

Photometric Typing Analyses of Three Young Supernovae Observed with the Robotic Palomar 60 Inch Telescope

ANNE M. RAJALA, DEREK B. FOX, AVISHAY GAL-YAM,¹ DOUGLAS C. LEONARD,²
ALICIA M. SODERBERG, AND S. R. KULKARNI

Department of Astronomy, MS 105-24, California Institute of Technology, Pasadena, CA 91125; amr@astro.caltech.edu, derekfox@astro.caltech.edu, avishay@astro.caltech.edu, leonard@astro.caltech.edu, ams@astro.caltech.edu, srk@astro.caltech.edu

AND

S. BRADLEY CENKO, DAE-SIK MOON,³ AND FIONA A. HARRISON

Department of Physics and Space Radiation Laboratory, MS 220-47, California Institute of Technology, Pasadena, CA 91125, cenko@srl.caltech.edu, moon@srl.caltech.edu, fiona@srl.caltech.edu

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ABSTRACT. We present photometric typing analyses of three young supernovae observed with the robotic 60 inch (1.5 m) telescope at Palomar Observatory (P60). This represents the first time that such phototyping, conducted in a blind fashion, has been attempted on newly discovered supernovae. For one of the target supernovae, SN 2004cs, our photometry provided the first constraint on the supernova type, which we predicted would be Type Ia. Contrary to expectations, however, our subsequent Keck spectroscopy shows it to be an unusual Type II supernova. For each of the other two supernovae (SN 2004dh [Type II] and SN 2004dk [Type Ib]), our phototyping results are consistent with the known event type as determined from ground-based spectroscopy. However, the colors of SN 2004dk are also consistent with a Type Ic or Type II classification. We discuss our approach to the challenges of phototyping—contamination by host galaxy light and the unknown photometric quality of the data—for cases in which it is desirable to complete the analysis with just one night of observations. The growing interest in the properties and behavior of very young supernovae, and the increased discovery rate for such events, mean that prompt phototyping analyses can provide useful input for observational campaigns. Our results demonstrate the value and feasibility of such a project for P60, at the same time illustrating its chief inherent shortcoming: an inability to identify new and unusual events as such without later spectroscopic observations.

1. INTRODUCTION

Supernovae (SNe) are classified into several commonly recognized categories on the basis of features in their optical spectra. These categories (SN Types Ia, Ib, Ic, and II) are not merely phenomenological distinctions; rather, they reflect real differences in the nature of the progenitor and the subsequent explosion (for a recent review, see Filippenko 1997).

As understanding of the nature of these differences has grown—and, moreover, as the number of SN discoveries has increased to more than 100 per year—the SN follow-up community has become increasingly specialized. Type Ia SNe have proven to be useful standard candles for cosmography (Perlmutter et al. 1997; Riess et al. 1998, 2004; Tonry et al. 2003; Knop et al. 2003) and have provided the first strong evidence for a cosmological constant or quintessence. Three Type Ic

SNe have been found in association with gamma-ray bursts: SN 1998bw (Galama et al. 1998), SN 2003dh (Stanek et al. 2003; Hjorth et al. 2003; Matheson et al. 2003), and SN 2003lw (Cobb et al. 2004; Thomsen et al. 2004; Malesani et al. 2004; Gal-Yam et al. 2004b). Indeed, Type Ib and Ic SNe provide the most likely population of “collapsar” events (Woosley 1993; MacFadyen & Woosley 1999). Finally, interest in Type II events has been focused by the Type II SN 1987A and its associated neutrino burst (Arnett et al. 1989 and references therein), which provided the first direct observation of core collapse. Type II SNe may also prove to be useful distance indicators if indications of strong correlations between their plateau-phase luminosities and expansion velocities (Hamuy & Pinto 2002) prove to be correct.

Given the diverse applications of SN observations—in addition to the various strategies employed by groups that study SNe—it follows that the efficiency of follow-up observations for any SN is dependent on the rapid identification of its type. These types are ultimately determined by the analysis of the

¹ Hubble Fellow.

² NSF Astronomy and Astrophysics Postdoctoral Fellow.

³ Robert A. Millikan Fellow.

optical spectra. However, spectroscopy time remains a somewhat precious commodity, and there is often a significant time delay—of days to weeks—before a SN can be properly typed in this fashion.

In two recent papers, Poznanski et al. (2002) and Gal-Yam et al. (2004a) have presented the outline of an alternative approach that can provide a probabilistic estimate of the type of newly discovered young SNe using multicolor photometry. With the proper facilities, this approach could be implemented on a rapid basis following the discovery of each new SN. Depending on the quality of the data obtained, and assuming that the SN spectra used to develop their test are sufficiently generic, the SN type can be determined in this way with a high degree of confidence before any spectra are taken.

The Poznanski–Gal-Yam method (PGM) makes use of three- or four-filter photometry of the SN, with the several magnitudes applied to calculate two colors for the object. The location of the object in this two-color space is then compared to the locations of SNe of various types and ages by referencing an extensive spectroscopic library. Since the PGM works from the basis of flux-calibrated optical (and, to an extent, UV and near-IR) spectra, the specific choice of filters and acceptable range of SN redshifts is not constrained a priori. In fact, Poznanski and Gal-Yam have implemented the method via an interactive Web page⁴ that presents their “typing machine,” which accepts as input an arbitrary set of Sloan or Johnson-Cousins filters. As Gal-Yam et al. (2004a) have pointed out, the similar spectra of all young SNe at redder wavelengths ($\lambda > 5500 \text{ \AA}$) means that classification of low-redshift events is best done with measurements in the B , g , V , and R filters.

When the redshift of the SN is known—typically, because the SN has been found to be in association with a cataloged local galaxy—the only remaining unknown is the quantity of extinction in the SN host galaxy. This parameter cannot be directly estimated from the photometric data; instead, an “arrow” in the two-color space shows the color correction that would account for 1 mag of extinction ($A_V = 1 \text{ mag}$) in the host. Since this is more or less the greatest extinction we expect to observe for SNe discovered in unfiltered optical searches, this provides a reasonable indication of the associated systematic uncertainty.

The first application of PGM phototyping by Poznanski et al. (2002) evaluated the likely type for SN 2001fg, which was discovered during the course of the Sloan Digital Sky Survey and had its redshift and type determined by follow-up Keck spectroscopy (Filippenko & Chornock 2001). Although the photometric analysis (based on the Sloan discovery photometry; Vanden Berk et al. 2001) suggested a ≥ 1 month old Type Ia identification for the event, in accord with the spectroscopy, this conclusion used the redshift of the event as de-

rived from the Keck data. Thus, it was more suggestive than diagnostic of the utility of the PGM.

We are therefore interested in making the first observational tests of PGM phototyping by obtaining four-filter imaging of young, low-redshift SNe. We are in a unique position to perform these tests, having recently completed the roboticization of the Palomar 60 inch (1.5 m) telescope (P60). Approximately 80% of the observing time on P60 is devoted to transient astronomy, and in the absence of high-priority campaigns, we are able to obtain images of new SNe quickly, within a day or two of the SN discovery. Indeed, in the 2004B semester, we have begun a Palomar large program, the Caltech Core Collapse Program (CCCP; Gal-Yam et al. 2004c), to monitor the photometric and spectroscopic evolution of a complete sample of low-redshift core-collapse SNe over the course of a year. Early-time SN phototyping observations provide a natural supplement to these extended CCCP photometric campaigns.

The organization of our paper is as follows. In § 2 we review our procedure for performing accurate photometry on the SNe. Section 3 presents our observations and data reduction and analysis. In § 4 we phototype our three target SNe: SN 2004cs, SN 2004dh, and SN 2004dk. In § 5 we present our spectroscopic observations of SN 2004cs, demonstrating its unusual Type II nature, and reflect on the erroneous phototyping result for this event. Section 6 presents our conclusions and discusses future prospects for this work.

2. METHODOLOGY

Accurate photometry of a newly discovered SN presents at least two challenges. First, the SN will be superposed on some unknown quantity of background light from its host galaxy; and second, the immediate field of the SN will have to be photometrically calibrated. Moreover, if a quick turnaround is desired, this calibration will generally have to be carried out in less than ideal conditions.

We address the first of these issues by performing point-spread function (PSF) photometry on the SN and on several reference stars, using the DAOPHOT package (Stetson 1987, 1990) in the IRAF⁵ environment. Although this will fail to account for any pointlike component of the host galaxy light (e.g., a compact underlying H II region), such contamination cannot be avoided without reference to pre- or post-SN imaging. Moreover, since we are studying low-redshift events in resolved galaxies, the strength of such contamination is not expected to be severe.

If the night is (close to) photometric, standard fields are analyzed with the Stetson photometric catalog⁶ using the PHOTCAL package in IRAF to derive the photometric transformation equations for the night and apply these equations to

⁵ For information on the NOAO Image Reduction and Analysis Facility, see <http://iraf.noao.edu>.

⁶ See <http://cadwww.dao.nrc.ca/standards>.

⁴ See <http://wise-obs.tau.ac.il/~dovip/typing>.

TABLE 1
DERIVED MAGNITUDES FOR SN 2004cs, SN 2004dh, AND SN 2004dk

SN	DATE (UT)	TIME (UT)	MAGNITUDES				
			<i>B</i>	<i>g</i>	<i>V</i>	<i>R</i>	<i>I</i>
SN 2004cs	2004 Jun 24	06:59	18.162(75)	18.233(52)	18.060(67)	17.865(84)	...
SN 2004dh	2004 Jul 25	07:58	18.364(44)	...	17.906(22)	17.584(31)	17.392(38)
SN 2004dk	2004 Aug 03	04:02	17.789(55)	17.500(37)	17.179(21)	16.791(17)	...

NOTE.—Positions and magnitudes of the reference stars used to calibrate the fields of these SNe are available from the authors on request.

the aperture magnitudes of the PSF stars in the SN field. The resulting “true” magnitudes of the PSF stars are then compared to their PSF magnitudes to derive the PSF-to-aperture zero-point shift to apply to the SN PSF magnitudes. If the night is not sufficiently photometric, we retain the phototyping observation sequence in the P60 queue for roughly a week and use the best available night for our analysis.

In general, we aim to perform our analysis of each SN promptly. As such, we sacrifice some accuracy by attempting to calibrate the images on the same night as the observations whenever possible, instead of waiting for a photometric night (which are rare at Palomar). We examine the coefficients of the transformation equations produced by the standard fields to determine if the night is photometric. If these parameters are unreasonable (implying, for example, that stars are appearing brighter at increased air mass), some subset of the standard observations may be dropped. To force reasonable coefficients, the air mass term can be dropped from the fit entirely, and only standards taken at an air mass similar to that of the target field used to calculate the photometric and color shifts. To control for associated systematic effects (e.g., clouds), we can observe the SN target field twice during the night. This does not add much time to the run, but allows the full analysis to be performed twice on quasi-independent sets of data. If consistent answers cannot be obtained for the magnitudes of the reference stars across the two observations, we may find that we can derive consistent answers for their colors (i.e., to the extent that we are subject to varying levels of approximately gray extinction). This introduces an uncontrolled systematic error in that it assumes the SN is similar enough in color to our reference stars that atmospheric and extinction effects are comparable; however, it does at least allow for a phototyping measurement to be made.

The Stetson standard fields are not calibrated in the *g* band; we calculate *g*-band magnitudes for stars in the standard fields from their *B* and *V* magnitudes, using the transformation equations of Smith et al. (2002).

To check the accuracy of the photometric errors estimated by IRAF, the calculated magnitudes of the reference stars from two independent data sets are then compared. Ideally, the second data set is taken on the same night, but it can also come from a different night with a distinct set of transformation equations. A χ^2 comparison can then be made to reject outliers

and estimate the factor needed to inflate the IRAF errors to get a reduced χ^2 value of 1. We have found that this is generally necessary, since IRAF tends to quote errors that are too small, partly because they are derived from an idealized model, and partly because the entire photometric calibration process presumes ideal photometric conditions. Separately, at these beginning stages of the P60, our observations were subject to significant seeing variations over the course of the night; the seeing at P60 tending to be poor at the beginning of the night, then improving and stabilizing by midnight. A similar χ^2 check is done for the calculated aperture-to-PSF zero-point shifts, on a star-by-star basis. The derived multiplicative factors required to make the IRAF-quoted errors acceptable are then applied to the SN errors.

While one goal of this project is to create the most automated process possible, a minimal amount of human interaction helps to ensure robust and repeatable results. First, it is advisable to have a human selecting or reviewing the reference stars used in the SN field; this does not take much time but is more reliable than IRAF’s selection methods, which occasionally select saturated stars, stars near bad pixels, cosmic rays, or nonisolated stars. In addition, constructing photometric calibrations for non-photometric nights can lead to variations that make it difficult to trust a single blind fit of the transformation equations. Indeed, the three-step process of progressively more conservative (and less precise) approaches to photometric calibration that we describe above can probably only be carried out in an interactive fashion, although an automated pipeline could take the alternative approach of carrying out all three approaches in parallel (later allowing human interaction to select the best of the three).

3. OBSERVATIONS AND DATA REDUCTION

We selected candidates that were discovered at a demonstrably young age and were observable from the Palomar Observatory. The target SNe were observed by P60 on the first available night in *BgVR* or *BVRI* (Table 1).

All of our images were taken with the new camera at P60, which is a two-amplifier, 2048 × 2048 SiTe CCD with a 12′9 field of view at Cassegrain focus. Readout (25 s for the full chip in single-pixel-binning mode) is accomplished by a two-channel Leach III controller card (details of the new camera and robotic observing system will be presented in a forthcoming

TABLE 2
TERMS OF TRANSFORMATION EQUATIONS

SN	FILTER	ZERO POINT	COLOR TERMS			AIR MASS		rms OF FIT
			$B - V$	$V - R$	$R - I$	Coefficient	Range	
SN 2004cs	B	0.917	1.031	...	...	0.099	1.1–2.3	0.117
	V	1.719	−0.022	...	...	0.121	1.1–2.4	0.099
	R	2.124	...	−0.801	...	0.101	1.1–2.3	0.103
SN 2004dh	B	1.277	−0.900	...	...	...	1.6 ^a	0.029
	V	2.243	−0.316	...	...	...	1.6	0.058
	R	2.362	...	−0.919	...	...	1.6	0.082
	I	2.400	...	...	−0.969	...	1.6	0.074
SN 2004dk	B	1.219	0.867	...	...	...	1.3 ^b	0.279
	V	1.473	0.377	...	...	...	1.3	0.183
	R	2.284	...	−0.808	...	...	1.3	0.190

NOTE.—This table denotes the coefficients of each term in the transformation equations used in photometric calibration.

^a The SN 2004dh calibration made use of a single standard field observed at air mass 1.6 (see text for details).

^b The SN 2004dk calibration made use of a single standard field observed at air mass 1.3 (see text for details).

ing paper). Data were overscan-subtracted, demosaicked, bias-subtracted, flat-fielded (using dome flats taken the preceding afternoon), bad pixel-masked, and had a blind-pointing world coordinate system (WCS) applied by the P60 image analysis pipeline. We refined this WCS by referencing Digitized Sky Survey images of the field.

SN 2004cs in UGC 11001 was discovered before peak (rising by >1 mag in 2 days) by Li & Singer (2004) on 2004 June 23.42 UT. We observed the SN on the night following discovery, 2004 June 24, starting at 06:59 UT. Images were taken in the B , g , V , and R filters at an air mass of 1.06 and with a seeing of $1''.8$. Each of these exposures lasted for 300 s.

This night was not photometrically calibrated, so additional images were taken of the SN 2004cs field, along with images of PG 1657, on the night of July 30, beginning at 04:13 UT ($1''.8$ seeing), 06:18 UT ($1''.7$ seeing), and 08:30 UT ($2''.0$ seeing). These 30 s exposures were taken at three different air masses, ranging from 1.1 to 2.3. PG 1657 is one of the Stetson photometric standard fields. These standard fields were used to fit transformation equations to the data in the B , V , and R filters. These parameters are listed in Table 2. Since these terms are reasonable, we applied them to the reference stars in the field of SN 2004cs to derive their true magnitudes. The two sets of observations used to calculate the true magnitudes of the reference stars were taken this night, beginning at 04:23 UT (at 1.07 air mass and $1''.9$ seeing) and 07:34 UT (at 1.30 air mass and $1''.6$ seeing). Each exposure was 60 s long.

In the case of SN 2004cs, since calibration was done on a separate night, the shifts of the reference stars were calculated separately; the first by finding the average shift between the true magnitudes (derived from the second night’s data) and the instrumental aperture magnitudes (from the first night’s data), and the second shift by finding the difference between the instrumental aperture magnitudes and the PSF magnitudes on the first night. These two shifts, applied to the SN to get its true

magnitudes (see Table 2), were respectively $-1.92(2)$ and $0.0016(50)$ mag in B , $-1.83(4)$ and $-0.76(2)$ mag in g , $-1.80(4)$ and $-1.06(3)$ mag in V , and $-1.87(5)$ and $-1.4(6)$ mag in R .

SN 2004dh in MGC +4-1-48 was discovered by Moore & Li (2004) in an image taken on 2004 July 21.47 and confirmed from an earlier image on July 11.45. Prompt spectroscopy by Matheson et al. (2004) classified this SN as a Type II before our analysis was complete. We observed the SN on 2004 July 25, beginning at 07:58 UT. A g -band image was not taken, and our analysis was performed with the B , V , R , and I filters. All exposures were taken for 120 s. This set was imaged at an air mass of 1.57 with $1''.5$ seeing.

For photometric calibration purposes, images of the standard field PG 1657 were taken in the B , V , R , and I filters at a similar air mass (1.597) and at a similar time (beginning at 07:44 UT). Each of these exposures was taken for 30 s with a seeing of $1''.4$. Only one set of observations was used to determine the photometric zero points. Since these images were taken at nearly the same air mass and time, the air mass terms were fixed at zero in the transformation equations. The coefficients of these equations are given in Table 2.

The average zero-point shift between the PSF magnitudes of each reference star and its true magnitudes was calculated, to be applied to the SN’s magnitudes (Table 1). These shifts were $-2.09(4)$ mag in B , $-2.71(1)$ mag in V , $-3.03(2)$ mag in R , and $-3.36(3)$ mag in I .

SN 2004dk in NGC 6118 was discovered before peak by Graham & Li (2004) on 2004 August 1.19 UT. This SN was identified as a Type Ic object (Patat et al. 2004b) before our analysis was complete (subsequent observations of the event suggest it is more likely Type Ib [Filippenko et al. 2004]). We observed the SN on 2004 August 3, beginning at 04:02 UT, two nights after its discovery, in the B , g , V , and R filters. Exposures lasting 90 s were taken in each filter at an air mass of about 1.26 and with a seeing of $3''.8$.

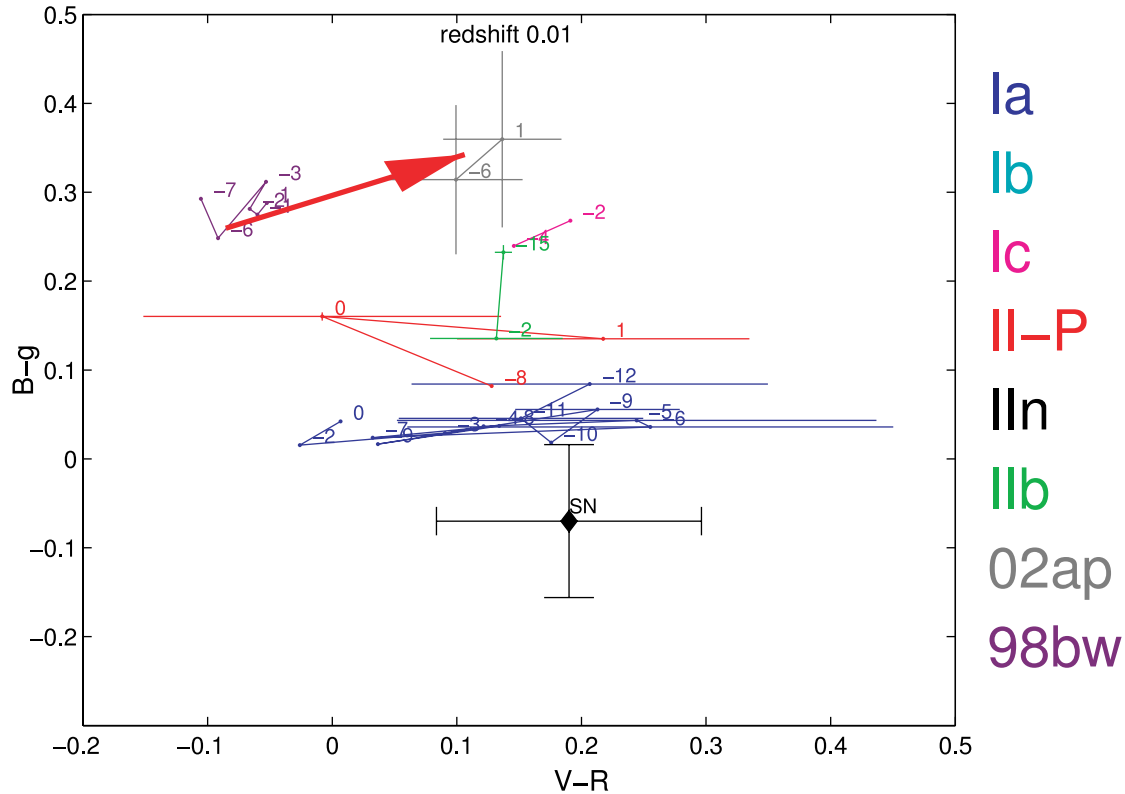


FIG. 1.—Plot of $B - g$ and $V - R$ colors of SN 2004cs on 2004 June 24.3 UT (black diamond) compared to tracks for typical SNe of each type (and two distinctive individual events, SN 1998bw and SN 2002ap) for SN ages from 20 days before to 1 day after maximum light. The tracks show the evolution in SN color for each of the comparison events, with numbers giving the age in days relative to maximum light at each point. A young Type Ia identification for SN 2004cs is indicated, as reported in Rajala et al. (2004a, 2004b, 2004c). However, our subsequent spectroscopy has revealed the SN to be an unusual Type II event (§ 5). The redshift of UGC 11001, the SN host galaxy, is 0.014060. The large red arrow indicates the color correction that would be required if SN 2004cs were subject to $A_V = 1$ mag of extinction in its host galaxy. This plot was created with the online PGM typing machine (see text for details).

On this night, images of the standard field PG 1657 were also taken, beginning at 05:56 UT, to photometrically calibrate the fields. These were taken in each filter (B , V , and R) for 30 s at an air mass of about 1.26 (similar enough to the air mass at which the SN images were taken to fit transformation equations without an air mass term). These images were taken with seeing of about $1''.65$. The transformation equations are given in Table 2.

The true photometry of SN 2004dk (see Table 1) was then derived by applying the same shifts calculated between the true magnitudes and the PSF magnitudes of the reference stars. These shifts are $-2.41(5)$ mag in B , $-2.85(2)$ mag in g , $-3.20(1)$ mag in V , and $-3.70(1)$ mag in R .

4. PHOTOTYPING OF SN 2004cs, SN 2004dh, AND SN 2004dk

To phototype each of our three target SNe, we used the calibrated magnitudes (Table 1), a restriction on the likely age of the SN relative to maximum light, and the known redshift of the SN host galaxy as input to the PGM typing machine.

The SN age restriction is derived from the time of the last prediscovery observation, included in the SN discovery reports. For inclusion in our “young” target sample, we required that the reference imaging be taken within 1 month prior to discovery. The resulting PGM typing machine plots (Figs. 1–3) compare the colors of each SN with the colors of typical SNe of each type, as well as the colors of several individual events of particular notoriety: SN 1998bw and SN 2002ap (see Gal-Yam et al. 2004a).

For SN 2004cs, the SN age was restricted to the range beginning 20 days before and ending 1 day after maximum light, and the redshift of its host galaxy, UGC 11001, is 0.014060. The corresponding PGM plot (Fig. 1) implies that this is a likely Type Ia event. Since no one had yet announced the type for SN 2004cs at the completion of our initial analysis, we announced this result in *Astronomer’s Telegram* 320 and *IAU Circulars* 8386 and 8387 (Rajala et al. 2004a, 2004b, 2004c). Our subsequent spectroscopic observations of this SN, however, reveal it to be an unusual Type IIb event (see § 5 below).

For SN 2004dh, the SN age was restricted to the range

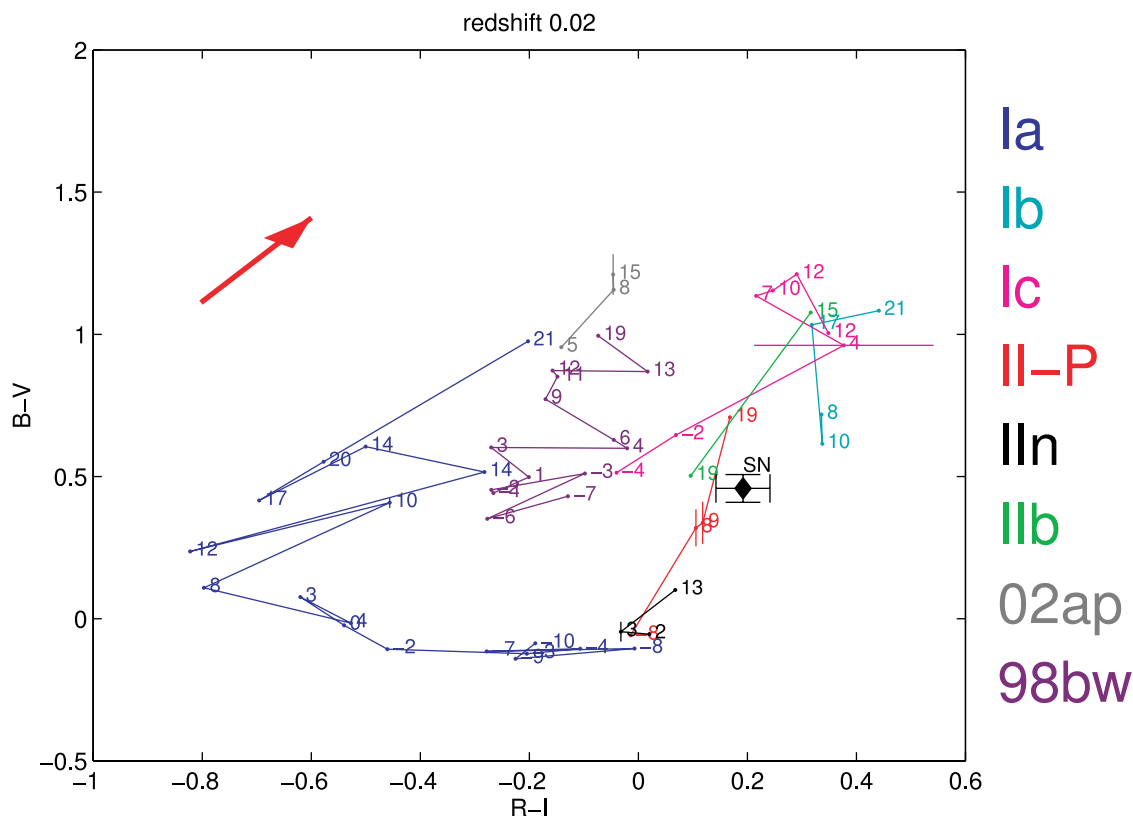


FIG. 2.—Plot of $B - V$ and $R - I$ colors of SN 2004dh on 2004 July 25.3 UT (black diamond) compared to tracks of typical SNe various types (and two distinctive individual events) for SN ages from 20 days before maximum light to 21 days after maximum light. A Type II identification for SN 2004dh is indicated, in agreement with the spectroscopic determination by Matheson et al. (2004). The redshift of MGC +4-1-48, the SN host galaxy, is 0.019327. This plot was created with the online PGM typing machine (for description of the figure elements, see Fig. 1).

beginning 20 days before and ending 21 days after maximum light, and the redshift of its host galaxy, MGC +4-1-48, is 0.019327. The plot of SN 2004dh (Fig. 2) implies that it is a Type II, and quite likely of subtype II-P. This agrees with the spectroscopic determination of Matheson et al. (2004).

For SN 2004dk, the SN age was restricted to the range beginning 20 days before and ending 10 days after maximum light, and the redshift is 0.005247, the same as its host galaxy, NGC 6118. The plot of SN 2004dk (Fig. 3) indicates a core-collapse (e.g., non-Ia) identification, although the data and template sets do not allow a strong conclusion to be reached regarding the specific type, which may be Type Ib, Ic, or II-P. This agrees with the Type Ib identification for this event as determined by Filippenko et al. (2004). Alternatively, it also agrees with the Type Ic identification of Patat et al. (2004b) suggested above.

5. SPECTROSCOPIC TYPING OF SN 2004cs

We observed SN 2004cs using the W. M. Keck I 10 m telescope Low Resolution Imaging Spectrometer (LRIS; Oke et al.

1995) on 2004 August 12, roughly 50 days after discovery and 45 days after peak brightness. The SN was quite faint at this time, so we used a nearby bright star offset provided by the Lick Observatory Supernova Search team (Moore & Li 2004) to place the SN on our 1" slit. The one-dimensional sky-subtracted spectrum was extracted optimally (Horne 1986) in the usual manner, with a width of 1"8 along the slit. Great care was taken to properly remove the background, since the SN is located in a complex region of its host galaxy, UGC 11001, with many bright H II regions. The spectrum was then wavelength- and flux-calibrated, corrected for continuum atmospheric extinction and telluric absorption bands (Wade & Horne 1988; Bessell 1999; Matheson et al. 2000), and rebinned to $10 \text{ \AA pixel}^{-1}$ to improve the signal-to-noise ratio. Finally, we removed a recession velocity of 4431 km s^{-1} from the spectrum, derived from the velocities indicated by the superposed H II regions. Additional details of the observation and reduction of this spectrum, along with the light curve of SN 2004cs, will be given in a forthcoming paper (D. Leonard et al. 2005, in preparation).

We present the extracted spectrum in Figure 4. The H α emis-

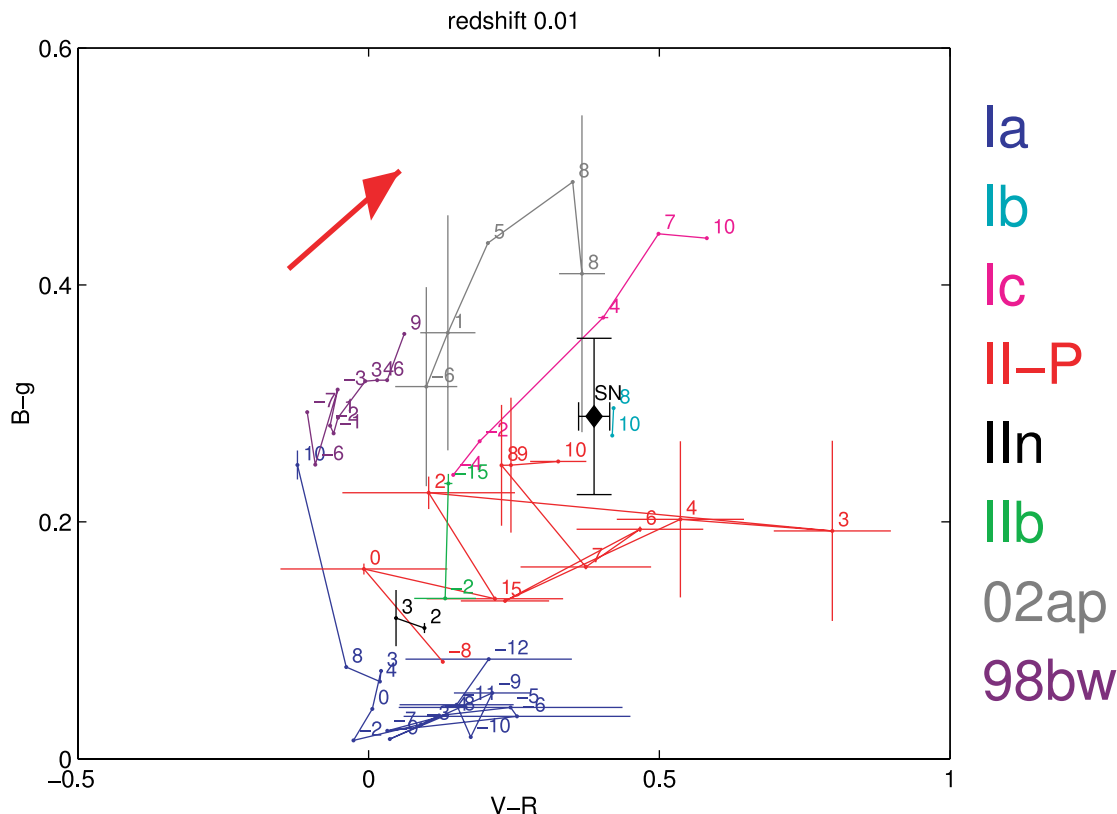


FIG. 3.—Plot of $B - g$ and $V - R$ colors of SN 2004dk on 2004 August 3.2 UT (black diamond) compared to tracks of typical SNe of various types (and two distinctive individual events) for SN ages from 20 days before maximum light to 10 days after maximum light. A Type Ib, Type Ic, or Type II identification for SN 2004dk is indicated. The Type Ib spectroscopic determination of Filippenko et al. (2004) is consistent with these findings. The redshift of NGC 6118, the SN host galaxy, is 0.005247. This plot was created with the online PGM typing machine (for description of the figure elements, see Fig. 1).

sion feature identifies SN 2004cs as a Type II event. The additional presence of P Cygni lines of helium suggests a Type IIb identification, although a confident determination will have to await a joint analysis of the spectrum and light curve of this event (D. Leonard et al. 2005, in preparation).

Although a color track for Type IIb SNe is presented in our phototyping plots, such SNe are rare, and SN 2004cs was discovered at an extremely young age. Our own observations were similarly prompt, and this combination of an unusual event and very early observations may explain our incorrect phototyping. Indeed, this shortcoming of phototyping was known a priori; the dense coverage of the color-color plane in Figures 1–3 means that some sort of identification is possible for almost every event, even for unusual SNe that do not adhere to previously identified spectrophotometric regimes. In short, although our phototyping result for this event is incorrect, it is nonetheless incorrect in an interesting fashion—misidentifying an unusual SN that presented us with unprecedented colors (for a Type II SN) at our first epoch of observation.

6. CONCLUSIONS

We have demonstrated the application of Poznanski–Gal-Yam method (PGM) phototyping (Poznanski et al. 2002; Gal-Yam et al. 2004a) to three young SNe observed with the robotic 60 inch telescope at Palomar Observatory. This represents the first real-world application of the PGM to the problem of typing young SNe soon after discovery, and (for the case of SN 2004cs) is only the second blind application of the PGM of which we are aware.⁷

For SN 2004cs, discovered before peak by Li & Singer (2004), our results provided the first constraint on the SN type, suggesting that it was likely to be a young Type Ia event (Rajala et al. 2004a, 2004b, 2004c; see Fig. 1). However, our subsequent Keck I+LRIS spectroscopic observations (Fig. 4) indicate that SN 2004cs is an unusual Type II SN, perhaps of subtype IIb.

⁷ During the course of our project, a PGM phototyping analysis of the newly discovered SN 2004dj (Nakano et al. 2004) was made by E. Ofek and collaborators at Wise Observatory. This analysis correctly identified the type (II) and age (roughly 1 month) of the event prior to the first spectroscopic reports (Patat et al. 2004a).

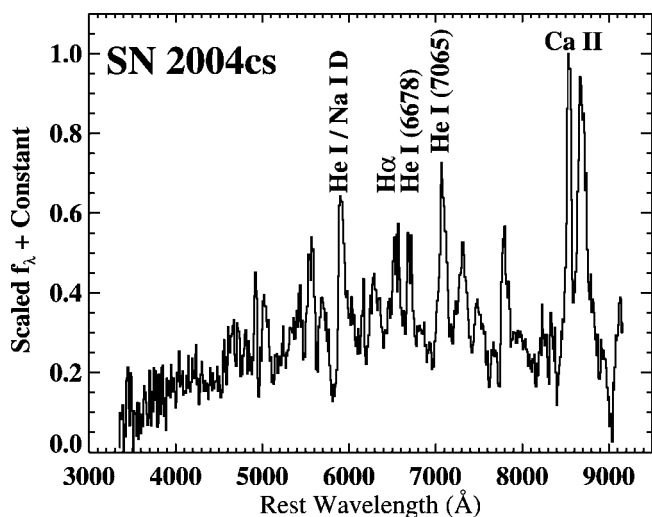


FIG. 4.—Optical spectrum of SN 2004cs from 2004 August 12, with prominent line features labeled; this date is 55 days after the estimated date of explosion. A systemic velocity of 4431 km s^{-1} , derived from the spectrum of H II regions in the host galaxy, has been removed. The prominent H α emission feature indicates a Type II identification, with the rarely seen He emission features suggesting that SN 2004cs is an unusual Type II, perhaps of subtype IIb.

For SN 2004dh, discovered close to peak by Moore & Li (2004), our PGM phototyping analysis suggests a Type II identification (Fig. 2), consistent with the Type II spectroscopic determination reported by Matheson et al. (2004). For SN 2004dk, discovered before peak by Graham & Li (2004), our PGM phototyping analysis suggests a core-collapse identification of either Type Ib, Ic, or II (Fig. 3), consistent with the Type Ib spectroscopic determination reported by Filippenko et al. (2004).

We have described in detail our approach to implementing PGM phototyping with multiband optical images from a small (1.5 m) robotic observatory. At the first available opportunity, we image the SN and photometric standard fields from the Stetson catalog, in four bands and at least two epochs. PSF photometry with the DAOPHOT package allows us to isolate the SN light from that of its host galaxy, and by imaging the SN field at two epochs during the night, or on two distinct nights, we are able to control for less than ideal photometric conditions. The derived magnitudes of the SN, its redshift as determined from its host galaxy, and the constraints on its age

as reported by the SN discoverers can then be input into the PGM “typing machine” to generate a plot comparing the SN colors with tracks corresponding to the color evolution of SNe of various types and appropriate ages. These plots in turn allow an estimate of the SN type to be made.

The success of two of our three test cases suggests that PGM phototyping may well be usefully applied to newly discovered young SNe and that the P60 is an appropriate facility for this work. At the same time, our failure to correctly identify the type for SN 2004cs points to an inherent limitation of phototyping; namely, that it is unlikely to distinguish new and unusual SNe from the majority of more or less typical events.

In the future, we plan to distill the various aspects of our PGM implementation into scripts that will help us to provide phototypes for newly discovered, young SNe in a timely fashion. It is our hope that this will prove a valuable service for the larger supernova community.

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