PHOTOMETRIC IDENTIFICATION OF TYPE Ia SUPERNOVAE AT MODERATE REDSHIFT

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ABSTRACT

Large photometric surveys with the aim of identifying many Type Ia supernovae (SNe) at moderate redshift are challenged in separating these SNe from other SN types. We are motivated to identify Type Ia SNe based only on broadband photometric information, since spectroscopic determination of the SN type, the traditional method, requires significant amounts of time on large telescopes. We consider the possible observables provided by a large synoptic photometry survey. We examine the optical colors and magnitudes of many SN types from \( z = 0.1 \) to \( 1.0 \), using space-based UV spectra and ground-based optical spectra to simulate the photometry. We also discuss the evolution of colors over the SN outburst and the use of host galaxy characteristics to aid in the identification of Type Ia SNe. We consider magnitudes both in the SDSS photometric system and in a proposed filter system with logarithmically spaced bandpasses. We find that photometric information in four bands covering the entire optical spectrum appears capable of providing identification of Type Ia SNe based on their colors at a single observed epoch soon after maximum light, even without independent estimates of the SN redshift. Very blue filters are extremely helpful, as at moderate redshift they sample the rest-frame UV spectrum where the SN types are very different. We emphasize the need for further observations of SNe in the rest-frame UV to fully characterize, refine, and improve this method of SN type identification.

Key words: cosmology: observations — supernovae: general

1. INTRODUCTION

Observations of Type Ia supernovae (SNe) have become a cornerstone of physical cosmology, providing some of the first hints of the presence of a cosmological constant, or dark energy (Riess et al. 1998; Perlmutter et al. 1999). Efforts to increase the robustness and precision of this result using Type Ia SNe fall into two categories. The first is the observation of Type Ia SNe at redshifts \( z \) greater than 1, where the effect of a cosmological constant becomes negligible and the luminosity distance-redshift relation for models containing a cosmological constant or dark energy deviates from most alternative models involving, for example, gray dust (Aguirre 1999) or secular evolution. A second method for verifying the SN results involves using large numbers of moderate-redshift (\( z \leq 1 \)) Type Ia SNe to investigate systematic effects such as dust extinction and SN evolution by comparing subsamples (Branch et al. 2001). Such a sample of moderate-redshift Type Ia SNe may also be used to constrain the equation of state of the dark energy. A combination of both methods will aid in constraining the time variation of the dark energy density (Wang & Garnavich 2001), leading to constraints on the source of dark energy. It is thus interesting to observe both some high-redshift and many moderate-redshift Type Ia SNe.

For photometric surveys designed to discover large numbers of moderate-redshift SNe, it is currently not practical to determine the type of every SN via spectroscopy. In addition, if the SNe are not discovered in nearly real time, then spectroscopic follow-up may be impossible. Another way to identify the cosmologically useful Type Ia SNe is therefore necessary. We examine here the idea of photometric identification of Type Ia SNe in the context of large synoptic photometric surveys. Aspects of such photometric identification have been explored extensively in Poznanski et al. (2002). Riess et al. (2004) provide an application of this method to very high redshift (\( z > 1.5 \)) SNe discovered with the Hubble Space Telescope (HST). Here we combine and extend these two studies by examining the blue magnitudes of moderate-redshift SNe (\( z \leq 1.0 \)), making use of the rest-frame UV differences between SN types that were noted by Riess et al. (2004). In a shift of emphasis from Poznanski et al. (2002) we explore the use of photometric properties for SN type identification when independent redshift information is not available but temporal information is available. We explore the possibility that identification of Type Ia SNe can be accomplished using information at a single observed epoch in the SN light curve, provided that the epoch is known. For the first time we attempt to estimate the uncertainties in this method due to the dispersion in observed SN colors that may arise from many sources. We also discuss the use of other information that is likely to be available in typical synoptic surveys.

Proposed projects such as the Large Synoptic Survey Telescope (LSST),\(^1\) which would image the entire visible sky once every few days, may benefit from a photometric method of typing SNe. By photometrically identifying objects that are unlikely to be Type Ia SNe, the LSST or other large, rapid-cadence SN surveys could greatly increase the efficiency of campaigns to observe Type Ia SNe spectroscopically. It may be possible that for certain restricted studies the SN spectra will not be necessary at all if the Type Ia SNe can be identified in such surveys by photometric means (Barris & Tonry 2004, 2006). Such methods have been considered by Sullivan et al. (2006) and Barris & Tonry (2006), although these authors are restricted to examining small differences between light curves and magnitudes in the redder observed-frame bands. A main aim of this study is to examine the additional utility of rest-frame UV photometry in type classification.

2. PHOTOMETRIC SN OBSERVABLES

The aim of this study is to determine which set of observables is most advantageous for separating Type Ia SNe from other types,
including which filters are most useful or necessary. Most other objects that vary with the timescale and amplitude of SNe have very different colors (e.g., Cepheids), are repeating, or are very rare (e.g., long-duration novae). For this reason we concentrate on separating Type Ia SNe only from other SN types. We assume that the SNe will be detectable in several wavelength bands with adequate signal-to-noise ratio (S/N) for at least 10 rest-frame days after maximum (for Type Ia SNe this translates into \( \leq 1 \text{mag below maximum light} \)).

Thus, the magnitude, several colors, and temporal information will be available to aid in the identification/separation of Type Ia SNe. Note that color, magnitude, and morphological information may also be available for the SN host galaxy. In § 4 we begin the discussion of type separation by using broadband colors at a single observed epoch to discriminate between SNe. In § 5 we discuss the addition of the magnitude observable to the color observables, and in § 6 we discuss combinations of observables that include time as well (i.e., multiple epochs). In each case we examine selected subsets of the observables. We are prevented from considering all observables at all redshifts simultaneously due to insufficient spectral data. Throughout the discussion in these sections it is assumed that independent redshift information is not available. In § 7 we discuss the possibility that some information about the host galaxy will be available as well, especially for the lower redshift sources. This may include the morphology and/or a photometric redshift.

In the following we denote Johnson-Cousins filters with capital letters and the Sloan Digital Sky Survey (SDSS) filters with primed lowercase letters. We also investigate the use of a filter system in which the central wavelengths are logarithmically spaced (hereafter referred to as the “logarithmic system”). This filter system has been designed such that the entire optical region is divided into four filters that redshift into each other [at redshift intervals of \((1+z) \approx 1.35\)]\(^\text{2}\), minimizing the cross-filter \(K\)-corrections at these redshifts (see Davis et al. 2006 for a more detailed investigation of this idea). It shares with the SDSS system the advantage that the \(O \lambda \lambda 5507 \) night-sky emission falls between two of the filters. This filter system is likely to be adopted for use on the Advanced Liquid-Mirror Probe of Asteroids, Cosmology, and Astrophysics (ALPACA, a liquid-mirror survey telescope; Corasaniti et al. 2006). These filters are labeled with lowercase unprimed letters. These three filter systems are shown in Figure 1. All synthetic magnitudes and colors are on the AB system (Oke & Gunn 1983). All epochs \( \tau \) are with respect to the quoted date of SN rest-frame maximum light in the \(B\) band, \(t(B_{\text{max}})\), and are given in days in the SN rest frame unless otherwise noted. Throughout this study we use a concordance cosmology: \( \Omega_m = 0.3\), \( \Omega_{\Lambda} = 0.7\), \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\).

3. THE TEMPLATE SPECTRA

We investigate the appearance of SNe in the photometry data using synthetic magnitudes derived from template spectra that are described in this section. We have two classes of spectra: a few with extensive UV coverage from space telescopes and many with poor UV coverage from ground-based telescopes.

3.1. UV+O Spectra

Table 1 gives the details of ultraviolet+optical (UV+O) template spectra with extensive UV coverage, and they are shown in Figure 2. Every major SN type except Type IIL\(^2\) is represented. We combine Type Ib and Type Ic into the single class Type Ib/c, since at the epochs considered here they present very similar broadband colors (Poznanski et al. 2002). The UV spectra are taken from the preview data generated by the Multimission Archive at Space Telescope (MAST).\(^3\) All the UV spectra are from the \(HST\) Space Telescope Imaging Spectrograph or Faint Object Spectrograph (FOS), except for the SN 1992A \(\tau = 9\) days spectrum.

\(^{2}\) Type IIL SNe have only been observed in the UV by \(IUE\), and there is a significant gap in the wavelength coverage between the \(IUE\) spectra and the available optical spectra, making normalization difficult at best.

\(^{3}\) Available at http://archive.stsci.edu/data.html.

### TABLE 1

| SN Name                | Type | Redshift | UT Date \((B_{\text{max}})\) | Epoch \((\tau)\) | Wavelength | \(A_T\) | References |
|------------------------|------|----------|-----------------------------|----------------|-------------|--------|------------|
| 1992A                  | Ia   | 0.0062   | 1992 Jan 19                 | 5, 9           | 2000–9820   | 0.1    | 1          |
| 1993J                  | IIb  | −0.0001  | 1993 Apr 15                 | 0              | 1600–9910   | 1.0    | 2, 3, 4, 5 |
| 1994I+1999ex           | Ic   | 0.0015, 0.011 | 1994 Apr 8                 | 10             | 2250–9650   | 1.2, 1.0\(^{a}\) | 6, 7, 8 |
| 1998S+bbody            | In   | 0.0028   | \(\sim 1998\) Mar 20       | 10             | 1200–10000  | 0.6    | 9, 10, 11, 12 |
| 1999em                  | IIIP | 0.0024   | 1999 Oct 31                 | 5\(^{b}\)       | 1200–10050  | 0.3    | 13, 14, 15, 16 |

\(^{a}\) The two values refer to SN 1994I and SN 1999ex, respectively.

\(^{b}\) The optical portion of the spectrum redder than 7700 \(\text{Å}\) was formed by interpolating between the \(\tau = +3\) and +8 spectra of reference 14.
which is from IUE. Except for the hybrid spectra discussed in § 3.2, there was significant overlap between the optical and the UV wavelength coverage, and the UV spectra were well matched to the optical spectra after multiplication by a constant (with a value on the order of 1). These UV+O spectra have been deredshifted and dereddened according to the values given in Table 1 (see the references for a discussion of the reddening values). The extinction law used is that of Cardelli et al. (1989) as modified by O’Donnell (1994), with $R_V = 3.1$. We note that in many cases the values of $A_V$ are highly uncertain, as there is no conclusive way to quantify the SN host extinction and reddening, especially toward core-collapse SNe.

The choice of $\tau$ for these templates was determined entirely by the availability of good-quality UV spectra within 20 days of $t(B_{\text{max}})$. This reflects the consideration that spectroscopic follow-up of Type Ib SN candidates should be conducted as close to maximum light as possible. We note that the Type Ib SN template spectrum is from $\tau = +0$ days, in contrast with the other template spectra, and that the reddening to SN 1993J has not been well determined.

### 3.2. Justification of Hybrid Spectra

Two of the UV+O templates were created by combining the UV spectrum of a SN with other sources. This was necessitated by the lack of publicly available digital optical spectra at the epoch of the UV spectrum. Here we justify this method for creating the template spectra in question.

#### 3.2.1. Type Ib/c: SN 1994I and SN 1999ex

SN 1994I was observed by the HST FOS on 1994 April 18 UT, and extensive optical spectroscopy of this SN has been carried out. However, the only spectrum that is publicly available in machine-readable form is from 1994 April 8 UT. Optical spectra of SN 1999ex at $\tau = 13$ days, on the other hand, have been made available in digital form. Both SNe were Type Ib and displayed very similar spectra (Hamuy et al. 2002). It is the strength of this similarity that gives us the confidence to form this hybrid spectrum. Unfortunately, the color evolution of these two SNe differed significantly. Stritzinger et al. (2002) showed that the $B - V$ color of SN 1994I was 0.25 mag redder than SN 1999ex at $\tau = 10$. This is due to the fast evolution of SN 1994I, which resembles that of SN 1999ex compressed in time. This is a general problem when exploring the colors of Type Ib/c SNe, which is discussed in more detail in § 4.1.3.

#### 3.2.2. Type IIn: SN 1998S and a Blackbody

SN 1998S displayed a relatively featureless blue continuum during its early evolution ($\sim 10$ days $< \tau < 40$ days). Leonard et al. (2000) show that the 27 March spectrum [$t \approx 7$, dereddened with $E(B - V) = 0.1$] can be approximated by a $T = 10,000$ K blackbody to within 10% for $\lambda > 5000$ Å. Fassia et al. (2001) show a 30 March spectrum with similar shape. We therefore approximate the $\tau = 10$ unreddened spectrum with a blackbody curve for $\lambda > 5500$ Å. As we mention in § 4.1.1 the $V - R$ and $R - I$ colors of this template agree well with the published photometry, thus increasing our confidence in the blackbody approximation of the spectrum.

### 3.3. Other Spectra

We have also collected many publicly available SN spectra, mostly from the SUSPECT database, that do not have good UV coverage (Table 2). They have been deredshifted and dereddened according to the values given in Table 2 and with the same reddening law described in § 3.1. We use these spectra to estimate the homogeneity (or lack thereof) of the colors of various SN types near the UV+O template epoch. Also, these spectra span a range of epochs and are used in the temporal analysis of spectra in § 6, i.e., in the examination of the color evolution of SNe as a possible SN type discriminator. Studies involving these spectra with poor UV coverage are necessarily limited to low redshift and/or the redder filters.

### 4. COLOR SEPARATION: COLOR-COLOR DIAGRAMS

We first attempt to separate Type Ia SNe from other SN types over a range of redshifts on the basis of their colors at a single observed epoch with respect to the observed date of maximum light, since we are assuming here that the redshift is not independently known. This is likely to be the problem faced by many synoptic SN surveys. Note that we implicitly assume here that enough light-curve (i.e., time and magnitude) information is available to identify the date of maximum light in a given observed band. Because of the paucity of existing UV SN spectra we are forced to consider only one observed epoch when investigating the appearance of SNe in the bluer bands and at higher redshifts. True multicolor SN surveys are likely to have measurements in several bands over a larger range of epochs. We address this in § 6 for the filter and redshift combinations in which this is possible. Here we consider only one observed epoch, assuming that enough measurements exist in at least one band to identify the time of maximum light in that band to reasonable accuracy ($\pm 1$ day).

In attempting to compare colors at a single observed epoch with respect to observed maximum light we must account for two systematic effects. First, for a given filter the time of SN maximum light in that filter [with respect to $t(B_{\text{max}})$] changes with redshift. This is because redshifting causes different portions of the rest-frame spectrum to be sampled by any one filter, and different parts of the spectrum may peak at different times. The general trend of this effect for all SN types is that the bluer parts of the spectrum peak before the redder parts, since the photosphere cools as the SN evolves. Second, cosmological time dilation will also change the relationship between $\tau$ and the observed epoch.

It is important to have clear notation when relating the observed epochs to $\tau$. We write the date of observed maximum light

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Footnote:

4 Available at http://bruford.nhn.ou.edu/~suspect.
where \( UT_{\text{obs}} \) is the date of the observation (in days) and \( z \) is the redshift of the SN. The first term accounts for the change in \( \tau \) due to the different wavelength region being observed, and the second term accounts for the change in \( \tau \) due to the time of observation and cosmological time dilation. Both terms are dependent on the redshift of the SN. In what follows the distinction between \( T \) (observed frame) and \( t \) (rest frame) is important.

Due to the availability of spectral data we choose \( UT_{\text{obs}} = T(\tau_{\max}) + 8 \) observer-frame days as the fiducial observed epoch at which we compare the SN colors. As shown below, this results in rest-frame epochs \( \tau \) that are close to those of the template spectra for a wide range of redshifts. With more complete template spectra we would be able to compare colors at several observed epochs. We address this problem in § 6 for a limited redshift and filter set that does not sample the rest-frame \( \lambda < 3600 \) Å spectrum of SNe.

As an example we consider a Type Ia SN at \( z = 0.1 \) and 0.5. The blueshifted band \( 0.1 \tau \) is approximately equal to the \( R \) band, and since \( t(\tau_{\max}) - t(B_{\max}) = 2 \pm 1 \) rest-frame days (see the template light curves of Leibundgut et al. 1991), then \( t(\tau_{\max}) - t(B_{\max}) = 2 \pm 1 \) rest-frame days as well. Thus, \( UT_{\text{obs}} = T(\tau_{\max}) + 8 \) observer-frame days corresponds to \( \tau \approx 9 \) rest-frame days. Similarly, for a Type Ia SN at \( z = 0.5 \), the blueshifted band \( 0.5 \tau \) is approximately equivalent to the \( B \) band, and so \( t(\tau_{\max}) - t(B_{\max}) = 0 \pm 1 \) days and \( UT_{\text{obs}} = T(\tau_{\max}) + 8 \) corresponds to \( \tau \approx 5 \) days. Thus, template spectra from different epochs \( \tau \) should be used when calculating the colors of a SN at a given observed epoch. For the Type Ia colors we can do this by using the \( \tau = 9 \) Type Ia SN UV+O spectrum to calculate colors at \( z = 0.1 \) and the \( \tau = 5 \) Type Ia SN UV+O spectrum to calculate colors at \( z = 0.5 \). We show the colors for both spectra in all subsequent figures. Given the similarity of the \( r \) and \( r' \) filters, the results are not significantly changed if we choose \( UT_{\text{obs}} = T(\tau_{\max}) + 8 \) observer-frame days as the fiducial.

Similar considerations can be made for Type Ib/c and Type II SNe (although for Type IIP SNe maximum light may not be well defined, especially in the redder bands), with similar results \( (T(\tau_{\max}) + 8 \) corresponds to \( \tau \approx 4-16 \) days). However, for these SN types we have only one template UV+O spectrum, so the colors cannot be adjusted for this effect. For this reason we add the systematic color differences caused by this effect to the error estimate in § 4.1, treating our lack of multiepoch spectral templates as, essentially, an uncertainty in the rest-frame epoch of the SN.

We use the spectra listed in Table 1, redshifted in steps of \( \Delta z = 0.01 \), and the filter+CCD transmission curves of Figure 1 to construct synthetic magnitudes. The results for the SDSS and logarithmic systems are shown in Figures 3 and 4, respectively. Note that for the Type Ib/c and Type Ia spectra we do not have complete UV wavelength coverage for the bluest filters at the highest redshifts.

We see that for both the SDSS and logarithmic filter systems the redder filters give better separation of Type Ia SNe from other types for lower redshifts, while the bluer filters give better separation at higher redshifts. Combining four filters into a \( u' - g' \) versus \( r' - i' \) diagram (Fig. 3) gives the best separation over all redshift ranges for the SDSS system. Comparable, and perhaps even better, results are obtained for the \( u - b \) versus \( r - i \) colors in the logarithmic system (Fig. 4).

### 4.1. Dispersion in SN Colors

For this method of identifying Type Ia SNe to be useful it is important to quantify the expected or typical difference between the colors of the different SN types calculated from templates and the colors of a real, observed SN. A difference between real,
observed colors and those calculated from templates can have several sources, which we list in detail as follows:

1. Photometric errors:
   A. Spectrophotometric errors in the template spectra. Only spectrophotometric errors that are a function of wavelength are relevant.
   B. Errors in the adopted filter+CCD response functions.
   C. Expected photometric errors of the observed SNe.
   D. Contamination by host galaxy light.

2. Reddening due to dust in the SN host and the Milky Way:
   A. Incorrect dereddening of the template.
   B. Reddening of the observed SN.

3. Intrinsic difference in SN spectra:
   A. Is the template spectrum typical for its type?
   B. What is the intrinsic scatter about the typical spectrum?
4. Epoch of the SN:
A. Uncertainty in the epoch of the template spectrum.
B. Error in correction for redshift effects (time dilation and change of maximum light date).
C. Stretch correction effects (for Type Ia SNe).
D. Uncertainty in the epoch of the observed SN.

Here we attempt to quantify these differences, which are referred to as $\delta c$, for each of the SN types.

4.1.1. All SN Types

Several of the effects in the above list can be considered simultaneously for all SN types, and we address them here. First, there are the expected photometric errors of the SN observation. These directly affect the $\delta c$, since the photometric errors can lead to inaccurate measurement of the SN color. For S/N > 10 the photometric errors are typically <0.1 mag, and the error in color is <0.14 mag if we assume the photometric errors are uncorrelated. This error will certainly depend on redshift and SN type, but we take 0.14 mag as an upper limit.

There are also errors associated with our method for creating synthetic spectra. These errors affect $\delta c$ by giving a color for the template SN that is incorrect and therefore not representative of the SN type as a whole. The error due to the numerical integrations involved is less than 0.005 mag, which is negligible compared to other sources. The error due to inaccurate spectrophotometry is investigated below. We note that only spectrophotometric errors in the template spectra that are a function of wavelength are of importance.

To investigate possible errors in the template spectrophotometry we have calculated synthetic magnitudes on the Johnson-Cousins system, using the transmission functions of Bessel (1990) and the template UV+O spectra, reddened again by the values given in Table 1. The Bessel (1990) transmission functions have been adjusted for use with photon spectra following Hamuy et al. (2001a). The conversion from AB to Vega-based magnitudes has been determined using the Kurucz (1979) model for the spectrum of Vega, with normalization at $\lambda = 5000$ Å from Hayes (1985). We then compare the colors calculated in this way to the published Johnson-Cousins photometry. We find that for the most part the colors agree to within 0.07 mag (even for SN 1999AS+blackbody). The exceptions to this are some of the $U-B$ colors and the colors of the Ib/c template spectrum. The larger discrepancy of the synthetic $U-B$ colors is most likely related to actual $U$-band effective filter functions that are significantly different from our assumed filter transmission function and are therefore difficult to transform to the standard system. This is a common problem in the $U$ band (Suntzeff et al. 1999; Richmond et al. 1994). Also, the effects of atmospheric extinction are more pronounced in the $U$ band. It is possible that there are significantly larger spectrophotometric errors in the SN templates in the $U$ band and farther in the UV where there is no photometry to provide a check. However, we believe this is unlikely due to the close correspondence of the UV and optical spectra in the region of overlap. This region of overlap often encompasses a significant portion of the $B$ and $V$ bands where the synthetic colors agree well with published photometry. However, the discrepancy between the synthetic and published colors of the template Type Ib/c spectrum is clearly due to the hybrid nature of the spectrum, since the $U-B$ and $B-V$ colors are close to those of SN 1994I but the $V-R$ and $R-I$ colors are close to those of SN 1999ex (see § 3.2.1).

As mentioned above, some discrepancy between synthetic magnitudes and measured magnitudes may occur due to incomplete knowledge of the filter+CCD+telescope+atmosphere transmission functions that characterize the observer’s system. For a large photometric survey we assume that the photometric system will be well characterized via calibration observations, and that this will be a negligible source of error-SN colors can be calculated for an arbitrary filter system.

We must also consider reddening. Reddening can affect $\delta c$ in two ways. First, if the reddening correction applied to the template SN spectra is incorrect, then the colors of the template spectrum will be different from that of the “true” unreddened template for a SN type. We refer the reader to the references listed in Tables 1 and 2 for a discussion of the SN template reddening. Second, observed SNe will be affected by various amounts of reddening and will thus have colors that are redder than the true unreddened template SN. We have investigated the effect of reddening in the SN host galaxy by applying $A_V = 1$ mag of dust to the rest-frame template spectra using both a Cardelli et al. (1989) dust law (containing the 2175 Å bump) and a Calzetti et al. (1994) starburst galaxy dust law. This is repeated for all redshifts studied here. These reddening vectors are shown in the color-color diagrams as arrows. Strictly speaking, the change in color for a given amount of extinction depends on the spectrum of the object, but we find that one reddening value for each color and redshift describes the effect of reddening for all the template spectra to within 0.05 mag. To more clearly show the effect of reddening on Type Ia SN separation, we have also created color-color diagrams with $A_V = 1$ reddening applied to just the Type Ia SN template (Fig. 5, left) and with the reddening applied to all the SN types except Type Ia (Fig. 5, right).

Lastly, for all SN types, contamination by host galaxy light may play a role. This will depend strongly on the color and magnitude of the local background due to the host galaxy. An investigation of the demographics of host galaxies and the distribution of location of SNe within the hosts is beyond the scope of the present study.

There are two more important effects that can add to $\delta c$. The first is the intrinsic variation in the spectra of SNe of a given type at a given epoch, referred to hereafter as “spectral inhomogeneity.” The second effect is due to differences between the epoch of the template spectrum and the epoch of the observed SN, since the spectra evolve with time, and is referred to in what follows as “spectral evolution.” These effects are type-dependent. Moreover, they are very difficult to quantify with the small number of SN spectra currently available, especially for the core-collapse SNe.

4.1.2. Type Ia

We first discuss the expected spectral inhomogeneity of Type Ia SNe based on published rest-frame Johnson-Cousins photometry. Nobili et al. (2003) have examined a large sample of well-observed Type Ia SNe in detail. Assuming that Type Ia SN colors are nearly identical at $t \sim +35$ days (Lira 1996) to correct for extinction, and correcting the time axis for the stretch parameter $s$ (Perlmutter et al. 1997), they determine intrinsic dispersions in $B-V$, $V-R$, and $R-I$ color. From $(t_{B_{\max}})$ to $t = 15$ the dispersions in all three colors are $<0.11$ mag. Thus, we see that intrinsic differences in the rest-frame optical color at a single stretch-corrected epoch are small, and it seems likely from the work of Phillips et al. (1999) and Wang et al. (2003) that much of the remaining difference is correlated with the absolute magnitude of the SN (which is related to $s$). To be conservative we use twice the dispersion given by Nobili et al. (2003) as the contribution to $\delta c$ for all colors (adjacent bands) and redshift combinations that sample the rest-frame 4000–9000 Å region of the SN spectrum.
To estimate the effect of Type Ia spectral evolution using published rest-frame Johnson-Cousins photometry we examine the change in color as a function of time. From \( t(B_{\text{max}}) + 5 \) to +20 the rate of change of the \( B/C_0 \), \( V/C_0 \), and \( R/C_0 \) colors is small, \( \Delta \text{color}/\Delta t \leq 0.05 \text{ mag day}^{-1} \) (Nobili et al. 2003). Differences between the true rest-frame epoch of a SN observed at \( T(r_{\text{max}}) + 8 \) and the epoch of the template spectrum can arise for several reasons. First, there is a randomly distributed uncertainty in the epoch of the observed SN due to the difficulty of determining the date of maximum light from a light curve with only a simple analysis. This uncertainty depends strongly on the specific observing scheme used and realistically will also have some dependence on the redshift of the SN, but for most surveys it should be \( \leq 2 \) days.

There are also errors in the epoch associated with the redshift effects described at the beginning of \( \S \) 4, which for Type Ia SNe will certainly be \( \leq 2 \) rest-frame days. The uncertainty in the epoch of the template spectrum is \( \Delta \text{epoch} \leq 2 \) days. Adding the known errors in quadrature we obtain a typical difference between the template epoch and the observed SN epoch of \( \pm \)2 rest-frame days, corresponding to an uncertainty in color of \( \pm 0.16 \) mag. We note that for Type Ia SNe an additional systematic source of uncertainty in

the epoch is the light-curve stretch parameter \( s \) [or \( \Delta m_{15}(B) \)], which for our purposes can be thought of as changing the spectral epoch. This was accounted for in the analysis of Nobili et al. (2003), so we must reintroduce the effect of this parameter on color assuming that \( s \) will not be known from simple, preliminary light-curve analysis (especially if the redshift is unknown). The template Type Ia SN, SN 1992A, had a stretch parameter of 0.84. Typical values of the stretch parameter range from 0.70 to 1.15, corresponding to a difference from the template epoch of \( \leq 2.5 \) days at \( \tau = 9 \). This would give an additional 0.1 mag difference in color (at least for the rest-frame optical colors).

However, to investigate spectral inhomogeneity and evolution in more detail and for the filter systems under consideration we calculate the colors of a number of different Type Ia SN spectra at epochs close to the template UV+O spectrum epoch. As an example Figure 6 shows the \( z = 0.1 \) and 0.2 color-color diagrams for five different Type Ia SNe (and other SN types) at 4 \( \leq \tau \leq 13 \). The range in color of these spectra should therefore be caused by spectral evolution, spectral inhomogeneity, and, to some extent, errors in reddening determinations. Note that SN 1992A at \( \tau = 7 \) would appear to fall near the middle of the range of Type Ia

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**Fig. 5.**—SN colors as a function of redshift in the \( u' - g' \) vs. \( r' - i' \) SDSS color-color diagram. Symbols are the same as in Fig. 3. **Left:** With \( A_V = 1 \) mag reddening (Calzetti et al. 1994 dust law) applied only to the rest-frame Type Ia SN spectrum. **Right:** With \( A_V = 1 \) mag reddening (Calzetti et al. 1994 dust law) applied to the rest-frame spectra of all SN types except Type Ia.

**Fig. 6.**—Left: \( g' - r' \) vs. \( r' - i' \) color-color diagram at \( z = 0.1 \) for SNe after maximum. The symbols encode the different SN types: Ia (stars), Ib/c (circles), IIP (triangles), and IIb or IIL (squares). The labels next to each SN indicate the SN name and epoch \( \tau \). **Right:** Same as left panel, but at \( z = 0.2 \).
colors. To be conservative, we take half of the full range of the resulting Type Ia colors to obtain an estimate of \( \delta c \). We do this for all redshifts and colors for which at least five spectra are available. The results are presented in Table 3, where the number in parentheses gives the number of spectra from different epochs and/or SNe available at that redshift. After adding a photometric error of 0.14 mag we can compare these values with our expectations from the rest-frame Johnson-Cousins photometry given above. For example, at \( z = 0.6 \) the \( r - i \) color approximates rest-frame \( B - V \). We see that \( \delta c \) as given by synthetic photometry using several different template spectra is generally smaller than the estimate based on Johnson-Cousins photometry. This may reflect the small number of template spectra used to determine \( \delta c \), but it gives us confidence that our estimate of \( \delta c \) from Johnson-Cousins photometry is not drastically low, even when applied to different redshifts and filter combinations that only approximate rest-frame \( B - V \). Obviously, a larger number of template spectra would improve the determination of \( \delta c \) from synthetic photometry.

We estimate total values for \( \delta c \) (for the SDSS system) in Table 4. These estimates are based on the behavior of the rest-frame Johnson-Cousins colors of Type Ia SNe, as described above. Little weight is given to the values of \( \delta c \) determined directly from template spectra, as these are likely to be too low due to our small sample. It is clear that not all the errors in color are uncorrelated or even normally distributed, but a more rigorous analysis of \( \delta c \) is unwarranted given the necessary approximations. At higher redshift and for bluer filters we do not possess sufficient photometric or spectral data in the rest-frame UV to estimate \( \delta c \) data. However, we expect that \( \delta c \) will be larger, due to both spectral inhomogeneity and spectral evolution. This is because we are sampling the rest-frame UV, \( \lambda < 3600 \) \AA, where there are many more spectral lines that can vary in strength and location depending on the metallicity and detailed evolution of the SN, causing variations in the broadband colors (Kirshner et al. 1993) due to spectral inhomogeneity. Note also that evolution is generally more rapid in the bluer bands, so errors in epoch will lead to larger errors in color for the bluer bands. We therefore adopt values of \( \delta c \) that increase with decreasing wavelength.

### 4.1.3. Type Ib/c

Detailed color studies such as that presented in Nobili et al. (2003) are not available for Type Ib/c SNe. In fact, color curves have been published for only a handful of Type Ib/c SNe. The three most complete published Type Ib/c color curves are collected in Stritzinger et al. (2002). Despite the dearth of observational data, it is often stated that Type Ib/c SNe fall into two groups: fast-evolving (in both luminosity and color) and slowly evolving. It is not clear whether there is a continuous distribution between these extremes or what the range in “speed” is of Type Ib/c SNe. However, as discussed in § 3.2.1 the difference in \( B - V \) at \( t(B_{\text{max}}) \) for the fastest and slowest known evolving Type Ib/c SNe is approximately 0.3 mag (the range decreases slightly at \( t = 10 \)). Near \( t(B_{\text{max}}) \) the rate of change of \( B - V \) is largest for the fast-evolving Type Ib/c SNe: \( \Delta(B - V)/\Delta t \approx 0.1 \) mag day\(^{-1} \). Near \( t(B_{\text{max}}) + 10 \) the rate is less for both fast and slowly evolving Type Ib/c SNe, approximately 0.06 mag day\(^{-1} \). This would give a ±0.3 mag error in color for a ±5 day error in epoch.

We can use these data to estimate \( \delta c \), as was done in § 4.1.2 for Type Ia SNe. The contribution of spectral inhomogeneity must be carefully considered, since our template spectrum is a hybrid spectrum formed from a fast-evolving SN in the UV and a more slowly evolving SN in the optical. As already discussed, this will cause the colors calculated from these different regions of the spectrum to be inconsistent with each other. However, an adequate estimation of \( \delta c \) will ensure that the correct, consistent SN colors will fall within the quoted range of color. We thus use the full range in \( B - V \) color for well-observed Type Ib/c SNe as the contribution of spectral inhomogeneity to \( \delta c \) for the appropriate redshifts and filters. Adding to this the contribution of spectral evolution noted above and photometric errors then gives an estimate for \( \delta c \) of approximately 0.5 mag. This will be an appropriate value for \( \delta c \) when the redshift and filter combination samples the rest-frame \( B \) and \( V \) region of the spectrum, i.e., \( \delta(g' - r') \) for \( z \leq 0.3 \) and \( \delta(r' - i') \) for \( 0.3 < z \leq 0.6 \). For colors and redshifts

### Table 3

| Redshift | \( \delta(u' - g') \) | \( \delta(g' - r') \) | \( \delta(r' - i') \) |
|----------|---------------------|---------------------|---------------------|
| 0.1...... | 0.15 (9)             | 0.10 (9)             |                     |
| 0.2...... | 0.15 (8)             | 0.08 (9)             |                     |
| 0.3...... | 0.12 (3)             | 0.05 (9)             |                     |
| 0.4...... | 0.15 (9)             |                     |                     |
| 0.5...... | 0.22 (8)             |                     |                     |
| 0.6...... | 0.12 (7)             |                     |                     |

### Table 4

| Redshift | \( \delta(u' - g') \) | \( \delta(g' - r') \) | \( \delta(r' - i') \) |
|----------|---------------------|---------------------|---------------------|
| Type Ia  |                     |                     |                     |
| 0.1...... | 0.30               | 0.30               | 0.30               |
| 0.2...... | 0.40               | 0.35               | 0.25               |
| 0.3...... | 0.50               | 0.35               | 0.20               |
| 0.4...... | 0.60               | 0.40               | 0.20               |
| 0.5...... | 0.70               | 0.50               | 0.30               |
| 0.6...... | 0.80               | 0.60               | 0.35               |
| 0.7...... | 0.70               |                     | 0.40               |
| 0.8...... | 0.80               |                     | 0.45               |
| 0.9...... | 0.80               |                     | 0.50               |
| 1.0...... |                     |                     | 0.55               |
| Type Ib/c|                     |                     |                     |
| 0.1...... | 0.4                | 0.4                | 0.3                |
| 0.2...... | 0.5                | 0.4                | 0.4                |
| 0.3...... | 0.6                | 0.5                | 0.5                |
| 0.4...... | 0.7                | 0.5                | 0.5                |
| 0.5...... | 0.8                | 0.6                | 0.5                |
| 0.6...... | 0.8                | 0.7                | 0.6                |
| 0.7...... | 0.7                |                     | 0.6                |
| 0.8...... | 0.8                |                     | 0.6                |
| 0.9...... | 0.8                |                     | 0.7                |
| 1.0...... |                     |                     | 0.7                |

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that sample bluer regions of the spectrum we again adopt values of δc that increase with decreasing wavelength.

4.1.4. Type II

We would need many UV+O spectra spanning a range of epochs for many Type II SNe of different subclasses to adequately investigate the contribution of spectral inhomogeneity and spectral evolution to δc. As these data do not exist, we must rely on studies of the optical photometric behavior of Type II SNe, the most comprehensive of which is presented in Patat et al. (1994). We can simultaneously consider the effects of spectral inhomogeneity and spectral evolution by examining their Figure 3, where they present $B - V$ color curves of 21 Type II SNe, including Type IIP, Type IIL, and Type IIpec (no correction for reddening has been applied). Spectral inhomogeneity is accounted for by including 18 SN color curves (we ignore SNe 1972Q, 1973R, and 1987A, which are all anomalously red; two of these are likely highly reddened, and we show the effects of reddening elsewhere) and determining the width of the $B - V$ color curve. We can simultaneously take into account the effect of spectral evolution by then considering the full range of colors for these 18 SNe from $\tau = 0$ to 30 days. We use a large range of $\tau$ to account for the difficulty in determining epochs for Type II light curves, especially Type IIP. This gives a ±0.5 mag range in color about the central value. The range in epoch that we have used for Type IIP is a pessimistic estimate when applied to Types IIb and IIn, but we use these ranges as a safe upper limit to δc. This is especially true of the Type IIb template colors, which were calculated using a $\tau = 0$ spectrum. Note also that the colors of the Type II template spectra that we use are somewhat bluer than the central value; this is to be expected when using a range in $\tau$ that extends to such late epochs while the template spectra come from very early epochs.

4.2. Discussion of Color-Based Separation

In the ideal case in which $u', g', r', and i'$ (or $u, b, r, and i$) magnitudes are available we see that the separation of Type Ia SNe from other types is very good, even when we take into account realistic errors in the determination of the $r_{\max} + 8$ day colors (Fig. 7). Separation is somewhat better with the logarithmic system. In both cases the most likely contaminant is low-redshift Type Ib/c SNe, which may be confused with higher redshift Type Ia SNe given the expected errors in color, although they can be separated from Type Ia SNe at the same redshift (e.g., Gal-Yam et al. 2004). Other possible contaminants include high-redshift ($z > 0.4$) Type IIP SNe and moderate-redshift Type IIb SNe. In Figure 5 we see that due to the direction of the reddening vectors, reddening does not appear to pose a significant problem for Type Ia SN identification in the $u' - g'$ versus $r' - i'$ diagram. The only exception is that reddened low-redshift Type Ia SNe look like higher redshift Type Ia SNe and can thus possibly be confused with low-redshift Type Ib/c SNe, as already mentioned. This will not affect the absolute rate of contamination of the Type Ia sample by Type Ib/c. To identify SNe that are...
likely to be of Type Ia using this diagram, one can choose SNe that are very red in $u' - g'$ color for a given value of $r' - i'$.

When fewer colors are available the difficulty of Type Ia SN identification significantly increases. In the $u' - g'$ versus $r' - i'$ diagram it is clear that while the contaminants will be similar, the amount of overlap between Type Ia SNe and these other types will increase, making it more likely that SNe are misidentified. It also appears that reddening begins to play more of a role. This is especially true of the $g'$ versus $r' - i'$ diagram, in which the only unambiguous Type Ia SNe are at $z \leq 0.2$, and these SNe can easily be reddened into regions of color-magnitude space occupied by other SN types. However, if a SN is observed to have $r' - i' \lesssim -0.2$ mag around 8 days after maximum light, then it is likely to be a Type Ia SN at very low redshift.

5. ADDING MAGNITUDE INFORMATION: COLOR-MAGNITUDE DIAGRAMS

It appears possible to use $u' - g'$ versus $r' - i'$ diagrams to aid in the selection of probable Type Ia SNe, since many regions in color-magnitude space that are occupied by non-Type Ia SNe are not occupied by Type Ia SNe at any of the redshifts considered here. Thus, objects populate these regions can be excluded from the Type Ia SN sample without any further information. But can we do better? Type Ia SNe have reasonably constant luminosity; therefore, it might be useful to look at magnitude information as an additional discriminator. Here we consider the addition of magnitude information in the form of color-magnitude diagrams.

We created color-magnitude diagrams of the template spectra in a manner similar to the way we created color-color diagrams in § 4. The flux scale of the spectra was calibrated so that the SNe have typical luminosities for their type (Richardson et al. 2002) and age.

5.1. Errors in the Diagrams

We have already examined the expected typical spread in color for the SN types, $bc$. Here we examine the dispersion in magnitude expected at a given redshift. Extinction will have the same effect in the magnitude axis that reddening does on the color axes. In addition, amplification by gravitational lensing can affect the observed magnitude, but this is expected to be a negligible effect at the redshifts investigated here. By far the largest effect, for all SN types, is the intrinsic dispersion in SN luminosity. Richardson et al. (2002) have examined this phenomenon for many SN types, and we use their results. Their central absolute $B$ magnitude values for each type, rescaled to $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, converted to AB magnitude, and combined with template light curves (or the published $m - m_{\text{max}}$ in the case of Types II and Ib), were used to flux-calibrate the template UV+O spectra from Table 1. In the case of the Type IIb template (not considered by Richardson et al. 2002) we have used a luminosity appropriate for a normal Type Ib/c or a normal Type IIIL. We do not add magnitude differences caused by uncertainty in the light-curve epoch or measurement errors, and we use the 1 $\sigma$ standard deviations of Richardson et al. (2002). The magnitude errors presented should thus be taken as lower limits.

5.2. Discussion of Color-Magnitude-Based Separation

Figure 8 shows that there is an enormous amount of overlap between Type Ia SNe and other SN types in the color-magnitude diagram. Especially problematic is the continued confusion of low-redshift Type Ib/c SNe with higher redshift Type Ia SNe. The essential problem is that while Type Ib/c SNe are redder than Type Ia at a given redshift, they are also intrinsically fainter. Type Ib/c SNe at $z = 0.1-0.3$ have colors similar to those of higher redshift Type Ia SNe and are intrinsically less luminous by an amount that is similar to the distance modulus from $z = 0.2$ to 0.4. Reddening and extinction by dust of $z = 0.1-0.2$ Type Ia SNe can make them look like these low-redshift Type Ib/c SNe, and reddening and extinction of these low-redshift Type Ib/c SNe will make them look like even higher redshift ($z > 0.5$) Type Ia SNe. Without independent redshift information there is a problem in separating Type Ia from some Type Ib/c SNe using only color and magnitude information at a single observed epoch. This is a generic problem that will occur for any combination of filters and SN redshift that samples the same wavelength region in the rest-frame spectrum.

However, Figure 8 does show that high-redshift Type IIP SNe, which have colors similar to those of low-redshift Type Ia SNe, are too faint to be confused with these Type Ia SNe, if indeed they are even detected. Even if we account more rigorously for dispersion in magnitude, using twice the standard deviation of Richardson et al. (2002), adding a typical photometric error of 0.1 mag, and adding a magnitude error due to uncertainty in the light-curve epoch, we find that magnitude combined with color information at a single known epoch can be used to separate Type IIP SNe from Type Ia, in agreement with, e.g., Sullivan et al. (2006). Even if Type Ia SNe are extincted by dust so that they have the same magnitude as these high-redshift Type IIP SNe, they will be reddened so that they have different colors. Thus, one of the contaminants given in § 4.2 has been removed.

6. ADDING TEMPORAL INFORMATION

We have examined SN colors only at one epoch, $\tau \approx 10$, because of the availability of UV spectra at that epoch (with the notable exception of Type Ib and Type IIL SNe). However, it is possible that similar color-based identification of Type Ia SNe can be accomplished by looking at colors at other epochs, for example, at maximum light or even before maximum. This would have the advantages that spectroscopic follow-up could be scheduled at or very close to maximum light and that the SN would be brighter and detectable to a larger redshift. Use of the time observable in conjunction with color or magnitude information may also provide another way to separate SN types if their evolution in color or magnitude space is unique. This may be especially useful when using $g' - r'$ versus $r' - i'$ colors, where identification of Type Ia SNe based solely on colors at one epoch is difficult. To investigate these questions we examine the time evolution of SN colors. Much of the following material has been presented in Poznanski et al. (2002). We change only the filters and restrict the SN epoch to less than 35 days after $t(B_{\text{max}})$.

6.1. Color-Color as a Function of Time

Because of the significant confusion in the $g' - r'$ versus $r' - i'$ diagram it is worthwhile to look deeper for methods to disentangle these populations using only photometry. While color-magnitude diagrams help with the problem of Type IIP SNe, we also consider the evolution of color with epoch, i.e., the paths traced out in the color-color diagram as a function of epoch, as a way to discriminate between SN types.

We have sufficient spectral and epoch coverage for a large number of SNe to investigate their paths in the $g' - r'$ versus $r' - i'$ color-color diagram at redshifts $z = 0.1$ and 0.2 (Fig. 9). This is not true of higher redshifts, where there are insufficient rest-frame UV spectral data. This example must then be taken only as indicative of the further information about SN type that may be gleaned from the full multicolor light-curve information, but see Sullivan et al. (2006) for a more detailed study of the use
of this information for the redder filters. As more data become available it will be possible to extend the use of color-color-time information to other filters and redshifts. We see, however, that at these low redshifts Type Ia SNe follow a particular path in color-color space, as shown by Poznanski et al. (2002) for Johnson-Cousins filters. They become bluer in $r_0/C0_i$ as they rise toward maximum, become redder in $g_0/C0_r$ as they pass maximum, and start to become redder in both $g_0/C0_r$ and $r_0/C0_i$ about 15 days after $t(B_{max})$. There is a hint that Type Ib/c and Type IIb SNe have a different evolution, moving to redder colors in both $g_0/C0_r$ and

![Color-color diagrams](image)

**Fig. 8.**—Color-magnitude diagram ($r' \text{ vs. } g' - r'$) of the template SNe as a function of redshift, with the Type Ia spectrum ($\tau = 10$) compared to other types. Error bars show the dispersion in color (from Table 4) and the dispersion in magnitude from Richardson et al. (2002). Symbols are the same as in Fig. 3. **Top left:** Type Ia spectrum compared to Type IIb spectrum. **Top right:** Type Ia spectrum compared to Type IIn spectrum. **Bottom left:** Type Ia spectrum compared to Type IIP spectrum. **Bottom right:** Type Ia spectrum compared to Type Ib/c spectrum.

**Fig. 9.**—Left: $g' - r'$ vs. $r' - i'$ color-color diagram at $z = 0.1$ for all SN templates with $\tau < 36$. The symbols encode the different SN types: Ia (stars), Ib/c (circles), IIP (triangles), and IIb or IIL (squares). The number in each symbol indicates the epoch $\tau$. For clarity, the symbols have also been color-coded by epoch: $\tau \leq 0$ (blue), $0 < \tau \leq 10$ (green), and $\tau > 10$ (red). **Right:** Same as left panel, but at $z = 0.2$.
$r' - i'$ as they evolve from just before maximum to after maximum. It may thus be possible, as Poznanski et al. (2002) suggest, to use the shape of the color-evolution tracks to help discriminate between SN types, although this will require information obtained at a large range of epochs. In particular, the confusion between Type Ia SNe at $z \approx 0.1$ and Type Ib/c SNe at $z \approx 0.3$ can be removed by using the shape of the color evolutions to discriminate between them. We have not been able to investigate how the shape of these tracks changes at higher redshifts, which could complicate the method without independent redshift estimates. It appears from Figure 9 that type separation at early epochs is more difficult, since the early colors of Type Ia SNe are closer to the early colors of other SN types at this redshift, not to mention the early colors of SNe at different redshifts. Indeed, it appears that a rest-frame epoch $\tau = 10$ days is optimal for type separation.

6.2. Magnitude as a Function of Time, i.e., the Light Curve

Throughout this discussion we have implicitly assumed that some information about the light curve is available, specifically the date of maximum light through a certain filter. If this is not true, then other information will be necessary to identify Type Ia SNe, such as an estimate of the redshift as suggested in Poznanski et al. (2002). But to what extent does the light curve itself constrain the SN type? We have already said that the light curves of Type IIP events are significantly different in shape from Type Ia light curves, marked by a rapid rise time and, by definition, a relatively slow decay (Leibundgut et al. 1991), especially in the redder bands. Indeed, this has been used informally by Barris et al. (2004). However, in the rest-frame $U$, $B$, and $V$ bands the decay is much more rapid, and the light curve of moderately redshifted events may superficially resemble those of Type Ia SNe. It is difficult to distinguish between any of the other types based on a simple light-curve analysis near maximum. While the different types have different decline rates (Richmond et al. 1996a), type separation based on this feature is complicated by the effect of cosmological time dilation. For a more complete discussion of this topic, see Sullivan et al. (2006).

7. ON THE USE OF HOST GALAXY CHARACTERISTICS

We have assumed that the redshift of the SN cannot be determined independently. However, photometric redshifts of the host galaxies may provide a redshift constraint that would be useful in SN type identification. In addition, if the Hubble type of the host can be determined, either morphologically or jointly with the photometric redshift estimate from galaxy spectral energy distribution fitting, then we will have a significant clue to the SN type. This is due to the extreme scarcity of Type II and Type Ib/c SNe in E/S0 galaxies. The two bluest filters in the SDSS and logarithmic systems are very sensitive to the redshifting of the 4000 Å break, which is important to the determination of the galaxy photometric redshift and galaxy type.

While the $(1 + z)^4$ cosmological surface brightness dimming is beneficial in reducing the photon background from the SN host galaxy, it makes detecting the host galaxy difficult. At faint magnitudes assigning a SN to a unique host galaxy may become problematic as well. It will be important to examine the redshift limit to which photometric redshifts and morphologies can be accurately determined. This limit will certainly be lower than the detection limit for Type Ia SNe unless co-added images from many different nights are used for photometry of the host galaxies. While photometric redshifts are typically not accurate to better than $\Delta z = 0.1$ (Hogg et al. 1998), even this accuracy is sufficient to distinguish low-redshift Type Ib/c from higher redshift Type Ia SNe. Also, removing this degeneracy requires photometric redshifts of host galaxies to only $z = 0.3$. To the extent that independent redshift information for the hosts is available, the problem of type separation is reduced to that presented in Poznanski et al. (2002), and it is possible to relax requirements on the knowledge of, e.g., the epoch of the SN. We note, however, that the use of blue magnitudes at moderate redshift ($z \geq 0.3$) significantly increases the ease of type separation. We do not consider here the possibility of determining the SN redshift from the SN photometry alone, which is explored by Barris & Tonry (2004) for moderate redshifts and touched on by Mesinger et al. (2006) for redshifts $z > 5$. Note, however, that redshift and reddening are nearly degenerate in the color-color diagrams that we present.

8. CONCLUSIONS

We have shown that it is possible to separate Type Ia SNe from other SN types simultaneously over a large range in redshift by using photometric information over the entire optical spectrum. This can be done using magnitude and color information from only a single observed epoch close to maximum light [$T(r_{\max}) + 8$], provided that the epoch is known to reasonable accuracy. There is still some confusion between $z \approx 0.1$ Type Ia and $z \approx 0.3$ Type Ib/c SNe, which can be removed by considering the color evolution of these events. Photometric redshifts of the host galaxies will aid in type separation. It is possible that type separation based on optical colors can be accomplished at epochs other than those studied here, but it is likely to be difficult at very early epochs. The use of very blue magnitudes appears to be crucial for separation of Type Ia SNe from other types at $z > 0.2$, at least without extensive additional temporal information or an independent constraint on the SN redshift. This is troubling, since the very characteristic of Type Ia SNe that makes blue magnitudes useful, their faintness in this wavelength region, also makes photometry difficult.

It is important to emphasize that in considering type separation we have attempted to estimate realistic values of the dispersion in SN colors, but that we are greatly hindered by the lack of rest-frame UV spectra. While we have noted the relevant sources of $\Delta c$ in § 4.1, in many cases the available data do not allow us to precisely determine the error introduced by each source. The errors that we have given in many cases reflect a lack of knowledge rather than an irreducible scatter in measurements. Also, many sources of error depend on the specific observing strategy that is used. We believe that the color dispersions are small enough to allow type separation in many cases, but more UV spectroscopy (or even photometry) of different SNe at a variety of epochs is necessary to confirm this claim. Further extensions of this method are the inclusion of the spectra of peculiar Type Ia SNe and hypernovae and spectra at SN maximum light. Taken to its logical conclusion the method presented here could be used with a spectral database covering many SNe of different subtypes over a large, well-sampled range of epochs and UV wavelengths to construct synthetic optical magnitudes as a function of redshift, time, color, and SN type for any filter system. Such a multidimensional parameter space could then be collapsed and/or binned in any dimension or dimensions to reflect the realities of a given survey or observation, and the resulting parameter space could be searched for the best photometric indicators of SN type while accurately characterizing the typical dispersion of those indicators.

The criteria presented here (and in Poznanski et al. 2002) for the photometric identification of Type Ia SNe would allow the
efficient targeting of Type Ia SNe discovered by imaging surveys for spectroscopic and photometric follow-up. A sample of Type Ia SNe derived from such surveys will have many uses. First, the method outlined here could be tested and improved, and errors could be quantified more precisely. This would allow yet more efficient spectroscopic follow-up in future large imaging surveys, such as those conducted with LSST. There is the potential for a large increase in our knowledge of the photometric phenomenology of all SN types, especially regarding their properties in the UV. Second, other new parameters related to Type Ia luminosity may be identified. For example, the large synoptic surveys will be very sensitive to the rise time of a SN, at least for low-redshift Type Ia SNe. This is thought to be related to the intrinsic luminosity of Type Ia SNe (Riess et al. 1999). The UV behavior of SNe may be important for investigating the effects of metallicity or dust on the luminosity of Type Ia SNe. Third, if one accepts the systematic effects as negligible, then it is possible to use a large sample of Type Ia SNe to confirm and refine measurements of cosmological parameters, especially $\Omega_{\Lambda}$ and $w$, the equation-of-state parameter of the dark energy. Some authors have suggested that time-consuming spectroscopic follow-up to obtain redshifts may not be necessary for such a study (Barris & Tonry 2004), but reliable photometric identification of the Type Ia SNe, using methods such as those outlined here, will be crucial.

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