spectra in different subgroups to create average host spectra and compare average spectra between subgroups. We then calculate average luminosities of various emission lines. Thereafter, we calculate SFR for these hosts, and using stellar mass from other work we calculate sSFRs. We present our analysis below.

3.1. Average Spectra

In order to study average spectra of SN Ia hosts in each group, we first split them according to SN Ia properties and coadded before coadding we interpolate each spectrum onto the rest-frame wavelengths. We then coadded observed spectra with no correction for distance effects, which gives higher weight to galaxies of greater apparent brightness. Average spectra of SN Ia hosts in each subgroup are shown in Figure 3.

It is easy to see from the top two panels of Figure 3 that, on average, slower ($x_1 > 0$) SN Ia hosts have relatively stronger emission lines compared to faster ($x_1 < 0$) SN Ia hosts. This result confirms earlier findings of Brandt et al. (2010) and Johansson et al. (2013). We do not see any significant difference in emission line strengths between the two subgroups.

![Figure 3](image.png)

**Table 2**

| Subgroup | Log Age (Gyr) | Metallicity [M/H] |
|----------|---------------|-------------------|
| $x_1 < 0$ | 0.875         | $-0.163$          |
| $x_1 > 0$ | 0.902         | $-0.403$          |
| $c < 0$  | 0.926         | $-0.304$          |
| $c > 0$  | 0.880         | $-0.238$          |

6 http://data.sdss3.org/
stronger in slower declining SN Ia hosts, indicating relatively younger and metal-poor stellar populations. From both pPXF fitting and Lick index measurements, we find that the redder SN Ia hosts have higher metallicities than bluer SN Ia hosts. This result is consistent with Childress et al. (2013), where they find that SNe Ia are redder when they explode in higher-metallicity hosts.

We calculate average luminosities of various emission lines in various subgroups and show them in Table 4. We find that hosts of slower declining SNe Ia on average are more luminous than hosts of faster declining SNe Ia. We also find that hosts of bluer SNe Ia are also more luminous than those of redder SNe Ia.

We further divide SN Ia hosts into four quadrants in the $x_1$–$c$ plane. Average spectra of them are shown in Figure 4. For faster SNe Ia, bluer and redder hosts seem to differ in the strength of the emission lines. Thus, SFRs (or more precisely, sSFRs) are different. Redder ones have weaker emission. We expect that the redder ones would have more dust arising from more recent star formation, but we see the opposite here. There are probably more metal-rich and/or older ones.

Figure 4. Average spectra of SN Ia hosts split according to four quadrants in the $x_1$–$c$ plane. Here, the observations are similar to what we see in Figure 3, but now with fewer host spectra in each stack.

Table 3
Lick Indices Measured from Average Spectra of Various SN Ia Subgroups

| Equivalent Widths     | $x_1 < 0$ | $x_1 > 0$ | $c < 0$ | $c > 0$ |
|-----------------------|-----------|-----------|---------|---------|
| Fe 4383 (Å)           | 3.109     | 1.987     | 2.061   | 3.206   |
| H$_\beta$ (Å)         | −0.090    | −2.437    | −1.329  | −1.339  |
| H$_\alpha$ (Å)        | 2.464     | 2.923     | 2.821   | 2.560   |
| Mg$_2$ (mag)          | 0.155     | 0.113     | 0.131   | 0.136   |

Note. Negative signs in $H_{\beta}$ values indicate that the line is in emission. Errors in measurements are about 1%.

Table 4
Luminosities of Various Emission Lines in Subgroups

| Emission Lines | $x_1 < 0$ | $x_1 > 0$ | $c < 0$ | $c > 0$ |
|----------------|-----------|-----------|---------|---------|
| $H_{\alpha}$   | 6.77      | 10.91     | 10.25   | 7.09    |
| $H_{\beta}$    | 1.45      | 2.66      | 2.67    | 1.40    |
| $H_{\gamma}$   | 0.75      | 1.18      | 1.26    | 0.64    |
| $H_{\delta}$   | 1.12      | 2.45      | 3.17    | 0.61    |
| [O ii]3729     | 1.34      | 2.21      | 2.27    | 1.27    |
| [N ii]6583     | 3.73      | 4.00      | 3.89    | 3.84    |

Note. Emission line luminosities are relatively higher for hosts of slower declining SNe Ia when compared with the hosts in faster declining ones. Similarly, bluer SN Ia hosts are relatively more luminous than redder SN Ia hosts.

For slower SNe Ia, there appears to be effectively no difference in host spectra between bluer and redder SNe Ia. If true, this would indicate that there is no real progenitor-related mechanism causing the color differences in these slower SNe Ia. Thus, there is probably something driving intrinsic color that may be completely stochastic. It is a promising result for cosmology because it means we do not have to worry about intrinsic color evolution with redshift.

3.2. Comparing Average Properties

After studying average spectra we now study several properties of SN Ia hosts in various subgroups. First, we calculate SFR. $H_{\alpha}$ is considered to be the best choice for calculating SFR because of its intrinsic strength. It is also suitably located in the redder part of the spectrum that avoids significant dust extinction. We obtain the integrated flux of $H_{\alpha}$ emission line per galaxy that was used in the coadds. We
then calculate luminosity of H\textsubscript{\alpha} in ΛCDM cosmological framework. To calculate SFR, we use an empirical formulation given by Kennicutt (1998):

\[ \text{SFR} = 7.9 \times 10^{-42} \times L(H_{\alpha}) \text{M}_\odot \text{yr}^{-1}. \] (1)

In Figure 5, we show distributions of SFR, stellar mass, and sSFR in faster and slower SN Ia hosts. In each case, two distributions seem to be different. See the text for details. Right: same as the left panels, but for bluer and redder SN Ia hosts. Here, the distributions in each case seem not to differ.

| Subgroup Pairs     | Host Property | D-statistics | p-value |
|--------------------|---------------|--------------|---------|
| Faster-slower      | SFR           | 0.17         | 0.10    |
|                    | Mass          | 0.32         | 3e-5    |
|                    | sSFR          | 0.36         | 2e-6    |
| Bluer-redder       | SFR           | 0.17         | 0.12    |
|                    | Mass          | 0.19         | 0.06    |
|                    | sSFR          | 0.17         | 0.11    |

**Note.** Looking at the probabilities (p-values) it is clear that faster and slower SN Ia hosts differ significantly in terms of stellar mass and sSFR.

We have studied average spectra and physical properties of slower, faster, bluer, and redder SN Ia host galaxies. We have seen that the average spectrum of slower declining SN Ia hosts has stronger emission line features compared with the average spectrum of faster declining SN Ia hosts. They also have metallicities that are, on average, 0.24 dex lower than their counterparts as derived using pPXF. Between bluer and redder SN Ia hosts, average spectra do not vary in terms of emission line features. We also perform Lick index analysis of metal and Balmer lines. Our results show that hosts of slower declining SNe Ia have relatively lower metal content and have a relatively older stellar population than hosts of faster declining SNe Ia. Similarly, redder SN Ia host have relatively more metal than bluer SN Ia hosts. We have calculated SFRs from H\textsubscript{\alpha} luminosities and found that slower declining SN Ia hosts have significantly (>5σ) higher sSFR and also are significantly (>4σ) lower-mass galaxies than faster declining SN Ia hosts. They are also younger than their counterparts. These properties do not seem to differ between the hosts of bluer and redder SNe Ia.

### 4. Summary

We have studied average spectra and physical properties of slower, faster, bluer, and redder SN Ia host galaxies. We have seen that the average spectrum of slower declining SN Ia hosts has stronger emission line features compared with the average spectrum of faster declining SN Ia hosts. They also have metallicities that are, on average, 0.24 dex lower than their counterparts as derived using pPXF. Between bluer and redder SN Ia hosts, average spectra do not vary in terms of emission line features. We also perform Lick index analysis of metal and Balmer lines. Our results show that hosts of slower declining SNe Ia have relatively lower metal content and have a relatively older stellar population than hosts of faster declining SNe Ia. Similarly, redder SN Ia host have relatively more metal than bluer SN Ia hosts. We have calculated SFRs from H\textsubscript{\alpha} luminosities and found that slower declining SN Ia hosts have significantly (>5σ) higher sSFR and also are significantly (>4σ) lower-mass galaxies than faster declining SN Ia hosts. They are also younger than their counterparts.
Results summarized above have some significance in understanding SN Ia progenitors. It has been shown that young (prompt) SNe Ia originate from younger, low-mass, actively star-forming galaxies (Childress et al. 2014). If we compare our results, we find that slower declining SNe Ia are young SNe Ia since they are hosted in high SFR galaxies.

In this paper, we have studied SN Ia light curve properties. The next step should be to study average properties of SN Ia hosts in SN Ia corrected luminosity subgroups, which will be important for addressing systematic uncertainties in SN Ia cosmology. We have performed this study within a redshift of $z \sim 0.5$. The Dark Energy Survey (DES; Bernstein et al. 2012) will discover $\sim 3500$ SNe Ia up to a redshift of $\sim 1.2$. The host spectra for these SNe Ia are coming from OzDES (Yuan et al. 2015), which will enable us to continue this study at higher redshifts.

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