A NOVEL COLOR PARAMETER AS A LUMINOSITY CALIBRATOR FOR TYPE Ia SUPERNOVAE

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ABSTRACT

Type Ia supernovae (SNe Ia) provide us with a unique tool for measuring extragalactic distances and determining cosmological parameters. As a result, the precise and effective calibration for peak luminosities of SNe Ia becomes extremely crucial and thus is critically scrutinized for cosmological explorations. In this Letter, we reveal clear evidence for a tight linear correlation between peak luminosities of SNe Ia and their $B - V$ colors ~12 days after the B maximum denoted by ΔC_{12}. By introducing such a novel color parameter, ΔC_{12}, this empirical correlation allows us to uniformly standardize SNe Ia with decline rates Δm_{15} in the range of $0.8 < \Delta m_{15} < 2.0$ and to reduce scatters in estimating their peak luminosities from ~0.5 mag to the levels of 0.18 and 0.12 mag in the V and I bands, respectively. For a sample of SNe Ia with insignificant reddenings of host galaxies [e.g., $E(B - V)_{\rm host} \lesssim 0.06$ mag], the scatter drops further to only 0.07 mag (or 3%–4% in distance), which is comparable to observational accuracies and is better than other calibrations for SNe Ia. This would impact observational and theoretical studies of SNe Ia and cosmological scales and parameters.

Subject headings: cosmological parameters — distance scale — supernovae: general

1. INTRODUCTION

The use of Type Ia supernovae (SNe Ia) as lighthouses or "standard candles" for cosmological studies became feasible upon the realization of an empirical correlation of peak luminosity with light-curve shape. The discovery of the relationship between light-curve shape and brightness led to a parameterization by the decline rate Δm_{15} in B-band brightness over 15 days after the maximum light (Phillips 1993). The "multicolor light-curve shape" method (Riess et al. 1996, 1998) is based on Δ, the difference in peak luminosity between an observed SN and a fiducial template. The "stretch" method (Perlmutter et al. 1997; Goldhaber et al. 2001) parameterizes light curves with a factor s, which broadens or narrows the rest-frame timescale of a single standard template to match with observed light curves. The "Bayesian adapted template match" method introduced by Tonry et al. (2003) estimates distances by comparing with a large set of well-observed nearby SNe Ia rather than a parameterized template. These methods are fundamentally equivalent by making use of light-curve shapes. Another distance measurement technique is the CMAGIC method (Wang et al. 2003), which uses the relationship between light-curve shape and brightness in a more indirect way than the above procedures. It is based on an observed linear relationship in color-magnitude space for a certain period after the maximum light to infer distances.

Besides the light-curve shape parameters, there are other parameters that have been introduced to correlate with peak luminosities of SNe Ia, such as line strengths of Ca and Si absorption lines (Nugent et al. 1995), the Hubble types or colors of parent galaxies (Hamuy et al. 1996; Branch et al. 1996), and the galactocentric distance (Wang et al. 1997). These parameters as peak luminosity descriptors are somewhat difficult to quantify, especially for an SN Ia at a higher redshift z. In comparison, the color $B - V$ at the maximum light seems to serve well as another important peak luminosity descriptor, which has been justified for further reducing statistical dispersions of distance estimates when combined with decline rates (Tripp 1997; Tripp & Branch 1999; Parodi et al. 2000). As to those peculiar and subluminous SNe Ia, the peak $B - V$ color was found to be a more effective indicator of peak luminosity than the fading rate (e.g., Garnavich et al. 2004). The difficulty of using this color parameter is that extremely accurate photometry and reddening estimates are required, yet this situation may be mitigated for the postmaximum $B - V$ color as differences in the color curves become more conspicuous.

The main thrust of this Letter is to show that the $B - V$ colors of SNe Ia, measured ~12 days after the B maximum, strongly correlate with their peak luminosities within a wide range of decline rates. With this important empirical finding, it is now possible to standardize all SNe Ia and use them to infer extragalactic and cosmological distances with precisions comparable to observational limits.

2. THE NOVEL COLOR PARAMETER ΔC_{12}

2.1. *The Color Curves*

Shown in Figure 1 are the $B - V$ colors and their evolution of nine well-sampled SNe Ia covering a broad range of observed light-curve decline rates. The $B - V$ color was K-corrected and dereddened by the Galactic reddening using the full-sky maps of dust infrared emission (Schlegel et al. 1998). These SN Ia events most likely suffer little or no reddening from dust in host galaxies, on the basis of certain basic criteria such as the absence of interstellar Na I or Ca II lines in the spectra, morphologies of host galaxies, and the location of an SN in the host galaxy. In reference to the light curves, the evolution of color curves appears more complex and basically undergoes three stages: they become bluer from the initial detection to about 5 days before the maximum, then evolve redward by ~1 mag during 2–3 weeks after the maximum, and eventually recover from the reddest color to zero when entering the nebular phase. Note that the $B - V$ colors of different SNe Ia converge ~30 days after the maximum

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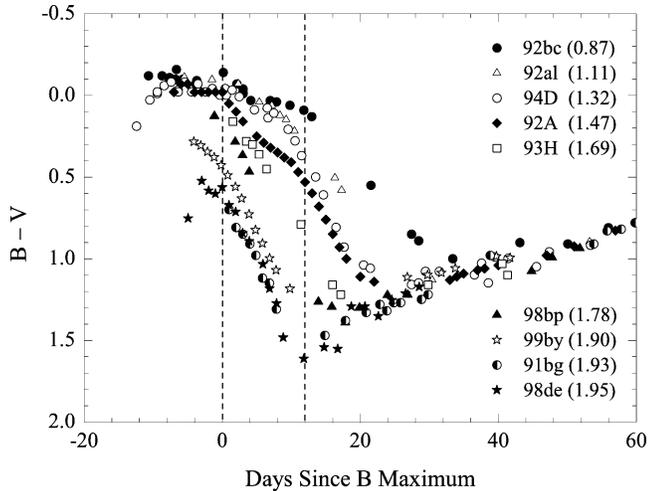
Fig. 1.—$B - V$ color evolution of nine SNe Ia most likely with negligible reddening from dusts in host galaxies. These nine events with their Δm_{15} parameters indicated in parentheses cover a wide range of initial decline rates and peak luminosities. The two vertical dashed lines mark the epochs of the B maximum and 12 days after the B maximum, respectively.

Fig. 2.—*Left*: $B - V$ colors ΔC_{12} of SNe Ia observed 12 days after the B maximum plotted against the decline rate parameter Δm_{15}. The open circles are SNe Ia with $E(B - V)_{host} > 0.06$ mag. The filled circles represent 38 events with $E(B - V)_{host} \lesssim 0.06$ mag; these SNe Ia most likely show little or no dust reddening of host galaxies. The solid curve is a cubic spline fit. *Right*: Host galaxy reddenings derived from the ΔC_{12}-Δm_{15} relation plotted against the estimates by P99.

light and evolve in a similar way thereafter. This color uniformity has proven very useful as an indicator of host galaxy reddenings (Phillips et al. 1999, hereafter P99).

Except for the peculiar SNe Ia, the color curves of normal SNe Ia appear to have similar shapes. Their $B - V$ colors approach zero near the maximum light (Parodi et al. 2000). Nevertheless, a careful examination of the early phase still reveals small shifts among color curves of different SNe Ia. This may be attributed to reddenings in host galaxies or to intrinsic differences among SNe Ia (including the mass of accreting CO white dwarfs, C/O ratio, metallicity, magnetic fields, etc.; e.g., Umeda et al. 1999; Timmes et al. 2003; Lou 1994, 1995). The prominent feature of the $B - V$ color evolution curve for those peculiar subluminous SNe 1991bg, 1998de, and 1999by is their unusually red $B - V$ colors in the early phase. At the B maximum, the $B - V$ colors for SNe 1991bg, 1998de, and 1999by are 0.69, 0.56, and 0.45 mag, respectively. In addition to shifts among the $B - V$ color curves of different SNe Ia, there are also variations in their shapes. For example, SNe 1991bg and 1998de show dramatic declines and reach their reddest colors earlier than normal SNe Ia do, at $t \sim 12$ days after the B maximum, rather than at $t \sim 30$ days for normal SNe Ia. Closer examinations of normal SNe Ia reveal diverse decline rates in the color curves immediately after the B maximum (see Fig. 1). This diversity is apparently associated with a slower flux variation in the V band than in the B band for different SNe Ia during this phase.

2.2. The Color Parameter ΔC_{12} as a Calibrator

The $B - V$ color measured at the B maximum is one of the most important secondary parameters used to calibrate peak luminosities of SNe Ia (Tripp 1997; Tripp & Branch 1999; Parodi et al. 2000; Garnavich et al. 2004) and even yields clues of host galaxy reddenings together with the decline rate parameter Δm_{15} (P99). Note that peak values of $B - V$ mostly concentrate in a range from ~ -0.1 to ~ 0.1 mag for normal SNe Ia. Within such a narrow range, it is very difficult to precisely measure the peak $B - V$ color. As apparent in Figure 1, the $B - V$ colors ~ 12 days after the B maximum clearly distinguish the SN Ia color curves that vary from ~ 0.1 to ~ 0.8 mag for normal SNe Ia and extend to ~ 1.6 mag for peculiar events (SN 1998de)
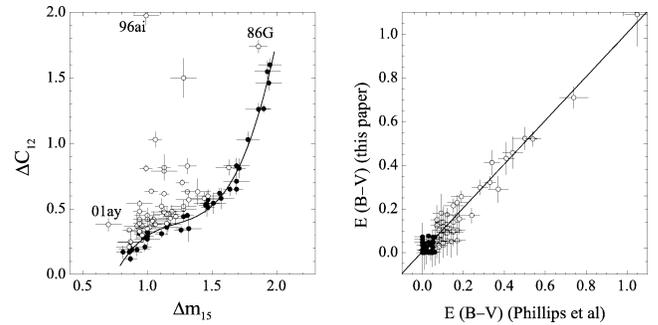
at this epoch. This postmaximum color not only contains the intrinsic color shift at the maximum light but also reflects, to a certain extent, the difference in light curves. We emphasize the usage of the $B - V$ color 12 days after the B maximum, referred to as ΔC_{12}, as a powerful calibrator for peak luminosities of SNe Ia.

The ΔC_{12} values for SNe Ia can be estimated directly from the photometry or from the best-fitting template. Uncertainties in ΔC_{12} include errors in observed magnitudes, in foreground reddenings, and in the K term. The ΔC_{12} "colors" of 84 well-observed SNe Ia[6] are plotted against the decline rate parameter Δm_{15} in the left panel of Figure 2. Those SNe Ia with light-curve coverage beginning $\gtrsim 7$ days after the B maximum were excluded in our sample of SNe Ia, as their extrapolated maximum magnitudes and ΔC_{12} and Δm_{15} parameters may be inaccurate owing to larger errors.

2.3. The Host Galaxy Reddenings Derived from ΔC_{12}

Lira (1995) has shown that SNe Ia with low extinctions tend to have the same $B - V$ colors between 30 and 90 days after the maximum. This fact was exploited by P99 to estimate dust reddenings of SNe Ia in host galaxies. Based on the late-time colors, we find that 38 out of 84 SNe Ia have values of $E(B - V)_{host} \lesssim 0.06$ mag. We thus assume below that these SNe Ia were essentially unreddened by dust in their host galaxies; their ΔC_{12} values approximately represent the intrinsic $B - V$ colors 12 days after the B maximum.

As is clear in the left panel of Figure 2, an empirical correlation exists between the color parameter ΔC_{12} and the decline rate Δm_{15} for those SNe Ia with $E(B - V)_{host} \lesssim 0.06$. This functional relation, covering the decline rates in the range of $0.81 \lesssim \Delta m_{15} \lesssim 1.95$, appears to be monotonic and shows a rapid change or a "kink" in the slope near $\Delta m_{15} \sim 1.65$. A cubic spline gives a reasonable fit to the "low-reddening" points, with a dispersion of only 0.05 mag. The fitting parameters are listed in Table 1. Despite this rapid change in slope, the fast-declining events connect well with the end of the "normal" color distribution. We utilize this ΔC_{12} color–Δm_{15} relation to infer dust reddenings of SNe Ia in host galaxies (P99).

In the right panel of Figure 2, we show the $E(B - V)_{host}$ values inferred by our ΔC_{12} method as a function of host galaxy reddenings derived by the P99 method for a sample of 84 well-

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[6] The photometric data are taken from Jha (2002 and references therein).

TABLE 1
A Cubic Spline Fit to the ΔC_{12}-Δm_{15} Relation
$\Delta C_{12} = a + b_1(\Delta m_{15} - 1.1) + b_2(\Delta m_{15} - 1.1)^2 + b_3(\Delta m_{15} - 1.1)^3$

a	b_1[a]	b_2[a]	b_3[a]	σ (mag)
0.347(016)	0.401(053)	−0.875(263)	2.440(280)	0.053

[a] Error estimates in parentheses are in units of ± 0.001 mag.

observed SNe Ia. A very strong correlation exists between the two reddening determinations, with no evidence for a difference in the zero points (the weighted average of the difference amounts to 0.005 ± 0.041). We are thus confident in using the ΔC_{12}-Δm_{15} relation for estimating reddenings of SNe Ia. The typical uncertainty in our color excess estimates is ~0.07 mag, slightly larger than that of P99; because of a stronger dependence of ΔC_{12} on Δm_{15}, this uncertainty may be as large as ~0.2 mag for SNe Ia with very high Δm_{15} values.

3. THE COLOR VERSUS LUMINOSITY RELATION

The left half of Figure 3 shows the absolute magnitudes of SNe Ia as a function of the color parameter ΔC_{12}. Both quantities were corrected only for Galactic reddenings and K terms. To mitigate deviations from the Hubble expansion caused by peculiar motions, we only considered a subsample of 63 SNe Ia with redshifts $0.01 \lesssim z \lesssim 0.1$. The distance to each SN Ia was computed with redshifts of host galaxies (in the reference frame of the cosmic microwave background) and with a Hubble constant $H_0 = 72$ km s^{-1} Mpc^{-1} (e.g., Freedman et al. 2001; Spergel et al. 2003). A possible peculiar velocity component of 600 km s^{-1} was included in error bars of the absolute magnitudes (e.g., Hamuy et al. 1996).

The resulting absolute magnitudes in the B, V, and I bands confirm the well-known fact that SNe Ia display a wide range of peak luminosities. It is clear that SNe Ia with larger ΔC_{12} (or redder color) are dimmer and vice versa. A remarkable correlation emerges naturally as SN 1992bc and SN 1998de appear as extreme source objects with blue and red colors, respectively. This color-luminosity relation may be caused by combined effects from reddenings in host galaxies and from intrinsic differences among SNe Ia, as the slopes given by linear fits to the data are only half of the values of the reddening coefficient R observed in the Galaxy. Dispersions around the best-fit lines in the B, V, and I bands are 0.25, 0.18, and 0.12 mag, respectively. The most discrepant points correspond to the severely reddened SNe 1995E, 1999gd, and 2000ce, but this discrepancy tends to disappear in the I band, where reddening effects on luminosity become unimportant.

In the right panel of Figure 3, this plot is repeated for a subsample of 30 out of these 63 SNe Ia for which we find insignificant reddenings from host galaxies [i.e., $E(B - V)_{host} \lesssim 0.06$]. These diagrams reveal more clearly the true nature of the peak luminosity–color parameter relations for SNe Ia. Elimination of those SNe Ia with significant reddenings of host galaxies not only decreases scatters in these correlations but also shows these correlations to be linear in the V and I bands and probably also in the B band. These simple linear correlations apply well to SNe Ia with different decline rates, including the peculiar events SNe 1997cn, 1998bp, 1998de, and 1999da. Corresponding dispersions are 0.10, 0.07, and 0.07 mag for the fits in the B, V, and I bands, respectively. These dispersions are comparable to observational errors and leave little room for a dependence on other unknown parameters.

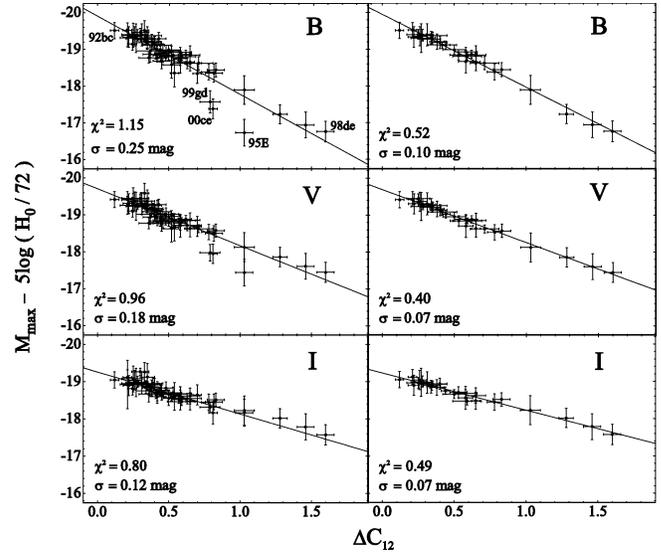Table 2 contains the fitting parameters for the ΔC_{12}-M_{max} linear

FIG. 3.—*Left*: Absolute B, V, and I magnitudes plotted against the observed ΔC_{12} for 63 SNe Ia with redshifts $0.01 \lesssim z \lesssim 0.1$. Both quantities are corrected for Galactic reddenings only. *Right*: Same as the left panel, but eliminating half of the sample with significant host galaxy reddenings. The ridge lines are weighed fits to the points in each panel.

correlations for the "low host galaxy reddening" subsample of 30 SNe Ia. When the four subluminous SNe Ia are excluded, the best-fit results remain nearly unchanged except for the B band, where the slope changes slightly to 1.74 ± 0.19 and the dispersion decreases further down to 0.08 mag. The impressively low dispersion of these fits strongly supports the validity of ΔC_{12} as an excellent peak luminosity calibrator for SNe Ia. Moreover, this shows that normal and peculiar SNe Ia may be calibrated in a unified manner and argues for their likely common physical origin. Clearly, more subluminous peculiar SN Ia events are needed to firmly establish this empirical correlation. The physics underlying this important correlation remains to be explored and understood.

In contrast to ΔC_{12}, the decline rate Δm_{15} as a linear function of peak luminosity cannot account for a wider range of peak luminosities of SNe Ia. A quadratic relation argued by P99 may improve but still cannot fit well for those peculiar SNe Ia with high Δm_{15} values. We adopt an exponential function (Garnavich et al. 2004) to match the decline rate with peak luminosity for 30 SNe Ia in the right half of Figure 3, which leads to dispersions of 0.16, 0.12, and 0.10 mag for the fits in the B, V, and I bands, respectively. The much larger and color-dependent dispersions indicate that a single Δm_{15} parameter is inadequate to fit all SNe Ia, whereas the overall fit can be significantly improved with a much reduced dispersion of ~0.10 mag in each band by introducing an additional parameter, namely, the $B - V$ color at the maximum light together with the decline

TABLE 2
Fits to the Color Parameter versus
Luminosity Relation Using $M_{max} = M_0 + R\Delta C_{12}$

Bandpass	M_0[a]	R[a]	σ (mag)	n[b]
B	−19.96(07)	1.94(13)	0.099	30
V	−19.72(07)	1.46(12)	0.070	30
I	−19.23(07)	1.03(13)	0.072	27

[a] Error estimates in parentheses are in units of ± 0.01 mag.
[b] The sample number of SNe Ia selected.

rate. This demonstrates again the crucial role the color parameter plays in standardizing SNe Ia.

It might seem that the ΔC_{12} parameterization resembles somewhat the CMAGIC method (Wang et al. 2003), as this color parameter is close to the linear regime of the color-magnitude diagram (CMD). Both methods utilize the postmaximum color curves to explore the color-magnitude relation of SNe Ia. However, the former specifically emphasizes color differences at a given epoch, while the latter tends to find out a more uniform magnitude at a given color. In the CMAGIC approach, a magnitude is inferred from the linear regimes of the CMD. In reference to peak magnitudes, the CMAGIC magnitudes are more uniform because of a color standardization, but they still depend strongly on Δm_{15} (see Fig. 10 of Wang et al. 2003); this means that they are still influenced by light-curve shapes. In contrast, this effect may become the weakest around day 12 after the B maximum, when maximum differences in color curves manifest among different SNe Ia. In fact, this particular epoch corresponds to the time when the brightest and the dimmest SNe Ia share the common CMAGIC linear regime. For this reason, we strongly prefer to use the $B - V$ color at this epoch, namely, ΔC_{12}, as a key input parameter for a more precise calibration of SNe Ia.

4. CONCLUSIONS AND DISCUSSION

We here demonstrate that ΔC_{12}, the $B - V$ color measured 12 days after the B maximum, provides effective discriminations among color curves of SNe Ia. There is a stronger dependence of ΔC_{12} on the decline rate Δm_{15} of SNe Ia, and this fact can be readily utilized for estimating reddenings of host galaxies. The reddenings determined from the ΔC_{12}-Δm_{15} relation agree remarkably well with those of P99. This would be potentially important for reddening estimates of those SNe Ia for which photometries are sparse or unavailable at late times (e.g., 30 days $\lesssim t \lesssim$ 90 days).

We have revealed a very tight linear correlation between ΔC_{12} and peak luminosities of SNe Ia. A simple linear relation seems to fit extremely well for both normal and peculiar SNe Ia, with a small dispersion of $\lesssim 0.10$ mag for a subsample

of SNe Ia, which suffer insignificant host galaxy reddenings. This much reduced dispersion is almost comparable to observational error limits. At this level, all observed SNe Ia can be more precisely calibrated in terms of ΔC_{12}. In comparison with Δm_{15}, ΔC_{12} can be readily quantified as such, and its relative error is smaller than that of $B - V$ at the maximum light. More importantly, it incarnates the color variations near the maximum light as well as the shape differences of the postmaximum light curves. These empirical properties make ΔC_{12} a more robust and reliable parameter for calibrating SNe Ia, which will bear significant impact for using SNe Ia as powerful standard candles for cosmological distances.

Given our success of using ΔC_{12} in calibrating peak luminosities of broader SNe Ia with a reduced dispersion at low redshifts $0.01 \lesssim z \lesssim 0.1$, it would be natural to extend this same color calibration for SNe Ia at higher redshifts $z \lesssim 1.7$. While probable effects of interstellar extinction for SNe Ia at $z \sim 1$ are not completely known, some preliminary empirical results suggest that the extinction or reddening per hydrogen atom decreases with increasing z (e.g., York 2000). If this is generally true except for peculiarities along particular lines of sight, then our novel color ΔC_{12} calibration holds great promise in determining the cosmological parameters more accurately using the probe of SNe Ia in full power.

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