OPTICAL CROSS-CORRELATION FILTERS: AN ECONOMICAL APPROACH FOR IDENTIFYING SNe Ia AND ESTIMATING THEIR REDSHIFTS

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ABSTRACT

Large photometric surveys of transient phenomena, such as Panoramic Survey Telescope & Rapid Response System and Large Synoptic Survey Telescope, will locate thousands to millions of Type Ia supernova (SN Ia) candidates per year, a rate prohibitive for acquiring spectroscopy to determine each candidate’s type and redshift. In response, we have developed an economical approach to identifying SNe Ia and their redshifts using an uncommon type of optical filter which has multiple, discontinuous passbands on a single substrate. Observation of a supernova through a specially designed pair of these “cross-correlation filters” measures the approximate amplitude and phase of the cross-correlation between the spectrum and a SN Ia template, a quantity typically used to determine the redshift and type of a high-redshift SN Ia. Simulating the use of these filters, we obtain a sample of SNe Ia which is ~98% pure with individual redshifts measured to \( \sigma_z \approx 0.01 \) precision. The advantages of this approach over standard broadband photometric methods are that it is insensitive to reddening, independent of the color data used for subsequent distance determinations which reduce selection or interpretation bias, and because it makes use of the spectral features its reliability is greater. A great advantage over long-slit spectroscopy comes from increased throughput, enhanced multiplexing, and reduced setup time resulting in a net gain in speed of up to ~30 times. This approach is also insensitive to host galaxy contamination. Prototype filters were built and successfully used on Magellan with LDSS-3 to characterize three SuperNova Legacy Survey candidates. We discuss how these filters can provide critical information for the upcoming photometric supernova surveys.

Key words: cosmology: observations – instrumentation: miscellaneous – supernovae: general

1. INTRODUCTION

Observations of high-redshift Type Ia supernova (SN Ia; Riess et al. 1998; Perlmutter et al. 1999) reveal evidence of an accelerated rate of cosmic expansion due to an apparently repulsive-like gravity. Understanding the phenomenon of this “dark energy” provides a fundamental challenge to cosmology and new data are vital to this endeavor. Initial efforts have focused on measuring the equation-of-state parameter of dark energy, \( w \equiv P/\rho c^2 \), where \( P \) is its pressure, and \( \rho \) is its energy density. To determine whether the dark energy is a static, cosmological constant (\( w(z) = -1 \)) to higher precision than past supernova surveys, future ones like the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS) and the Large Synoptic Survey Telescope (LSST) will attempt to populate the SN Ia Hubble diagram with 10^4–10^6 SNe Ia at redshifts 0.2 < \( z < 0.8 \). SNe Ia remain one of the best tools for understanding the properties of dark energy in the local volume because they can be discovered in large sample sizes and their individual measurement precision is high.

Unfortunately, obtaining a SN spectrum to determine its type and redshift is observationally demanding and limits the rate at which SNe Ia can be collected. If Pan-STARRS obtains as much time for spectroscopic follow-up as the SuperNova Legacy Survey (SNLS; Astier et al. 2006), it will still acquire spectra for only ~5% of the sample. Purely photometric determination of redshifts from multi-band light curves of SNe Ia (Gong et al. 2009), explicitly varying reddening, age, and light-curve shape, and assuming the SN is Type Ia, yields \( \sigma_z \approx 0.1 \) for 0.2 < \( z < 0.5 \) and \( \sigma_z \) as high as ~1 for \( z > 0.5 \). The cosmology fitting with only this photometric data leads to a factor of 4 degradation in the dark energy figure of merit compared with the case of fitting with spectroscopic data. While the photometric approach can be successful in distinguishing core collapse SNe from SNe Ia (Sullivan et al. 2006), the ultimate accuracy of photometric typing cannot be determined until there is a more complete characterization of the variations in core collapse SN light curves, specifically how often they resemble those of SNe Ia. An additional complication arises when using photometric measurements to identify SNe Ia (either for follow-up or for inclusion in the Hubble diagram); they cannot subsequently be employed for the determination of cosmological parameters without introducing a selection bias. Rather, it is important to make use of the wavelengths of spectral features (which are far narrower than broad bands) for type and redshift determination, particularly since SN classification is based on spectroscopy (e.g., see Filippenko 1997).

Here we propose a method of observation that will exploit the speed of photometric observations and most of the accuracy of spectroscopic observations to determine the types and redshifts of SNe Ia by using customized optical filters, each with multiple, discontinuous passbands on a single substrate. This approach to characterizing SNe Ia is more economical and can be used to more fully harvest the yield expected from large-scale SN surveys. In Section 2, we quantify the fortuitous periodicity in the spectral features of SNe Ia that enables one to distinguish them from other common transients and determine their redshifts when imaged with a semi-periodic passband. SN photometry measured with two of these filters approximates the cross-correlation of a coarse SN Ia spectrum with a template SN Ia spectrum commonly used to determine the type and

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4 The integration time required scales as \((1 + z)^\alpha\), with \( \alpha \) between 4 and 6 depending on the redshift and instrumentation.
redshift of a SN Ia candidate. In Section 3, we describe our design of these filters and their use. We discuss the advantages of these filters as a new tool for the follow-up of large-scale supernovae surveys in Section 4. In Section 5, we present a demonstration of the SuperNovAe Cross-Correlation (SNACC) filter prototype design.

2. CROSS-CORRELATION FORMALISM

2.1. Spectroscopic Characteristics

Among common transients (see Figure 1), SNe Ia are distinguished in the range 3500–5500 Å by large undulations in flux which are deep, broad, and surprisingly sinusoidal. The origin of these spectral features is the blending of overlapping P-Cygni profiles of singly ionized, intermediate-mass elements (e.g., see Filippenko 1997; Baron et al. 1996). SNe Ia are classified spectroscopically by the absence of hydrogen in their spectra and the presence of Si II (Ca II, S II, O I, Mg II as well as Fe II are also present). Individual spectral lines (absorption and emission) have widths of ~100–150 Å, due to expansion velocities ~10,000 km s⁻¹. In contrast, the spectra of SNe II are continuum-dominated with only a few individual hydrogen P-Cygni profiles because their hydrogen shells are intact. The blended spectral features in SN Ia have equivalent widths that are typically 3–4 times greater than those in SNe II spectra at 3000–5500 Å.

Although the spectral classification of SNe Ia was originally based on the presence or absence of specific ions, the loss of some features outside of the observable wavelength range at high redshifts and the typically low signal-to-noise ratios (S/Ns) of such spectra preclude relying on any single ion. As a result, the entire spectrum is considered. Supernova type is determined by a strong resemblance to a template spectrum $t_i(\lambda)$ at a trial redshift, $z_s$, where each type is given by a different $i$. Following Blondin & Tonry (2007), one determines the most likely template and redshift to be those which maximize the cross-correlation function of the template and spectrum:

$$c(z_s,i) = \int s(\lambda) \cdot t_i(\lambda \times [1 + z_s]) d\lambda.$$  (1)

Ideally, high S/N spectra would be obtained for all SNe in a survey. In practice, as seen in the ESSENCE survey (Matheson et al. 2005) or SNLS survey (Howell et al. 2005; Ballard et al. 2009), the need to obtain many spectra with limited observing time results in the collection of many spectra with low S/N degrading the information content of the measured cross-correlation function to the point where multiple $z_s$ are possible. The cross-correlation function of both a high- and a low S/N SN Ia spectrum with SNe Ia and SNe IIP spectral templates is shown in Figure 2. As expected, the SN Ia templates at the right redshift have a higher correlation function amplitude than the SN II templates. For high S/N (~50 per ~10.0 Å bin), the correct redshift is found with $\sigma_z = 0.01$. However, for spectra with low S/N (~10 per ~10.0 Å bin), a periodicity in the SN Ia correlation as a function of trial redshift is apparent, favoring a discrete set of preferred redshifts, $z_{\text{true}}$, and $z_{\text{true}} \pm n \times 0.2$ ($n = \pm 1, \pm 2, \ldots$), where each local peak yields $\sigma_z = 0.01$. With a photometric redshift of $\sigma_z < 0.08$, or a host spectroscopic redshift, this degeneracy can be removed.

We can readily see the cause of this redshift degeneracy by viewing the spectra of SN Ia and SN II spectra in Fourier space. $S(k)$ and $T(k)$, the discrete Fourier transforms of the supernova
and template spectra, can be written as

\[ S, T(k) = \sum_{n=0}^{N-1} s, t(n)e^{-2\pi i nk/N}, \]  

where we have assumed spectra are observed with \( N \) equal-sized wavelength bins with \( s(\lambda) \equiv s(n) \) and \( t(\lambda) \equiv t(n) \). \( n \) represents the wavelength bin such that \( \lambda = n \times \Delta\lambda \), and \( k = 2\pi/n \). Following Blondin & Tonry, we remove the color information in the spectra by dividing it by a cubic spline before taking its Fourier transform. The resultant SN Ia and SN II spectra in Fourier space are shown in the top panel of Figure 3. The significant feature of the SN Ia spectrum is the high power at wavenumbers at \( k = 6 \), corresponding to wavelengths \( \Delta\lambda \sim 500 \text{ Å} \), or spectral feature widths of \( \sim 250 \text{ Å} \). In the bottom panel of Figure 3, a sine function with this wavelength is compared to a SN Ia spectrum showing their similarity in the range 2500–5500 Å. This periodicity in the spectral features appears to be a forlornous feature of SNe Ia. While it is possible that multiple spectral lines that occur in a narrow wavelength range could produce such a sinusoidal shape, randomly populating the phase space with a comparable density of lines shows that a Fourier transform correlation amplitude as strong or stronger than that seen in Figure 3 occurs \(<5\%\) of the time. The distinctive shape of SN Ia spectra is recognized as “wiggly” by high-redshift SN spectroscopists even without certainty of its redshift.

The correlation amplitude for lower wavenumbers \( (k < 5) \) depends on the intrinsic colors of the SN and reddening. While such spectral color information is not utilized here it may be used elsewhere for distance determinations.\(^5\) The correlation amplitudes for higher wavenumbers \( (k > 10) \) show features that are not detected with significance in low S/N spectra. Therefore, from spectra with low but atypical S/Ns, the only information available to determine the type and redshift of a candidate SN Ia is the power and phase of the \( k = 6 \) mode. The corresponding wavelength scale (500 Å) for this wavenumber scales with redshift as 500 Å \( \times (1+z) \). Thus, the peak wavenumber depends on \( z_\text{T} \) such that \( k_6 = 6/(1+z_\text{T}) \), but changes little over a modest fractional change in \( (1+z_\text{T}) \), as shown for 0.3 < \( z < 0.7 \) in Figure 4. As expected, there is a large correlation amplitude near \( k = 4 \), or 500 Å \( \times (1+0.5) \approx 750 \text{ Å} \), throughout this redshift range. Thus, a SN Ia feature centered at a true rest-frame wavelength \( \lambda_\text{True} \), and observed at \( \lambda_\text{Obs} \) due to the redshift \( z_\text{T} \), can be confused with a similar rest-frame feature at \( \lambda_\text{False} \) such that

\[ \lambda_\text{Obs} = \lambda_\text{True}(1+z_\text{True}) = \lambda_\text{False}(1+z_\text{True} + n\Delta z), \]  

where

\[ \Delta z = \frac{n \times 500 \text{ Å} \times (1+z_\text{True})}{\lambda_\text{True}}. \]

For example, values of \( \lambda_\text{T} = 3600 \text{ Å}, z_\text{T} = 0.5 \), then \( \Delta z \approx \pm 0.2 \text{ for } n = \pm 1 \). Therefore, the undulations in SN Ia flux with a periodicity of 500 Å \( \times (1+z) \) cause the redshift degeneracy of \( \Delta z \approx 0.2 \), as in Figure 2.

SNe II spectra do not share this periodicity, and their normalized correlation amplitude at \( k = 6 \) is 3.5 times lower than that of a SN Ia, as seen in Figure 3. Thus, measuring the power of SNe Ia and SNe II spectra at \( k = 6 \) allows one to distinguish between these two types of SNe and the phase of that power provides the redshift of a SN Ia.

In practice, the determination of SN Ia type and redshift may be acquired with just two samplings of the cross-correlation function at different trial lags. An example of this is shown in the right panel of Figure 2. Two samplings break the degeneracy of the phase, \( \pi \), of the sine curve and the two measurements are optimally made with phases \( \phi_1 = 0, \phi_2 = \pi/2 \) (\( \Delta z \approx 0.05 \text{ in redshift space} \)). Since these two measurements are out of phase, at least one of the amplitudes measured reveals high power at \( k = 6 \) if the SN type is Ia. If a redshift prior (photometric or host spectroscopic) with \( \sigma_z < 0.1 \) is also available, one can also

\(^5\) In practice, SN colors are more accurately measured from photometry from which host light can be subtracted. This also avoids chromatic slit losses which occur from long-slit spectroscopy obtained off the parallactic angle (Filippenko 1982).
confidently determine a SN Ia redshift with \( \sigma_r \approx 0.01 \), similar to the precision of a local peak in the SN Ia cross-correlation function.

### 2.2. Imaging Approach

The convolution theorem states that the convolution of an input spectrum and a template is equivalent to the product of their Fourier transforms:

\[
F(s(n) * t(n)) = b \times S(k) \times T(k). \tag{5}
\]

Our definition of the cross-correlation, given in Equation (1), is similar to a convolution and thus Equation (5) is applicable. Since low S/N spectra have most of their information in the power and phase of the \( k = 6/(1 + z) \) mode, the template that maximizes the product of the Fourier transforms, and thus the amplitude of the cross-correlation, should have the majority of its power in the \( k = 6/(1 + z) \) mode as well. Therefore, we can replace the SN Ia template spectra with sinusoidal functions with \( \lambda = 500 \times (1 + z) \) with no loss in information in the cross-correlation function.

These simplified templates, \( t(\lambda, \phi_1) \) and \( t(\lambda, \phi_2) \), can now be replaced with optical transmission functions (i.e., optical filters) which can be used to evaluate the cross-correlation as shown in Figure 2 and can be expressed as

\[
CC - B - ZP = -2.5 \times \left( \log_{10} \left( \frac{F_{CC}}{F_B} \right) \right) - ZP. \tag{6}
\]

where \( F_{CC} \) is the flux through the template filter, \( F_B \) is the flux through the broadband filter, and ZP is a zero point that will be discussed later.

Hereafter we will refer to optical filters which mimic \( t(\lambda, \phi) \) as SNACC filters. With two such filters, these measurements identify a SN in the \( CC_1 - B \) (mag) versus \( CC_2 - B \) (mag) plane. If one of these SNACC filters is chosen to be \( \pi/2 \) out of phase with another filter, then SN Ia, over a moderate redshift range, delineate a circle in this correlation space with values of \( CC - B \sim 0.25 \) mag when the spectral features of the SNe are correlated with the template bandpasses, and \( CC - B \sim -0.25 \) mag when the features are anti-correlated with the template bandpasses. The period of the SN Ia circle with radius 0.25 mag is the same as the degeneracy of the cross-correlation versus redshift relation for low S/N spectra: \( \Delta z \approx 0.2 \). With a host photometric redshift \( \sigma_r \approx 0.08 \), two measurements with \( \sigma_{CC-B} \sim 0.04 \) mag in \( CC - B \) space reveal the redshift of a SN Ia to \( \sigma_z \approx 0.01 \), the precision inherent in the SN Ia correlation curve.

All SNe II (IIP, IIL, IIn) remain clustered near \( CC - B \sim 0 \) which provides the means to distinguish them from SN Ia. Since SNe II have low correlation amplitudes at \( k = 6/(1 + z) \) for \( 0 < z < 1 \) in the observed frame for a broad range of \( z \), there is little difference between the relative flux in a template filter and the broadband filter. In addition, the few features of SNe II have lower equivalent width with respect to the mean flux than those of SNe Ia, so that if one or two features (at most) align with the template filter teeth, the value \( |CC - B| \) is still smaller for SNe II than for SNe Ia.

### 3. IMPLEMENTATION

Optical filters with multiple passbands may be designed to mimic the spectral features of SNe Ia and used to constrain the type and redshift of SNe. While important properties of these filters have already been discussed (e.g., separation between the passbands \( \sim 500 \) Å \( \times (1 + z_{\text{median}}) \)), the precise determination of the filter specifications requires greater rigor. Here the optimal filters are determined as those which maximize the precision of the determination of redshift and SN type.

We define an extended broadband filter, \( b' \), to transmit the sum of flux from Sloan g' and r' so \( F_{b'} = F_g + F_r \). For convenience, we define \( ZP \equiv CC_{\text{GVY}} - B_{\text{GVY}} \) for Equation (6) so that a G8V star has \( CC - B - ZP = 0 \) mag. Since a G8V star has a thermal spectrum with \( T = 5310 \) K, and similar colors as the spectra of SN Ia at \( z = 0.5 \),\(^6\) setting \( ZP = CC_{\text{GVY}} - B_{\text{GVY}} \) provides a useful reference for measurements at \( (CC_1 - B, CC_2 - B) = (0, 0) \). Stars with the same spectral type but different luminosity class will differ by \( < 0.03 \) mag.

The flux \( F_{CC} \) through a filter \( P \) with discontinuous passbands or “teeth” \( p_1, p_2, \ldots \) is given by

\[
F_{CC} = \int S(\lambda(1 + z)) P(p_1, p_2, \ldots) d\lambda. \tag{7}
\]

A single passband, or “tooth”, \( p_i \), can be described with three parameters: a central position \( (\lambda_i) \), a width \( (\Delta \lambda_i) \), and a transmission fraction \( (r_i) \). The set of values \( \lambda, \Delta \lambda, r, \) for a total of \( 3 \times 2(\text{filters}) \times n(\text{passbands}) \), can be varied to optimize a merit function and thus the design of a filter.

To construct a useful merit function, we first simulate a generic SN survey with a few assumptions about the properties of the SN and their redshift distributions. For later optimizations, the survey assumptions are designed for a specific survey, e.g., Pan-STARRS-I. Our simulated population is composed of 5000 SNe Ia and 5000 SNe II. The SN Ia spectral templates from Hsiao et al. (2007) are used for our SNe Ia spectral template; the spectrum of SN IIP 1999em (Baron et al. 2000) is used as a SNe II spectral template. SNe IIn and SNe IIL spectra have even narrower features than those of SNe IIP, and should be even easier to discriminate from SNe Ia, so SNe IIP will represent an upper limit for difficulty in discriminating SNe Ia from SNe II. SNe Ib/IC/IbC, as well as other transients, are rarer and will be deferred to Section 3.5. The number of simulated SNe grows with the redshift due to increasing volume, then decreases with redshift as the brightnesses of all SNe no longer exceed the magnitude limit. We find the redshift distribution of our simulated SN Ia survey can be approximated as a truncated Gaussian distribution for a limit of \( r' = 25 \) mag and mean SN Ia brightness of \( -19.16 \) mag (Richardson et al. 2002): \( \bar{z} = 0.55, \sigma = 0.15, z_{\text{min}} = 0.30, z_{\text{max}} = 0.75 \). The SNe II redshift distribution, with mean brightnesses for SNe IIP, SNe IIL, SNe IIn of \( -16.6, -17.4, -18.78 \) mag, can be approximated as \( \bar{z} = 0.45, \sigma = 0.15, z_{\text{min}} = 0.20, z_{\text{max}} = 0.7 \). For each SN, we determine its \( CC - B \) values from its template spectrum, redshift, and the filter parameters. We then simulate noisy measurements with our assumed photometric errors.

Because our goal is to find the type of SN, and if a Ia, its redshift, the following chi-squared statistic is minimized with

\footnote{Supernovae have temperatures \( \sim 10,000 \) K. At \( z = 0.5 \), then \( 10,000 K/(1 + z) \sim 6500 \) K.}
respect to type and $z$ for an individual SN:

$$
\chi^2(\text{type}, z) = \left( \frac{(CB_1 - CB_{1p})}{\sigma_1} \right)^2 + \left( \frac{(CB_2 - CB_{2p})}{\sigma_2} \right)^2 + \left( \frac{z_p - z}{\sigma_z} \right)^2,
$$

(8)

where $CB_1$ and $CB_2$ are simulated measurements for $CC_1 - B$ and $CC_2 - B$, $CB_{1p}$ and $CB_{2p}$ are the expected values of $CC - B$ positions for a SN of a particular type and redshift, $\sigma_{1,2}$ are the simulated measurement errors of $CB_1$ and $CB_2$, $z_p$ is the available redshift prior, and $\sigma_z$ is its error. The measurement errors, $\sigma_{1,2}$, include image calibration errors and photon statistics. We estimate the errors resulting from empirically calibrating the $CC - B$ value of the supernova from stars in the field to be $\sim 0.02$ mag (see Section 5). The photon statistics are calculated from the brightness of the SN and the amount of time allotted for imaging on the low-dispersion survey spectrograph (LDSS-3, upgraded from LDSS-2, Allington-Smith et al. 1994), on the 6.5 m Magellan Clay Telescope.

We also expect some variation of the SNe Ia spectra, and hence $CC - B$, which correlates with the luminosity-light-curve-shape parameter or "stretch," the age of the SN and with individual reddening (Guy et al. 2007). The remaining, intrinsic variation of SNe Ia spectra is small compared to variations arising from these three parameters (Figure 4 of Guy et al. 2007).

Depending on the circumstances in which the SNACC filter data will be analyzed, we may be able to make use of knowledge about the age, stretch, and reddening of a SN Ia. The available SN light curve may be complete, sparsely sampled, or consist of only the discovery point. If a well-sampled light curve is obtained, then a SN Ia template with the corresponding age, stretch, and reddening of the SN candidate would be used to improve the chi-squared diagnostic (Equation (8)). Likewise, $\sigma_z$ depends on whether a host galaxy redshift is known photometrically (e.g., $\sigma_z = 0.08$), spectroscopically ($\sigma_z = 0.01$), or unavailable ($\sigma_z = \infty$). Classification resulting for these various follow-up scenarios as well as the effects of age, stretch, and reddening on the success of determining the type and redshift will be discussed in Sections 3.3 and 3.4.

3.1. Merit Metrics for Optimizing Filters

The two categories of metrics to be used for optimization are the success of determining the type of SN and if Ia, its redshift. Let us assume the two most common SN populations, SNe Ia and SNe II. We define $Y_{1a}$ as the fraction of known SNe Ia that are inconsistent with SNe II. Similarly, $Y_{1Ia}$ is the fraction of SNe II that are inconsistent with SNe Ia. The purity of the SNe Ia sample that would be added to the cosmological sample is then

$$
Purity = \frac{Y_{1a} \times N_{1a}}{Y_{1a} \times N_{1a} + (1 - Y_{1Ia}) \times N_{II}},
$$

(9)

where $N_{1a}$ and $N_{II}$ are the numbers of known SNe Ia and known SNe II, respectively.

The success in determining the redshift for SNe Ia is quantified by $\sigma_{z_{\text{spec}}} \sim \text{SNACC}$, where $z_{\text{spec}}$ is the known redshift and $z_{\text{SNACC}}$ is the redshift that minimizes the chi-squared diagnostic (Equation (8)).

3.2. Prototype Three-tooth Design

To design prototype filters, we assumed the availability of a photometric redshift prior with $\sigma_z \approx 0.08$ at $0.3 < z < 0.8$ and a light-curve-based age of the SN (which is $\pm 5$ rest-frame days from peak brightness when the $CC - B$ magnitudes are obtained). We also assumed integration times would be sufficient to reach combined photon statistics and calibration errors of $\sim 1.2 \leq 0.05$ mag and that the photon statistics would depend on avoidance of the skylines in the passbands.

We first attempted to design a simple filter model with just two discontinuous passbands. With filters of this kind, the ability to discriminate type of SN is not strong over a redshift range of $\Delta z = 0.5$. Next, we searched for a three-tooth design for our SNACC filters, which is the solution we show here. A filter with four teeth, designed by optimizing both the throughput of the filters and the discrimination power, will be discussed in Section 6.

A pair of three-tooth filters, which maximizes the purity of SNe Ia, is shown in Figure 5, and the expected positions of SNe Ia and SNe II are shown in Figure 6. The widths of each tooth is $\sim 160$ Å, but with different transmission heights (0.42, 0.4, 0.66), thus these three-tooth SNACC filters have an effective width of $\sim 325$ Å, or $\sim 33\%$ that of a broadband filter. The mean wavelength

$$
\langle \lambda \rangle = \frac{\int \lambda T(\lambda) d\lambda}{\int \lambda d\lambda},
$$

(10)

of the two SNACC filters ($\langle \lambda \rangle = 5750, 5650$ Å respectively) and the broadband filter ($\langle \lambda \rangle = 5550$ Å) are quite similar which greatly limits the effect of reddening on the observed $CC - B$ values. Also, the bandpasses of the second filter avoid all major skylines, but because the center bandpass of the first filter is near the 5887 Å Na D line, this filter transmits 20% more sky flux than the first. As shown in Figure 5, SNe Ia $CC - B$ magnitudes trace roughly concentric circles tracking counterclockwise with increasing redshift. As expected, SNe II lie closer to the origin due to their lack of spectral features as strong as SNe Ia, with an average separation from the origin.
of ±0.05 mag. For measurement errors of \( \sigma_m = 0.04 \) mag (as we obtained with the first use of the SNACC filters, discussed in Section 5.2), the SNe Ia and SNe II are separated in \( CC - (g + r) \) space by \((3.5) \times \sigma_1,2\), allowing for a SNe Ia sample purity of ~98%.

The redshift distributions are centered around \( \bar{z} \approx 0.0 \) and \( z \approx 0.0 \), and the SN Ia redshifts have an average radius \( \bar{r} \approx 0.25 \) mag. For measurement errors \( \sigma_1,2 = 0.04 \), the SNe Ia are separated from the SNe II in \( CC - (g + r) \) space by \((3.5) \times \sigma_1,2\), allowing for a SNe Ia sample purity of ~98%.

3.3. Effects of Light-curve Shape, Age, and Reddening on \( CC - B \) Magnitudes

Variations in SN Ia spectra are mainly due to variations in reddening, light-curve shape, and age. The effects of ignorance of these parameters (using the SNe Ia variations modeled in Guy et al. 2007) on our purity and redshift errors are shown in Figures 8 and 9, respectively. Typical usage of SNACC filters would avoid these errors using light curves to choose a SN Ia spectral template corresponding to the appropriate age, light-curve shape, and reddening.

Due to the near-equality of the mean wavelength of the SNACC filters and the broadband filters, the fraction of SN Ia correctly classified at most redshifts is quite insensitive to reddening, affecting \( Y_{1a} \) at the 1% level, as shown in Figure 8. Selection purity is also insensitive to the light-curve—luminosity relation, varying by ~2% (except for \( z > 0.75 \)). Ignorance of SN age has a stronger impact on \( Y_{1a} \) and limits the time range in which it is optimal to use SNACC filters for follow-up. The purity is very robust for ages from −7 to +5 days but degrades for older SNe Ia. \( Y_{1a} \) is < 90% for SNe with \( z \leq 0.35 \) past +5 days and for SNe with \( z \geq 0.75 \) past +8 days. For SNe Ia with \( 0.35 < z < 0.75 \), \( Y_{1a} \) on average is ~95% up to an age of 10 days, and even for ages past this, \( Y_{1a} \) for parts of the redshift range remains as high. Prior to 5 days before peak, the overall purity remains >95%, but SNe Ia with \( z \sim 0.55 \) (for −10 days) or \( z \sim 0.65 \) (for −15 days) will approach the origin in \( CC - B \) space. While it is difficult to simulate how peculiar SNe Ia with similar early ages and high redshifts appear in \( CC - B \) space because of the limited set of UV spectra, SNe like SN 1991T (Jeffery et al. 1992), for redshifts \( 0.25 < z < 0.40 \), are located in \( CC - B \) space with the same phase and at most a ~0.05 mag relative distance to the origin as their normal SNe Ia counterparts (and \( Y_{1a}/\sigma \) values of 92%/0.012). For these peculiar SNe Ia, the strengths of the spectral features vary from those of normal SNe Ia, but since three separate passbands are correlated with the spectrum, the overall difference between these two categories of SNe Ia in \( CC - B \) space is not large. The effects of age, light-curve shape, and reddening are most noticeable at the limits of our redshift range (\( z \sim 0.35, 0.75 \)) since the spectral features at these redshifts that correlate with the passbands are weak compared to the correlating features at \( z \sim 0.5 \).

Both reddening (\( 0.0 < E(B - V) < 0.4 \)) and stretch (\( 0.85 < s < 1.15 \)) cause errors in \( z_{SNACC} - z_{spec} \) that are all < 0.02 as shown in Figure 9. Anytime before 5 days past peak, age has a limited effect on the redshift errors (<0.02), but afterward the effect is much more significant (typical errors ~0.05) for all redshifts.

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8 Available at http://supernova.lbl.gov/~nugent/nugent_templates.html.
9 \( \Delta d = 5 \log \frac{d_0}{d} - 5 \log \frac{d_0}{d_{0.05}} = 5 \log \frac{0.5r}{0.5r_{0.05}} \approx 1.0 \text{ mag} \) for \( E_T \sim 0.5 \).
Figure 8. Effects of reddening, stretch, and age on the resulting fraction, $Y_{Ia}$, of SNe Ia correctly classified (type) for various redshifts. Reddening has very little effect on classification, except for the lowest redshifts, while stretch has a similarly small effect except for the highest redshifts. The filters were optimized for use around peak ($\pm$5 days), and the classification is generally $>$ 90% this range.

Figure 9. Effects of ignorance of reddening, stretch, and age on the errors in determined redshift. Variations in reddening and stretch have a very small effect, producing redshift errors $<$ 0.02. The filters were optimized for use around peak ($\pm$5 days), and the redshift error for this age range is mostly $<$ 0.02. Knowledge of the reddening, stretch, and age would eliminate these errors.

3.4. Usage Scenarios

SNACC filter measurements may be used in conjunction with other data to yield more precise results. For example, the host galaxy of the SN may be apparent, and the multi-band light curves may have been acquired. If a host galaxy is visible, a photometric redshift ($\sigma_z = 0.08$) or spectroscopic redshift ($\sigma_z = 0.01$) may be obtained. If a light curve has been acquired, values of the age, stretch, reddening, and photometric redshift ($\sigma_z/(1+z) = 0.06$, based on Sullivan et al. 2006) can be fit on the condition the SN is Ia. An available photometric or spectroscopic redshift breaks the $\Delta z = 0.2$ cross-correlation degeneracy of SNe Ia and knowledge of the age, stretch, and reddening reduces the spectral variations because the appropriate spectral template can be used.

As realistic examples, the medium deep Pan-STARRS survey, which images the same area of sky every 4 days, should provide well-sampled light curves. In contrast, the 3π Pan-STARRS survey covers the entire sky only twice a month, and will not provide light curves well sampled enough to fit accurate values of the type, stretch, reddening, or age of the SN.
with frame days from the peak, a Gaussian distribution of stretches \( Y \) one obtains only a photometric redshift of the host. Generally, if CC selection. There are other types of transients, and we list here and therefore their separation is most important to good SN Ia space have been considered because they are the most common, results expected after SNACC follow-up. We simulate a realistic set of SNe Ia with a uniform distribution of ages within \( \pm 5 \) rest frame days from the peak, a Gaussian distribution of stretches with \( s = 1 \) and \( \sigma_s = 0.1 \), and an exponential distribution of reddening values, with a peak at \( E(B-V) = 0 \) and \( \tau = 0.1 \).

Table 1 shows that the fraction of SNe Ia correctly classified and the redshift determination both improve with the amount of information one obtains about the supernova or host galaxy. With a well-sampled light curve and host galaxy but no SNACC filter measurements, we assume a baseline of \( Y_{\text{IA}} \) = 80% and \( \sigma_s/(1+z) \approx 0.06 \) (Sullivan et al. 2006). \( Y_{\text{IA}} \) is 97.0% if one obtains a well-sampled light curve of the SN because then one can use the correct template in the chi-squared diagnostic of Equation (8). Similarly, the precision of the redshift determination is also greater if a well-sampled light curve is obtained. The best case is the scenario in which one obtains a spectroscopic redshift from the host galaxy in addition to a well-sampled light curve of the SN. Here, \( Y_{\text{IA}} \) is 99.0%, although this is not significantly better than the case in which one obtains only a photometric redshift of the host. Generally, if one gathers supplementary information about the SN in addition to the SNACC filter measurements, one achieves \( Y_{\text{IA}} \) > \( \sim 95\% \) with \( \sigma_s < 0.015 \).

### 3.5. Other Transient Candidates

Until now, only the properties of SNe Ia and SNe II in \( CC - B \) space have been considered because they are the most common, and therefore their separation is most important to good SN Ia selection. There are other types of transients, and we list here some that may be confused with SNe Ia (Matheson et al. 2005) and their characteristics in \( CC - B \) space.

**SNe Ib/Ic/Ibc.** The progenitors of SNe Ib/Ic/Ibc (hereafter called SNe Ib–c) are believed to be stars stripped of their original H-rich envelope (Georgy et al. 2009) and the spectral features of these supernova are similar to those of SNe Ia (as seen in Figure 1). The SNe Ib–c spectral templates we use are updated versions of those given in Nugent et al. (2002). The characteristic spectroscopic difference between Type Ia and Ib–c SNe is the deep absorption trough at 6150 Å in Type Ia spectra, which is due to the blueshifted Si II \( \lambda \lambda 6347, 6371 \) feature (Homeier 2005). Unfortunately, this is redshifted out of the optical passband for \( z > 0.4 \), making it difficult to distinguish SNe Ia from SNe Ib–c. Although there are other spectroscopic differences between SNe Ia and Ib–c (e.g., Si II \( \lambda \lambda 4130 \), Coil et al. 2000), they are too slight for the two types with the same redshift to appear in different locations in \( CC - B \) space. There are two branches of redshifts, \( 0.1 < z < 0.18 \) and \( 0.3 < z < 0.38 \) in which the SNe Ib–c are clustered in the center, but for other redshifts, their \( CC - B \) positions are often less than 0.05 mag away from a SN Ia with the same redshift. However, they are rare enough (<3% of photometric SN Ia candidates targeted for spectroscopy in the ESSENCE project (Matheson et al. 2005)) to not simultaneously affect our SN Ia purity. We also note that SNACC filter observations of SNe Ib–c fair no worse than typical high-redshift spectroscopy whose S/N is frequently (Riess et al. 1998; Matheson et al. 2005) too low to identify Si \( \lambda 4130 \) and which is not even present for many SNe Ia. For the set of ESO/VLT spectroscopy of SNLS candidates (Balland et al. 2009), 38 out of 124 of the classified SN Ia spectra were called “probable” SNe Ia because other types, in particular SNe Ic, could not be excluded given the S/N or the phase of the spectrum. In any case, one learns the correct redshift for SNe Ib–c which aids their elimination from the Hubble diagram with Bayesian techniques (Kunz et al. 2007).

**Active galactic nucleus.** There are several subclasses of active galactic nuclei (AGNs, e.g., Seyfert 1, Seyfert 2, LINER) and the AGNs in each subclass have unique spectral features (Osterbrock 1989). Here we use the set of 12 AGN spectra obtained by the ESSENCE project which are particularly relevant because they were photometrically identified as SN Ia candidates. In the project, AGNs were discovered with redshifts \( 0.18 < z < 2.6 \), so we must include a large redshift range when determining the location of an AGN in \( CC - B \) space. For the ESSENCE set of spectra, over the redshifts in which the spectra cover the entire optical range, the AGN will deviate from the origin > 0.05 mag only \( \sim 5\% \) of the time. Thus, > 11 out of 12 ESSENCE AGNs would have been rejected from the SN Ia sample. For spectra at select redshifts (e.g., spectra similar to those of the Seyfert 1 AGN at \( z \sim 2.57 \); see Francis et al. 1991 for spectral templates), the position of the AGN in \( CC - B \) space may deviate as far from the origin as SNe Ia. Many AGNs can be discriminated from SNe Ia with broadband color measurements and possibly a time-series history (Poznansko et al. 2007), and SNACC filters would provide an additional method to differentiate the AGN from SNe Ia.

**Variable stars.** During the course of the ESSENCE project, as well as other recent supernova surveys, several variable stars

| Scenario | Details | Results | \( \sigma_z \) |
|----------|---------|---------|-----------|
| Host galaxy, light curve | \( \sigma_z = 0.10, \sigma_s/(1+z) \approx 0.06 \) | 80.0 (5.00) | 0.090 (0.010) |
| SNACC, host galaxy w/photo-z, no LC | \( \sigma_z = 0.10 \) | 94.50 (0.2) | 0.015 (0.003) |
| SNACC, host galaxy w/spec. z, no LC | \( \sigma_z = 0.01 \) | 95.6 (0.3) | 0.014 (0.002) |
| SNACC, no host galaxy, w/LC | \( \sigma_z/(1+z) \approx 0.06 \), known age, stretch, reddening | 97.0 (0.2) | 0.012 (0.002) |
| SNACC, host galaxy w/photo-z, w/LC | \( \sigma_z = 0.10, \sigma_s/(1+z) \approx 0.06 \), known age, stretch, reddening | 98.2 (0.1) | 0.010 (0.002) |
| SNACC, host galaxy w/Spec-z, w/LC | \( \sigma_z = 0.01 \) | 99.0 (0.1) | \( \cdots \) |

**Note.** These photometric redshifts, derived from the broadband colors of the SN, are dependent on whether the SN is known to be a SN Ia.
as well as unclassified stars were discovered. In the spectra published from the ESSENCE project, the spectra of the stars were mostly continuum and are located near the origin of \(C - B\) space with little deviation. Thus, rarely should any variable stars be confused with SNe Ia.

4. OBSERVATIONS

4.1. SNACC Filter Fabrication for LDSS-3

The technology used to fabricate SNACC filters, with multiple discontinuous passbands on a single substrate, has become popular for a wide range of applications in many fields, like fluorescence microscopy in biology (e.g., Yelin & Silberberg 1999). We canvassed multiple vendors but ultimately Iridian Spectral Technologies Ltd. was best able to match our specifications for the prototype within a reasonable cost.

Iridian constructs thin-film filters (TFF; see Macleod 2001, for a review) by layering materials of alternating refractive index with thicknesses on the order of visual wavelengths, \(\sim 5000\) Å, to produce optical filters that transmit and/or reflect specific wavelengths. A thin-film coating is a stack of such layers having boundaries of greater refractive index (reflecting light 180° out of phase) and less refraction index (reflecting light in phase) that if at precise spacings will modify the reflected and transmitted components by interference.

The filter design team at Iridian use a proprietary design and process control technology, PrecisionSpectrum@IST, to develop the optimal multilayer design for the requested filter specifications and requirements (both physical and optical). The SNACC filters were designed with a TFF layering on the front side and simple two-layer anti-reflective type coating on the backside.

The filters were specified for use in the LDSS (LDSS-3, upgraded from LDSS-2, Allington-Smith et al. 1994), on the 6.5 m Magellan Clay Telescope. Our specified transmission function of the filters was adjusted to include the effect of the camera efficiency. Our request, Iridian’s expected design, and the design they achieved are shown in Figure 10. The bandpasses of the filters Iridian produced had width, height, and position values that were all within 5% of our specifications.

In the LDSS-3 setup, an input \(f/11\) beam enters a collimator before passing through a SNACC filter. The light is then focused by the camera onto an external detector with a final focal ratio of \(f/2.5\). Due to off-axis rays, there is a correlation between the incident angle on the filter and the radial field position. For 2/3 of the field, there is a maximum angle of incidence of \(\sim 4.6\) of the beam on the filter. Because of the construction of the interference filter, there is a shift in the effective filter wavelength to the blue (i.e., at 6000 Å, this is a shift of about 10 Å). The filters were analyzed in the optics lab at the Johns Hopkins University to measure their transmission functions in a similar setup with a tungsten halogen lamp, a silicon photodiode, and a collimator. We measured filter transmissions which were very close to what Iridian stated they achieved in a parallel beam, and that the out-of-band rejection was > 99.5% over the wavelength 3000–11000 Å. When collimated beams have an angle of incidence of up to 5° on the filter, the shifts in the bandpasses were fairly coherent with values up to 8 Å, negligible for our purpose.

10 For more information, see http://www.iridian.ca/.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure10.png}
\caption{Bandpasses, Iridian’s expected design, and Iridian’s actual design, as well as the strongest skylines (\(\mathrm{O}I\)), Na D with relative strengths as found at Magellan) in the optical range. Iridian was able to build filters with bandpasses of an accuracy better than 5% of the specified widths, heights, and positions of the teeth.}
\end{figure}
The observations obtained for the SNe and calibration stars are given in Tables 2 and 3, respectively. We observed SN NU and SN OE on UT 2008 May 3 with the SNACC filters on LDSS-3 for 300 s each, and SN JH on May 5 for 300 s as well. The G8V and M4V stars were observed for exposure times of 180 s on UT 2008 May 3. Flat-field images and bias frames were also acquired. A custom pipeline was used to perform photometry of the bias-subtracted, flat-fielded images, using aperture photometry via the APER routine in IDL and point-spread function photometry via the DAOPHOT routines in IDL.

We also acquired spectra of the SNe NU, JH, OE on UT 2008 May 4, 5, 9 with the VPH-All grism on LDSS-3 with a 1" slit for integration times of 2 × 1200 s, 2 × 900 s, and 2 × 1800 s, respectively. The VPH-All grism (400 lines mm⁻¹) allowed us to acquire 4000–9900 Å spectra with an average resolution of λ/Δλ ≈ 860 across the entire chip. Dispersion along the chip was 1.9 Å pixel⁻¹. All spectral observations were accompanied by HeNeAr arc lamps exposures to measure dispersion and the pixel-to-pixel response was removed with flats from a quartz lamp. The spectral data were reduced using the standard IRAF¹¹ packages including APALL (extraction), DISPCOR (assigning the dispersion function from the calibration arc lamp), and CALIBRATE (using sensitivity function to flux calibrate the spectra). Flux calibration (using STANDARD) of the spectra was performed by means of spectrophotometric standard stars observed at similar air mass on the same night as the SN. For all the spectra observed, the slit was always aligned along the parallactic angle to avoid differential chromatic refraction.

5. ANALYSIS OF OBSERVATIONS

5.1. SNACC Filter Calibration: Photometry for G’ and M’ Stars

Using spectra from the Gunn & Stryker spectrophotometric atlases (Gunn & Stryker 1983) and the known transmissions of the broadband and SNACC filters, we use the relation between the $CC - B$ values and $g - r$ values for standard stars to determine their zero points.

The $CC - B$ values of the stars are linearly related to their $g - r$ values, as seen by the diamonds in Figures 11 and 12 such that one can write the relation for stars:

$$CC - B = m(g - r) + Y \quad \text{for} \quad g - r < 1.0,$$

where $CC - B$ has already been offset by the zero point as defined previously, $ZP \equiv CC_{G8V} - B_{G8V}$. The slope and intercepts can be found by a least-squares fit: $(m_1, Y_1) = (-0.14, 0.04), (m_2, Y_2) = (-0.19, 0.07)$. These relations are highly linear for $g - r < 1.0$ and have a dispersion of less than

---

¹¹ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
values found for the G8V field were ZP 1 and M4V field are shown in Figures 11 and 12. The ZP with the photon statistics error. The G8V and M4V stars were stars with their synthetic spectrophotometric measurements field and M4V can be combined, as can be seen in Figures 13 and 14, and we can compare the values of the G8V and M4V stars with their synthetic spectrophotometric measurements.

0.02 mag. Stars with $g-r > 1.0$ are generally M-type stars with strong spectral features that break the $CC - B/g - r$ relation.

For a set of $n$ observed stars, each with $CC$, $B$, $g$, and $r$ values ($g$ and $r$ have been corrected for zero point offsets), the $CC - B$ color zero points $ZP_1$ and $ZP_2$ for a field can be determined from

\[
CC_1 - B - ZP_1 = -0.14(g - r) + 0.04, \tag{12}
\]

\[
CC_2 - B - ZP_2 = -0.19(g - r) + 0.07. \tag{13}
\]

To find the zero points, one minimizes $\chi^2$ with respect to ZP:

\[
\chi^2 = \sum_{i=0}^{n} \frac{(ZP - ((CC_i - B_i) - m(g_i - r_i) + Y)^2}{\sigma_i^2}, \tag{14}
\]

where $g_i - r_i < 1.0$ and $\sigma_i$ is the quadrature sum of star $i$’s measurement errors. Having determined ZP$_{1,2}$, the $CC - B$ values of the SNe in the field can be placed in our diagnostic $CC - B$ space.

The results of this calibration method for the G8V field and M4V field are shown in Figures 11 and 12. The ZP values found for the G8V field were ZP$_1 = 0.33 \pm 0.01$ and ZP$_2 = 0.24 \pm 0.005$. The ZP values found for the M4II field were ZP$_1 = 0.33 \pm 0.015$ and ZP$_2 = 0.22 \pm 0.01$.

The $CC_1 - B$ and $CC_2 - B$ values of all the stars in the G8V field and M4V field can be combined, as can be seen in Figures 13 and 14, and we can compare the values of the G8V and M4V stars with their synthetic spectrophotometric measurements (spectra from SDSS DR7). To determine the total photometric error, the calibration error of the stars were added in quadrature with the photon statistics error. The G8V and M4V stars were $\sim 17$ mag in the $r'$ band, and the total photon statistics error from the SNACC filters and broadband filters was $\sim 0.015$ mag. As seen in Figures 13 and 14, the synthetic measurements are within one standard deviation of the photometric measurements.

5.2. Results of Imaging and Spectroscopy

The extracted SN spectra, as observed with the LDSS-3, are presented in Figure 15. Bluer than 4300 Å, the S/N < 5 due to the decreased sensitivity of the spectrograph and lower object flux with respect to the sky. Template spectra of the same type and age were used to graft this part of the spectrum. The SNID program (Blondin & Tonry 2007) was used to determine that NU and OE are both SNe Ia, with redshifts $z = 0.56 \pm 0.01$ and $z = 0.42 \pm 0.01$, respectively, and JH is a SN IIP with $z = 0.23 \pm 0.01$. The quality of correlation is determined by the rlap quality parameter, which is the product of the correlation height noise and the spectrum overlap parameter, and is 0.63, 0.68, and 0.74 for NU, OE, and JH, respectively. Using the extracted spectra as well as transmission functions of the SNACC filters and broadband filters, the synthetic spectrophotometric $CC - B$ values of the SNe can be evaluated and compared to the observed values.

Details of the SNe ages, broadband colors, and redshifts (host galaxy photo-z, SN photo-z from broadband colors, and spectroscopic) are given in Table 4. Observations of the SNe were sky-noise limited, so the photon statistics error is determined from the dispersion of the photometry when a model psf with the source’s amplitude is placed at random locations in the field. The 300 s of imaging yielded S/Ns of about 35 for NU
and JH, and 30 for OE. Using the calibration approach discussed in Section 5.1, with meagprime $g'$ and $r'$ filters and SNLS calibrated stars to calibrate the $G$ and $R$ values, we obtained calibration errors for ($ZP_1$, $ZP_2$) of (0.01, 0.015), (0.01, 0.14), (0.007, 0.009) for NU, OE, and JH, respectively. The positions of the SNe candidates in $CC - B$ space are shown in Figure 16. The photometric positions in $CC - B$ space are within one standard deviation from the corresponding synthetic positions, giving us confidence we are properly quantifying the SN flux through the SNACC filters with our photometry.

To determine the probability function a SN is a certain type and redshift, we employ the $\chi^2$ diagnostic of Equation (8). We make use of the sparse SN light curves to determine that our near-maximum SN templates are appropriate for the $\chi^2$ diagnostic. The photometric redshifts from the host galaxy are $0.54 \pm 0.13$ for NU, $0.47 \pm 0.20$ for OE, and $0.27 \pm 0.03$ for JH, respectively. The probability distributions for each SN are shown in Figure 17. For SN NU, the probability that the SN is Type Ia with $z = 0.56$ is $\sim 20\times$ the probability of any SNe II at any redshift. There are negligible probability tails at $z = \pm 0.2$ because the photometric redshift from the host galaxy is $\sigma_z = 0.13$ and because of the NU’s $CC - B$ position. The measured redshift error uncertainty is thus $\sigma_z = 0.01$ and the most probable redshift is within this error from the spectroscopic redshift. For SN OE, the SN fell in the region of $CC - B$ space where there is a local degeneracy of $CC - B$ values. The

| SN  | Type | Age$^a$ (days) | $g'$ (mag) | $r'$ (mag) | Host Gal. Photo-$z^b$ | SNLS Photo-$z^b$ (if SN Ia)$^c$ | Spec. $z^d$ |
|-----|------|----------------|-----------|-----------|----------------------|-----------------------------|-------------|
| NU  | Ia   | +1            | 23.4      | 22.5      | 0.54 $\pm$ 0.13      | 0.42                        | 0.56        |
| OE  | Ia   | -3            | 23.3      | 22.9      | 0.47 $\pm$ 0.20      | 0.42                        | 0.42        |
| JH  | IIP  | +30           | 23.3      | 22.5      | 0.27 $\pm$ 0.03      | 0.36                        | 0.22        |

Notes.

$^a$ Relative to the epoch of $B$-band maximum.

$^b$ Redshift of the host galaxy, as determined by the SDSS pipeline for SDSS galaxies.

$^c$ SNLS calculated redshift using broadband colors of a SN.

$^d$ SNID redshift from our LDSS-3 spectra.

Figure 15. Observed spectra for NU, OE, and JH with SN templates overlapped. Using the SNID program, the supernovae are classified as: NU, a SN Ia with $z = 0.56 \pm 0.01$; OE, a SN Ia with $z = 0.42 \pm 0.01$; and JH, a SN IIP with $z = 0.22 \pm 0.01$. These correlations have SNID rlap values of 0.63, 0.68, and 0.74, respectively.

Figure 16. NU, OE, and JH in $CC - B$ space (with error bars), as well as their synthetic positions (highlighted symbols). The synthetic positions of the SNe are within the standard deviations of the photometric positions. The distribution of SNe Ia in $CC - B$ space appears different than from Figure 6 because here the Megacam Sloan $g'$ and $r'$ filters make up the broadband filters. From the positions of the SNe in $CC - (g + r)$ space, one can find the type of SN, and if Ia, its redshift.

Figure 17. Normalized probability distribution for both redshift and type (SN Ia, SN II) for NU, OE, and JH from the chi-squared diagnostic (Equation (8)). The spectroscopic redshifts are also marked with a solid vertical line at its redshift value. For NU, the probability distribution for SNe Ia at different redshifts is a Gaussian centered at $z = 0.56$ with $\sigma_z = 0.01$. The peak is $\sim 20\times$ greater than the probability ($< 0.01$) of the flat SNe II distribution. For OE, the SN is clearly Ia, but there are degeneracies in the probability distribution due to the large photometric error and OE’s position in $CC - B$ space. For JH, there is no likely SN Ia candidate.
measurement strongly indicates that SN OE is Type Ia, but with a poor photometric redshift \( z = 0.47 \pm 0.2 \), it is difficult to determine the true redshift. The spectroscopic redshift 0.42 can be seen in one of the degenerate probability tails. As seen in Figure 16, the photometric and synthetic positions are within one standard deviation of each other, so a more accurate measurement would not improve the classification. While our three-tooth prototype suffered from the degeneracy in the upper-right quadrant of the \( CC - B \) space, we were able to correct this in our four-tooth solution, which will be used in the future and has no degenerate areas. Lastly, for SN JH, the probability that the SN is a SN Ia at a given redshift is <0.01. Although one cannot say the redshift of the SN, the low probability for all SNe Ia would allow us to discriminate this SN from SNe Ia and remove it.

6. DISCUSSION

While the use of multi-bandpass filters to measure a complex cross-correlation function is novel, such filters have had a prior use in astronomy. They were used to monitor blazars in multiple colors simultaneously (Wu et al. 2007). The light passing through the different passbands may be differentially refracted by an objective prism and can then be spatially passing through the different passbands may be differentially refracted by an objective prism and can then be spatially refracted by an objective prism and can then be spatially passed through the different passbands may be differentially passed through the different passbands may be differentially passed through the different passbands may be differentially passed through the different passbands may be differentially passed through the different passbands, and the other as a dashed line. The line, and the other as a dashed line. The light of our four-tooth solution, which will be used in the future and will be used in the future and will be used in the future and will be used in the future and will be used in the future.

Figure 18. Optimized four-tooth filter design, with one filter portrayed as a solid line, and the other as a dashed line. The \( g' \) and \( r' \) SuprimeCam filters are seen in gray. SN Ia spectra at \( z = 0.38 \), 0.58 are overplotted to illustrate how the SNACC filter passbands correlate with the SNe Ia spectral features. A SN IIP spectrum at \( z = 0.50 \) is also shown to demonstrate little correlation between the SN II features and the filter teeth. These four-tooth filters have an equivalent width of \( \sim 600 \, \AA \).

Figure 19. \( CC - B \) diagram for the four-tooth filter design of the SNe Ia (outside) and the SNe II (inside). While the SNe Ia radius is slightly smaller (0.20 mag), the cluster of SNe II is tighter around the center, and there is a similar separation between the SNe Ia and SNe II as from the three-tooth case, except here there is no local degeneracy of the SNe Ia. The SNe Ia purity and redshift determination for the three-tooth and four-tooth cases are approximately equal.

than long-slit spectroscopy. For example, with SNACC filters designed for SuprimeCam at Subaru (Miyaizaki et al. 2002), acquiring images of SNe (S/N > 30) is \( \sim 4 \) times faster than acquiring spectra (with S/N \( \sim 30 \), using the Subaru Exposure Time Calculator), and the expected space density of SNe Ia in a Pan-STARRS-like survey allows one to collect 4–8 SNe per pointing (with a field of view of 0.25 deg\(^2\)), so using SNACC filters is up to \( \sim 30 \) times faster than spectroscopy.

Spectra of high-z SNe (\( z > 0.5 \)) with a sufficient S/N for identification may be acquired on a large telescope (e.g., the Very Large Telescope (VLT), 8 m; see Appenzeller et al. 1998) in \( <1 \) hr, but the field of views for these telescopes’ spectrographs are too small (e.g., FORS1 on VLT, 36 square arcmin) to allow any multiplex advantage from multi-slit spectroscopy. On smaller telescopes (e.g., Magellan Baade and Clay Telescope, 6.5 m; see Dressler 2004), it is more common to obtain spectra of SNe with redshifts \( 0.2 < z < 0.5 \) (e.g., Foley et al. 2009), and while the field of view may be larger (e.g., IMACS on Baade, 239 square arcmin), the viewing depth is not large enough to allow any significant multiplex advantage from multi-slit spectroscopy.

In future surveys, measurements with SNACC filters should yield a likelihood distribution for each individual SN candidate being Type Ia within a measured redshift range. Such a distribution will be easily incorporated into a Bayesian cosmology analysis. While there are small tails in this probability distribution from the SNACC measurements of \( \Delta z = \pm 0.2 \), an error in \( z = \pm 0.2 \) should be easily distinguishable in a Bayesian cosmological analysis of the Hubble diagram since the difference in distance for two SNe Ia with this redshift separation is \( \sim 1.0 \) mag. Also, while there are certain transients, like SNe Ib-c, that are easily mistaken for SNe Ia, measurements with the SNACC filters will still provide the correct redshift of the SNe Ib-c. With the right redshift, the rarity of these objects, and the known brightness difference between supernovae types, a Bayesian cosmological analysis should easily be able to cope with these contaminants (Kunz et al. 2007).

Aside from speed, there are a number of advantages provided by the SNACC filters, which can be valuable depending on
the application. The measurements with SNACC filters are much less sensitive to reddening and allow for a more precise determination of redshifts than usual photometric methods. Image subtraction allows for a measurement free from the host contamination afflicting spectroscopy, which can be essential near the centers of hosts. Indeed, a well-known selection effect pertains at high redshift by the inability of long-slit spectroscopy to identify SNe Ia for cosmological analysis. This bias may be lifted with SNACC filters. And lastly, using the SNACC filters is independent of the color data used for subsequent distance determinations so there is no selection or interpretation bias (R. Kessler, et al. 2009, in preparation), and because it makes use of the spectral features, its reliability is greater. Although there are other approaches, like the use of multiple dichroic stacks, the precision of the supernova sample and its constraining power for dark energy.

7. SUMMARY

To obtain the needed type and redshift information of the candidate SN, we have developed a method of supernova observation which exploits the speed of photometric observations and much of the accuracy and precision of spectroscopic observations to determine the type of SN, and if Ia, its redshift. Our approach is based on the use of multiple narrow passbands in a single filter. Observations of supernovae through two of these filters effectively provide equivalent information as the evaluation of a spectral cross-correlation, typically used to measure the redshift and type of a SN from a low S/N spectrum. Simulating the use of SNACC filters as a follow-up tool, we can obtain a sample of SNe Ia which is ∼98% pure with redshifts of individual precision σz = 0.01 at a rate up to ∼30 times faster than typical high-z SN spectroscopy, a speed advantage which could greatly benefit future wide-area transient surveys.

Prototype SNACC filters were built and tested on Magellan with LDSS-3 and used to follow up three SNLS candidates. We acquired images with the SNACC filters as well as spectra of each candidate and we were successful in classifying the three candidates. In the future, we plan to apply this new technology for the next generation of supernova surveys and try to improve the precision of the supernova sample and its constraining power for dark energy.

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Facilities: Magellan: Clay (LDSS-3), CFHT.

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