Constraints on Dark Energy with the LOSS SN Ia Sample

Mohan Ganeshalingam,1,2⋆ Weidong Li,1,3 Alexei V. Filippenko1

1Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
2Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
3Deceased December 12, 2011

ABSTRACT

We present a cosmological analysis of the Lick Observatory Supernova Search (LOSS) Type Ia supernova (SN Ia) photometry sample introduced by Ganeshalingam et al. (2010). These supernovae (SNe) provide an effective anchor point to estimate cosmological parameters when combined with data sets at higher redshift. The data presented by Ganeshalingam et al. (2010) have been rereduced in the natural system of the KAIT and Nickel telescopes to minimize systematic uncertainties. We have run the light-curve-fitting software SALT2 on our natural-system light curves to measure light-curve parameters for LOSS light curves and available SN Ia data sets in the literature. We present a Hubble diagram of 586 SNe in the redshift range \(z = 0.01–1.4\) with a residual scatter of 0.176 mag. Of the 226 low-z SNe Ia in our sample, 91 objects are from LOSS, including 45 without previously published distances. Assuming a flat Universe, we find that the best fit for the dark energy equation-of-state parameter \(w = -0.86^{+0.13}_{-0.16}\) (stat) \(\pm 0.11\) (sys) from SNe alone, consistent with a cosmological constant. Our data prefer a Universe with an accelerating rate of expansion with 99.999% confidence. When looking at Hubble residuals as a function of host-galaxy morphology, we do not see evidence for a significant trend, although we find a somewhat reduced scatter in Hubble residuals from SNe residing within a projected distance \(<10\) kpc of the host-galaxy nucleus (\(\sigma = 0.156\) mag). Similar to the results of Blondin et al. (2011) and Silverman et al. (2012c), we find that Hubble residuals do not correlate with the expansion velocity of Si II \(\lambda 6355\) measured in optical spectra near maximum light.

Key words: supernovae: general – cosmology: observations – distance scale

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are believed to be the thermonuclear explosion of a white dwarf undergoing mass transfer from a companion star; see Hillebrandt & Niemeyer (2000) for a review. At peak brightness, the luminosity of a SN Ia \((M_B \approx -19.2\) mag) can rival that of its host galaxy and is reasonably standard from event to event \((\sigma \approx 0.5\) mag). Observed correlations between light-curve properties and luminosity further allow SNe Ia to be standardized to within \(\sim 0.2\) mag \((\sim 10\%\) in distance; Phillips 1993; Riess et al. 1994; Hamuy et al. 1996a; Tripp 1998; Phillips et al. 1999). These properties make SNe Ia an ideal distance indicator on extragalactic scales.

Application of large samples of SNe Ia led to the discovery that the Universe is currently accelerating in its expansion (Riess et al. 1998; Perlmutter et al. 1999; see Filippenko 2005) for a review. Subsequent observations of large samples of SNe Ia out to high redshifts (Riess et al. 2004; Astier et al. 2006; Riess et al. 2007; Wood-Vasey et al. 2007; Hicken et al. 2009a, 2009b; Kessler et al. 2009; Amanullah et al. 2010; Sullivan et al. 2011; Suzuki et al. 2012) have led to precise estimates of cosmological parameters when combined with measurements of baryon acoustic oscillations (BAO) and anisotropy in the cosmic microwave background (CMB). Ongoing surveys to collect large samples of SN Ia light curves include the Palomar Transient Factory (PTF; Rau et al. 2009), the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS; Kaiser et al. 2010), the Catalina Real-time Transient Survey (CRTS; Drake et al. 2009), the Lick Observatory Supernova Search (Filippenko et al. 2012), and...
Reconstructing the expansion history of the Universe with SNe Ia requires data sets spanning the widest possible range in redshift. Nearby SNe are less sensitive to cosmological parameters, but they provide an anchor on the Hubble diagram to determine the relative brightness of a SN without the influence of cosmological parameters. Leverage on cosmological parameters comes from the luminosity distance to higher redshift SNe sensitive to the details of cosmological evolution. To this end, data sets at both ends of the redshift range play important roles in determining cosmological parameters.

Many groups have undertaken the challenge of collecting large samples of SN Ia light curves. The first sample of 29 low-z objects was presented by the Calán/Tololo Supernova Survey (Hamuy et al. 1996a). The SN group at the Harvard/Smithsonian Center for Astrophysics (CFA) has produced four large samples of low-z SN Ia light curves (Riess et al. 1999; Jha et al. 2006; Hicken et al. 2009a, 2012) comprising a significant bulk of published low-z light curves. The Carnegie Supernova Project (CSP) has released two data sets of SN Ia light curves (Contreras et al. 2012; Stritzinger et al. 2011) with an impressive wavelength coverage of $uBVLri$ along with $YJHK$ for a fraction of the objects. Moreover, soon the Nearby Supernova Factory (SNFactory) is expected to release their dataset of spectrophotometric observations that can be used to synthesize measurements in any arbitrary optical broad-band filter (Aldering et al. 2002).

At intermediate redshifts ($0.05 < z < 0.35$), the Sloan Digital Sky Survey (SDSS) has published light curves for 146 SNe Ia in $ugriz$ (Holtzman et al. 2008) from observations of Stripe 82. At higher redshifts ($0.15 < z < 1.1$), the Supernova Legacy Survey (SNLS) has released the results of their three-year rolling survey (Guy et al. 2010), netting a total of 252 objects with $griz$ photometry. ESSENCE (Equation of State: SupErNovae trace Cosmic Expansion) has published their first set of $R$- and $J$-band light curves for 102 objects (Miknaitis et al. 2007) and should soon publish photometry of their 6-year sample of 228 SNe Ia (Narayan et al., in prep.). The search for SNe Ia extends out to space with programmes utilizing the Hubble Space Telescope (HST) to find even more-distant SNe to probe the epoch of cosmic deceleration, constrain the evolution of dark energy (DE), and search for possible evolution of SNe Ia (Riess et al. 2004, 2007; Rodney et al. 2012; Jones et al. 2013, e.g.,). Imminent or future surveys to gather large data sets at high redshift include the Dark Energy Survey (DES) and the Large Synoptic Survey Telescope (LSST).

SN Ia cosmological analyses utilize an observed correlation between light-curve width and intrinsic luminosity to standardize SN Ia luminosity (i.e., the “Phillips relation”; Phillips 1993; Hamuy et al. 1996a; Phillips et al. 1999). In addition to applying corrections to light-curve width, distance fitters also make assumptions about SN colour and host-galaxy extinction to further standardize SN Ia luminosity and improve distance estimates (Tripp 1996; Tripp & Branch 1999). Many tools have been developed using well-observed SNe as a training set to refine these relationships and produce reliable distance estimates, including Multicolour Light-Curve Shape (MLCS2k2; Riess et al. 1999; Jha et al. 2007), Spectral Adaptive Light-curve Template (SALT2; Guy et al. 2007, 2010), SITPo (Conley et al. 2008), and BayeSN (Mandel et al. 2003, 2011).

With the success of the light-curve width and colour parameters, the question has turned to what other observables correlate with luminosity (but remain uncorrelated with light-curve width and SN colour) to further improve distance estimates. For example, as discussed in Section 5.3, ejecta velocity may be a significant variable (Wang et al. 2009a; Foley & Kasen 2011; Foley et al. 2011). Many studies have tried to correlate Hubble residuals with other light-curve (Folatelli et al. 2010), spectral (Bailey et al. 2004; Blondin et al. 2009; Silverman et al. 2012c), and host-galaxy properties (Kelly et al. 2010; Sullivan et al. 2011; Lampeitl et al. 2011). The relative ease of access to small- or medium-aperture telescopes makes low-z samples an ideal choice for pursuing a third parameter.

In this paper, we present a cosmological analysis highlighting the addition of the Lick Observatory Supernova Search (LOSS) sample of nearby SNe Ia ($z < 0.05$). LOSS is an ongoing survey to find and monitor optical transients in the nearby Universe within days or weeks of explosion (Li et al. 2000; Filippenko et al. 2001; Li et al. 2003a). The LOSS SN Ia sample is the first data release of high-quality $BVRI$ light curves of 165 objects observed in the years 1998–2008; see Ganeshalingam et al. (2010) for details. The light curves of these objects are well sampled (typical cadence of one epoch every 3–4 days) and on average start a week before maximum light. The LOSS sample has been used to measure the rise-time distribution of SNe Ia (Ganeshalingam et al. 2011), correlate photometric properties with spectral features (Silverman et al. 2012c), and identify specific subsets of SNe Ia that may prove to be more precise distance indicators (Wang et al. 2009a; Foley & Kasen 2011).

The aim of this paper is to combine the LOSS dataset with previously published samples to derive constraints on the cosmological parameters $\Omega_m$, $\Omega_{\Lambda}$, and the DE equation-of-state parameter $w = P/\rho c^2$, where $P$ is the pressure and $\rho$ is the density. In addition, we study the effects of systematic uncertainties, and we look for trends underlying residuals in our cosmological fits. The ultimate goal is to find another parameter (be it photometric, spectroscopic, or host-galaxy property) that correlates with luminosity but is uncorrelated with light-curve width and SN colour to further standardize SN Ia luminosity.

This paper is organized as follows. In Section 2, we introduce the data sets from various photometric samples across a wide range of redshifts. Section 3 describes the methods by which we measure light-curve properties to estimate distances. The results from our sample of S86 SNe Ia along with joint constraints from other cosmological probes are presented in Section 4. Additionally, we explore the impacts of systematic calibration uncertainties on our ability to determine cosmological parameters. In Section 5, we focus on the low-z sample (a significant fraction from LOSS) to search for physical systematics which may hint at the
long-sought third parameter for improving SN Ia distance estimates.

2 DATA

In an idealized SN Ia cosmological analysis, the full dataset would comprise SN Ia photometry over the entire range of redshifts taken with a perfectly homogeneous telescope network with well-characterized throughput curves. Currently, the single largest contribution to systematic uncertainties in SN Ia distance estimates and cosmological parameters is the photometry zero-point (Conley et al. 2011). Future data sets from LSST, Pan-STARRS, and DES will bypass this issue by providing a stand-alone, self-consistent dataset with well-understood throughput curves that will replace existing low, intermediate, and high-redshift data sets. However, until the realization of such a dataset, we must rely on combining data sets from multiple observing programs covering the largest possible redshift range. Here we describe the LOSS dataset, as well as the other published data sets used for our cosmological analysis.

2.1 The LOSS Sample

The LOSS sample is the first data release of 165 BVRI light curves of nearby (median $z_{\text{CMB}} = 0.0194$) SNe Ia presented by Ganshalingam et al. (2010). A majority of the light curves in LOSS are well sampled and start a week before maximum light in the B band. The main discovery engine for the SNe Ia in our sample was the 0.76-m Katzman Automatic Imaging Telescope (KAIT) as part of a targeted search for nearby SNe (Li et al. 2000; Filippenko et al. 2001; Li et al. 2003a; Leaman et al. 2011). KAIT discoveries account for $\sim 70\%$ of the objects in the LOSS sample. Our photometric follow-up data were acquired with KAIT and the 1-m Nickel telescope at Lick Observatory.

The processing of data is described in detail by Ganshalingam et al. (2010). In summary, point-spread-function fitting photometry is performed on images from which the host galaxy has been subtracted using templates obtained $> 1$ yr after explosion. Following the convention set by previous photometry data releases (Hamuy et al. 1996a; Riess et al. 1999; Jha et al. 2006), data were transformed to the Landolt system (Landolt 1983, 1992) using averaged colour terms determined over many photometric nights. Calibrations for each SN field are obtained on photometric nights with an average of five calibrations per field.

The motivation to publish light curves on the Landolt system is to allow light curves from multiple sources to be compared easily. However, the simple colour corrections used to transform natural-system magnitudes to a given standard photometry system is based on coefficients derived from stellar spectral energy distributions (SEDs) which do not accurately describe the SED of a SN (especially at late times when the SN becomes nebular). Applying such colour corrections does not guarantee that the SN photometry will necessarily be on the Landolt system. To properly account for the SN SED, second-order “S-corrections” (Stritzinger et al. 2002; Wang et al. 2005a) must be performed using a representative spectral series. In the case of SN 2005cf (a nearby, well-observed SN Ia caught well before maximum light), S-corrections improved the discrepancy between photometry systems from a root-mean square (rms) of 0.06 mag to 0.03 mag (Wang et al. 2009b).

However, there is a changing tide in how large data sets of low-$z$ SN Ia photometry are being released. Starting with the CfA3 dataset (Hicken et al. 2009a) and the CSP data sets (Contreras et al. 2010; Stritzinger et al. 2011), groups have begun to release SN photometry in the natural system of their telescope along with transmission curves of their photometry system, avoiding colour corrections altogether. This has the obvious disadvantage that photometry from two telescope systems cannot be readily compared. Instead, photometry must be transformed from one system to the other using a SN spectral series coupled with the transmission functions of the telescope system.

The true advantage of natural-system photometry is only realized when the transmission function of the telescope system is well characterized. Using natural-system photometry reduces systematic errors in cosmological fits and better constrains cosmological parameters (Conley et al. 2011; Sullivan et al. 2011). The necessary requirement is precise and accurate measurements of the transmission curves to correctly characterize their properties, and low-$z$ SN groups have started to satisfy this requirement (Stritzinger et al. 2011; Hicken et al. 2012).

The original data release of the LOSS SN Ia light curves (Ganshalingam et al. 2010) was in the Landolt system. To better take advantage of our dataset, here we re-release our data in the natural system of the KAIT and Nickel telescope$^2$. We caution that during our follow-up photometry campaign, KAIT went through a change in filter set and three different CCDs with different quantum-efficiency curves. In total, there are four different KAIT transmission curves for each bandpass, and these configurations are referred to as KAIT[1–4]; see Ganshalingam et al. (2010) for details on the characteristics of the bandpasses. Analysis of the dataset as a whole without accounting for differences in the photometry system is ill advised. We recommend either using the results on the Landolt system or transforming all of the data to a common system using an appropriate spectral series (e.g., Hsiao et al. 2007). We document the procedure for transforming our SN photometry into the telescope natural-photometry system in Appendix A.

2.2 Additional Low-Redshift data sets

In addition to the LOSS dataset, we also include contributions from the Calán/Tololo sample (29 SNe; Hamuy et al. 1996a), CfA1 (22 SNe; Riess et al. 1999), CfA2 (44 SNe; Jha et al. 2006), CfA3 (185 SNe; Hicken et al. 2009a), CSP (35 SNe; Contreras et al. 2010), and light curves of individual SNe available in the literature. The Calán/Tololo, CfA1, CfA2, and individually published light curves are in the Landolt system, while of all the other samples are presented in the natural system. We will combine all light curves on the Landolt system into the “Lit” (i.e., literature) sample for the

---

$^2$ At present, data in both the natural and standard photometric systems can be downloaded from http://hercules.berkeley.edu/database.
purposes of our analysis. We analyse all other light curves in the natural system of the telescope using published transmission curves.

The common practice within SN cosmology analyses is to combine low-\(z\) samples from different observing programmes. There is significant overlap between the CSP, CfA3, and LOSS samples. Instead of combining data for SNe in common, we choose the light curves that have the best temporal coverage and are best sampled.

The overlapping SNe among the data sets offer an opportunity to study systematics between these programmes. In Ganeshalingam et al. (2011), an analysis between the CfA3 and LOSS data sets found that individual SNe could suffer from systematic offsets of up to \(\sim 0.05\) mag, likely owing to differences in calibrations. Ganeshalingam et al. (2011) found a typical scatter of 0.03 mag between CSP and LOSS data sets. Hicken et al. (2012) found a similar level of disagreement between the three data sets. In Section 4.4, we study the impact that calibration zero-point uncertainties have on our measurement of cosmological parameters.

Throughout the rest of this paper, we refer to the combined sample of LOSS + CfA3 + CSP + Lit as the “low-\(z\)” sample.

2.3 SDSS SNe

The dataset of 146 SNe Ia released by SDSS (Holtzman et al. 2003; Kessler et al. 2009) fills in the once sparsely populated intermediate-redshift range \((0.1 < \z < 0.4)\). The data are in the natural system of the SDSS filter set on the AB photometry system (Oke 1974). Following Holtzman et al. (2008) and Conley et al. (2011), we only use data flagged \(< 1024\) and SNe that do not show signs of peculiarity (e.g., SN 2002cx; Li et al. 2003b; Phillips et al. 2007). We omit \(\text{u-}\) and \(\text{z-band}\) photometry which have been shown to suffer from obvious systematic errors that are not well understood (Kessler et al. 2009; Conley et al. 2011).

2.4 SNLS SNe

For higher redshifts \((0.4 < \z < 1)\), we use the third-year data release from SNLS (SNLS3; Guy et al. 2010) consisting of \textit{griz} photometry of 252 spectroscopically confirmed SNe Ia in the natural system of the Megacam instrument of the Canada-France-Hawaii telescope (CFHT). We do not include other older high-\(z\) samples such as those of the Supernova Cosmology Project (SCP; Perlmutter et al. 1999) and the High-\(z\) SN Search Team (Riess et al. 1998), which do not have as strong a handle on systematics and could bias results when combined with the SNLS3 sample. Similarly, we do not include \(\text{R-}\) and \(\text{I-band}\) photometry of 102 SNe from the ESSENCE program (Miknaitis et al. 2007). While the ESSENCE sample is large, the systematics are not as well characterized. The SNLS3 sample represents a large sample of high-\(z\) SNe with a well-controlled handle on systematic errors (Conley et al. 2011).

3 DISTANCE FITTING

The method by which one turns SN Ia light curves into a distance estimate is a topic of some debate. There is universal agreement regarding a strong correlation between light-curve width and luminosity (Phillips 1993; Phillips et al. 1999) that can be used via a linear (or quadratic) correction to standardize SN Ia luminosity. However, debate continues on how to correct SN luminosity for the effects of variations in intrinsic colour and host-galaxy extinction. In the absence of host-galaxy extinction, SNe Ia with redder colours are intrinsically fainter (Riess et al. 1996; Jha et al. 2007). Similarly, SNe Ia that suffer from host-galaxy extinction will also have redder colours and a diminished observed brightness. Both effects act in the same direction (i.e., a redder SN is fainter), making it difficult to disentangle the two effects.

The Bayesian optimist would say, all is not lost: we have prior information on host-galaxy extinction which can only act to make the SN colour redder and is likely drawn from a distribution that we can infer (e.g., the galactic line of sight prior; Hatano et al. 1998). Making simple assumptions, we can place constraints on what we think is the probability distribution function of host-galaxy extinction. If we then train a model on a sample of low-extinction SN light curves, we can apply our model to data light curves to estimate an extinction value within a Bayesian framework. This is the approach taken by the MLCS fitter (Riess et al. 1996; Jha et al. 2007). BayeSN (Mandel et al. 2009, 2011) takes a similar approach, but also incorporates SN Ia infrared data to infer properties of host-galaxy extinction.

An alternative viewpoint is that the two effects cannot be disentangled and we should deal with the combined effect. The relationship that governs intrinsic colour and luminosity appears to act in the same way that host-galaxy extinction diminishes brightness. Similar to the linear correction between light-curve width and luminosity, another
linear correction for the observed SN colour (which includes contributions from both intrinsic colour and host-galaxy extinction) can be applied to further standardize the SN luminosity. This is the approach of two-parameter empirical fits like SALT2 and SIFTO.

MLCS has been successful at predicting SN Ia distance estimates. However, there are indications that the framework by which it treats host-galaxy reddening may have systematic problems. Using the updated MLCS2k2.v06, Jha et al. (2007) found the existence of a somewhat sharp discontinuity in the Hubble expansion rate, suggesting that the region within $H_{0}\Delta SN < 7400 \text{ km s}^{-1}$ is underdense compared to the global average — the so-called “Hubble bubble.” Conley et al. (2008) found that this result may be due to how MLCS2k2.v006 treats dust extinction, and using MLCS2k2 with a lower $R_V$ value may be more appropriate (Hicken et al. 2009). Kessler et al. (2009) found that MLCS2k2.v006 produced distance estimates that favoured a Universe with $w = -0.72 \pm 0.07 \text{(stat)} \pm 0.11 \text{(sys)}$ assuming a spatially flat Universe (i.e., $\Omega_m + \Omega_{DE} = 1$). This is in strong disagreement with other distance fitters, whose results are consistent with $w = -1$, and it was traced back to how MLCS2k2.v006 treats $U$-band observations. The MLCS2k2.v006 $U$-band model was trained on low-$z$ $U$-band observations which are notoriously hard to calibrate. Other distance fitters such as SALT2 were trained on high-$z$ rest-frame $U$-band observations which fall into redder optical bandpasses, typically the $g$ band. Alternatively, the discrepancy might be attributed to intrinsic differences between low-$z$ and high-$z$ SNe Ia in the ultraviolet rather than to calibrations (Ellis et al. 2005; Cooke et al. 2011; Foley et al. 2012). However, Conley et al. (2011) point out that the direction of this evolutionary difference between low-$z$ and high-$z$ SNe runs in the opposite direction, exacerbating the difference in $U$-band photometry of low-$z$ and high-$z$ SNe. We note that the root of this problem is not the methodology of MLCS2k2, but the implementation of the training process. Current analyses opt to exclude observer-frame $U$-band observations to avoid the issue entirely.

For the purpose of deriving SN Ia distances, we will adopt the empirical approach of fitting coefficients to linear corrections for light-curve width and SN colour. We will use SALT2 (Guy et al. 2007, 2010) to derive light-curve parameters. Then, using a $x^2$ minimisation and marginalisation process, we will fit for linear-correction coefficients that minimize the Hubble residuals. Below we discuss our implementation of this procedure.

### 3.1 SALT2

The first version of SALT was developed by SNLS (Guy et al. 2003). SALT2 is an updated version of SALT with a larger training set of light-curve templates; it is the version implemented in this work. SALT2 is trained on data from low-$z$ SNe from the literature and SNe from the first two years of the SNLS (Guy et al. 2007, 2010). Light-curve parameters are measured using a time-varying spectral series of SNe along with an adopted exponential colour law to model light-curve data given the bandpass of those data. SALT2 measures a parametrisation of the light-curve width ($x_1$), the SN colour ($c$), and the apparent $B$-band magnitude at maximum light ($m_B$). The parameter $x_1$ is similar in concept to the stretch parametrisation of light-curve width (Perlmutter et al. 1997; Goldhaber et al. 2001), with increasing $x_1$ values corresponding to broader (and more luminous) SNe Ia. The parameter $c$ is a measurement of the $B_{\text{max}} - V_{\text{max}}$ pseudocolour relative to the average pseudocolour of the SALT2 training set.

For our implementation of SALT2 on the LOSS data, we do our fitting in the natural-photometry system of LOSS using the KAIT[1–4] and Nickel throughput curves presented by Ganeshalingam et al. (2010). The LOSS throughput curves are obtained by multiplying the transmission function of each filter by the quantum efficiency of the CCD and the atmospheric transparency at Lick Observatory. The quantum-efficiency curves for the the KAIT and Nickel CCDs are taken from the manufacturer’s claims. Filter transmission curves for the two different KAIT filter sets were measured in a laboratory using a Varian Cary 5000 spectrophotometer.

Transformations of natural-system magnitudes derived from spectrophotometry of standard stars with our transmission curves from Stritzinger et al. (2002) into the Landolt system produced slightly different colour terms than those determined from our multiple nights of photometric observations. Following Stritzinger et al. (2002), we shift our transmission curves in wavelength until we recover our observed colour terms. These shifts can be found in table 5 of Ganeshalingam et al. (2010) and are reflected in our transmission curves.

The zero-point adopted in the most recent version of SALT2 is the flux standard BD +17°4806; it has well measured Landolt magnitudes as opposed to Vega, which is too bright for most photometric systems and consequently does not have well-measured Landolt magnitudes. Since fitting is done using the transmission curves of the LOSS photometry system, we estimate the magnitudes of BD +17°4806 in the the KAIT[1–4] and Nickel systems by transforming the Landolt magnitudes (Landolt & Uomoto 2007) using the colour terms in Table 4 of Ganeshalingam et al. (2010).

With light-curve parameters for our full SN Ia sample obtained, a model for the corrected apparent magnitude of a SN, $m_{B,\text{corr}}$, is adopted which applies linear corrections for the light-curve width and colour at peak brightness to the measured apparent magnitude, $m_B$. The corrected apparent magnitude has the form

$$m_{B,\text{corr}} = m_B + \alpha \times \text{(light-curve width)} - \beta \times \text{(colour)},$$

or in terms of the distance modulus ($\mu_{SN}$) and the SALT2 parametrisations of light-curve width ($x_1$) and colour ($c$),

$$\mu_{SN} = m_{B,\text{corr}} - M,$$

$$= m_B + \alpha x_1 - \beta c - M.$$

The constants $\alpha$, $\beta$, and $M$ (the fiducial absolute magnitude of a SN Ia) are determined using a large sample of SNe Ia to fit against a cosmological model. We marginalize over $M$ in our cosmological fits, while including $\alpha$ and $\beta$ in our fitting process. Marginalizing over $\alpha$ and $\beta$ has been shown to produce biased results (Kowalski et al. 2008; Conley et al. 2011).
The $\chi^2$ statistic of interest given $N$ SNe is

$$\chi^2 = \sum_{i=1}^{N} \frac{(\mu(z_i, \Omega_m, \Omega_D, w) - \mu_{SN, i})^2}{\sigma_{m,s}^2 + \sigma_{pec,s}^2 + \sigma_{int}^2},$$

(4)

where $\mu(z_i, \Omega_m, \Omega_D, w)$ is the luminosity distance modulus of the SN in the CMB rest frame given cosmological parameters $(\Omega_m, \Omega_D, w)$, $\sigma_m$ is the measurement error in light-curve properties accounting for covariances between measured parameters, $\sigma_{pec}$ is the uncertainty due to deviations from Hubble’s law induced by gravitational interactions from neighbouring galaxies, and $\sigma_{int}$ is a constant intrinsic scatter added to each SN to achieve a reduced $\chi^2 \approx 1$. Uncertainties are assumed to be Gaussian, although there are likely slight departures from this assumption in the light-curve parameter error estimates. We adopt 300 km s$^{-1}$ as the peculiar velocity for each SN. Changing this value has little effect on the final cosmological results, although increasing $\sigma_{pec}$ slightly decreases the leverage of the lowest-redshift objects by increasing the uncertainty associated with them. For example, for a SN at $z = 0.01$, increasing the peculiar velocity from 300 to 400 km s$^{-1}$ increases $\sigma_{pec}$ by 0.066 mag. For a SN at $z = 0.10$, increasing the peculiar velocity increases $\sigma_{pec}$ by 0.007 mag.

Following Conley et al. (2011), we adjust $\sigma_{int}$ for each photometry sample (low-z, SDSS, SNLS, and HST) such that the reduced $\chi^2$ for that sample is $\approx 1$ using the best-fitting values for $(\Omega_m, w)$ in a flat Universe. We fix $\sigma_{int}$ to the values found in Table 1 for all subsequent fits. The $\sigma_{int}$ term captures both the intrinsic dispersion in SN Ia luminosity (after correcting for light-curve width and colour), unaccounted photometric uncertainties within a survey, and possible selection biases. As noted by Conley et al. (2011), this comes at the cost of the ability to discern subtle differences in cosmological models. However, the goal of this paper is to study more common cosmological models, in which case we are willing to accept the increased uncertainty in our distance measurements.

Cosmological parameters are estimated using two complementary techniques: $\chi^2$ minimization and $\chi^2$ marginalization. Both techniques were used by Conley et al. (2011) and are described in their Appendix B. The $\chi^2$ minimization approach uses the Minuit minimization package (James & Roos 1974) to find the cosmological parameters and linear coefficients that minimize Equation 4. Parameter errors are estimated using standard assumptions that uncertainties are Gaussian and the model is linear over those uncertainties. The $\chi^2$ marginalization procedure calculates Equation 4 over a grid of possible cosmological and linear-coefficient values and then converts $\chi^2$ into a relative probability via $P \propto e^{-\chi^2/2}$. Confidence intervals are constructed by finding the bounds covering the desired fraction of the total probability. The two different methods will not generally produce exactly the same results since they have different mathematical meanings (Upadhye et al. 2005; Conley et al. 2011). Both codes were downloaded from the SNLS three-year data release website.5

Recent cosmological analyses of SNe Ia (Conley et al. 2011; Sullivan et al. 2011; Suzuki et al. 2012) have taken into account a correlation found between Hubble residual and host-galaxy mass (Kelly et al. 2010; Sullivan et al. 2010; Lampeitl et al. 2011). Sullivan et al. (2011) found that SNe Ia in galaxies more massive than $10^{10}$ M$\odot$ are $\sim 0.075$ mag brighter than SNe hosted in less massive galaxies.

\begin{table}[h]
\centering
\begin{tabular}{lcc}
Sample & $\sigma_{int}$ (mag) & RMS (mag) \\
\hline
Low-$z$ & 0.113 & 0.176 \\
SDSS & 0.097 & 0.160 \\
SNLS & 0.088 & 0.182 \\
HST & 0.105 & 0.247 \\
\hline
\end{tabular}
\caption{Intrinsic dispersion and rms of SN Samples}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{cccc}
Sample & Redshift range & $N_{SN}$ & $N^{a}_{\text{points}}$ \\
\hline
Low-$z$ & 0.01–0.13 & 226 & 43 \\
SDSS & 0.04–0.42 & 122 & 42 \\
SNLS & 0.12–1.03 & 230 & 37 \\
HST & 0.84–1.34 & 8 & 13 \\
\hline
LOSS & 0.01–0.10 & 91 & 51 \\
CIA3 & 0.01–0.07 & 55 & 32 \\
CSP & 0.01–0.08 & 22 & 77 \\
Lit & 0.01–0.15 & 58 & 31 \\
\hline
\end{tabular}
\caption{Summary of SN samples}
\end{table}

$^{a}$Median number of photometry epochs used in SALT2.
The SALT2 parameter distribution for the SN sample presented in this work. The left-hand panel shows the $x_1$ distribution for our photometric samples and the right-hand panel shows the $c$ distribution. The low-$z$ sample has more underluminous (smaller $x_1$) and redder (higher $c$) objects compared to other samples.

Conley et al. (2011) implemented this by essentially fitting for two $M$ values depending on a cutoff host-galaxy mass ($10^{10}$ M$_\odot$ in the SNLS analysis; Conley et al. 2011; Sullivan et al. 2011). We are currently in the unfortunate position of not having host-galaxy measurements for a majority of the LOSS objects. We are in the process of combining $BVRI$ photometry of our host galaxies taken as part of the LOSS follow-up program with SDSS (Abazajian et al. 2009) and GALEX (Martin et al. 2005) photometry to produce estimates of host-galaxy properties. In this work, we do not make any corrections for host-galaxy mass and instead fit for a single $M$ value.

3.2 Fitting

For a given SN, we fit all photometry simultaneously within the range 3000–7000 Å, excluding observer-frame $U$-band and $w$-band data (because of the $U$-band anomaly discussed in Section 3). SN rest-frame $I$, $i$, and $z$ bands are not well represented in the SALT2 training set of SNe; thus, they are also excluded.

3.3 Selection Criteria

We employ selection criteria to ensure that we are only including SNe Ia that are adequately fit by the SALT2 model. We require SALT2 fits to have a reduced $\chi^2 < 2$, although each fit is also visually inspected. Many of the low-$z$ objects have spectroscopic identifications from Silverman et al. (2012a) or Blondin et al. (2012), allowing us to securely eliminate peculiar SNe that are not represented in the SALT2 model training set. These include objects similar to SN 2000cx (Li et al. 2001), SN 2001ay (Krisciunas et al. 2011), SN 2002cx (Li et al. 2003b), SN 2002es (Ganeshalingam et al. 2012), SN 2006bt (Foley et al. 2011), or SN 2009dc (Yamanaka et al. 2009; Silverman et al. 2011; Taubenberger et al. 2011).

Cuts on $c$ and $x_1$ are required to ensure that we are within a parameter space described by the SALT2 training set. This also helps eliminate peculiar objects that are either subluminous (e.g., SN 1991bg-like objects; Filippenko et al. 1992; Leibundgut et al. 1993; Taubenberger et al. 2008), super-Chandrasekhar-mass candidates (e.g., SNLS-03D3bb, SN 2006gz, SN 2007if, SN 2009dc; Howell et al. 2006; Hicken et al. 2007; Yamanaka et al. 2009; Scalzo et al. 2010; Silverman et al. 2011; Taubenberger et al. 2011), or highly reddened objects that may follow a different host-galaxy extinction law (e.g., SN 2006X; Wang et al. 2008). We restrict our sample to objects with $c < 0.50$ and $-3 < x_1 < 2$. In general, we found that relaxing these constraints had little effect on our final results, although it significantly increased the number of individual outliers in our fits.

A minimum redshift cutoff is employed to minimize the impact of peculiar velocities. Previous analyses have used cutoffs in the range of $z = 0.01$–0.02. More conservative cutoffs have been used to eliminate any influence of a Hubble bubble. Our analysis does not find evidence for a Hubble bubble, consistent with what is found by Conley et al. (2007) and Hicken et al. (2009a) (see Section 5.1). To maximize the number of objects in the low-$z$ sample we adopt a cutoff of $z = 0.01$. Increasing our minimum redshift does not significantly alter our results. Objects along a line of sight with a Milky Way reddening of $E(B-V) > 0.20$ mag as measured by the dust maps of Schlegel et al. (1998) are...
Table 3. SALT2 Parameters and Distances for SNe

| SN          | z_CM  | m_B (mag) | x₁    | c     | μ (mag) | Sample Reference |
|-------------|-------|-----------|-------|-------|---------|------------------|
| SN 1998bp   | 0.010 | 15.294    | -2.520| 0.197 | 33.363  | Low-z 1          |
| SN 2002dj   | 0.010 | 13.880    | -0.276| 0.004 | 32.889  | Low-z 2          |
| SN 2002cr   | 0.010 | 14.178    | -0.601| -0.047| 33.299  | Low-z 2          |
| SN 1999cp   | 0.010 | 13.927    | -0.084| -0.045| 33.119  | Low-z 2          |
| SN 2002dp   | 0.010 | 14.456    | -0.830| 0.020 | 33.333  | Low-z 2          |
| SN 2006bh   | 0.011 | 14.344    | -1.561| -0.063| 33.777  | Low-z 3          |
| SN 1999ee   | 0.011 | 14.872    | 0.719 | 0.237 | 33.289  | Low-z 4          |
| SN 2001fh   | 0.012 | 14.062    | -2.412| -0.230| 33.498  | Low-z 2          |
| SN 2005bc   | 0.012 | 16.236    | -1.652| 0.348 | 33.954  | Low-z 2          |
| SN 1999ej   | 0.013 | 15.378    | -1.723| -0.018| 34.244  | Low-z 2          |
| SN 2001ep   | 0.013 | 14.853    | -0.855| 0.018 | 33.732  | Low-z 2          |
| SN 2006lf   | 0.013 | 13.721    | -1.304| -0.211| 33.260  | Low-z 5          |
| SN 2002ha   | 0.013 | 14.679    | -1.373| -0.086| 33.813  | Low-z 2          |
| SN 2005al   | 0.013 | 14.848    | -1.174| -0.093| 34.033  | Low-z 3          |
| SN 1997E    | 0.014 | 15.097    | -1.612| 0.014 | 33.877  | Low-z 1          |
| SN 1999dq   | 0.014 | 14.397    | 0.836 | 0.045 | 33.438  | Low-z 1          |
| SN 1991ag   | 0.014 | 14.448    | 0.697 | -0.042| 33.744  | Low-z 6          |
| SN 2005kc   | 0.014 | 15.493    | -0.670| 0.161 | 33.947  | Low-z 3          |
| SN 1999dk   | 0.014 | 14.783    | -0.171| 0.001 | 33.816  | Low-z 2          |
| SN 1992al   | 0.014 | 14.461    | -0.226| -0.111| 33.840  | Low-z 6          |
| SN 2006N    | 0.014 | 15.094    | -1.939| -0.041| 33.998  | Low-z 5          |
| SN 2001bt   | 0.014 | 15.271    | -0.874| 0.157 | 33.707  | Low-z 7          |
| SN 2001fe   | 0.014 | 14.658    | 0.704 | -0.053| 33.991  | Low-z 5          |
| SN 2000dm   | 0.015 | 15.029    | -1.853| -0.058| 34.003  | Low-z 2          |
| SN 2004ey   | 0.015 | 14.704    | 0.008 | -0.131| 34.181  | Low-z 3          |

Only a portion of this table is shown here for guidance regarding its form and content. Uncertainties are 1σ.

References. (1) [Jha et al. 2006]; (2) Ganeshalingam et al. [2010]; (3) Contreras et al. [2010]; (4) Stritzinger et al. [2002]; (5) Hicken et al. [2009a]; (6) Hamuy et al. [1996b]; (7) Krisciunas et al. [2004b]; (8) Riess et al. [1999]; (9) Krisciunas et al. [2004b]; (10) Krisciunas et al. [2001]; (11) Holtzman et al. [2008]; (12) Guv et al. [2010]; (13) Ries et al. [2007].

4 COSMOLOGICAL RESULTS AND SYSTEMATICS

In this section, we present the results from our cosmological analysis using the full cosmological sample, with the inclusion of the LOSS sample, which contributes 91 SNe, 45 having distance measurements published for the first time. We present both the results of our χ² minimisation and marginalisation procedures (see Section 3) and discuss the significance of our results. We then examine the impact of systematic uncertainties and their effect on our ability to measure cosmological parameters.

4.1 Best-fitting Cosmology

In Figure 3 we show our combined best-fitting Hubble diagram for the entire cosmological set of 586 SNe. The sample covers the redshift range 0.01–1.34. Overplotted is the best-fitting cosmology assuming a cosmological constant (i.e., $\omega = -1$). We find a scatter of 0.176 mag for the entire sample. Objects are colour coded by the sample to which they belong. Plotted in the bottom panel are the residuals as a function of redshift. We define the Hubble residual as $\Delta H(z) = H(z) - H(z_{\text{model}})$, where $H(z)$ is the observed Hubble constant at redshift $z$ and $H(z_{\text{model}})$ is the model Hubble constant at the same redshift.

Table 3 shows our SALT2 light-curve parameter values as well as distance estimates using fitting coefficients derived from our best-fitting cosmology (see Section 4 for details).

In Figure 2 we plot the $x_1$ (left-hand panel) and $c$ (right-hand panel) distribution for our different samples. The low-$z$ sample has the clearest differences compared to other higher redshift samples. This is not unexpected since most low-$z$ SN discoveries are from targeted searches like LOSS or by amateur astronomers which are biased compared to an untargeted sample. SDSS and SNLS, on the other hand, are rolling searches which do not target pre-selected galaxies. The low-$z$ sample has significantly more underluminous objects (i.e., smaller $x_1$) and redder objects (i.e., larger $c$) compared to the other samples.

Also excluded are concerns that $R_V \neq 3.1$ (Conley et al. 2011).

In Figure 4 we show our combined best-fitting Hubble diagram for the entire cosmological set of 586 SNe. The sample covers the redshift range 0.01–1.34. Overplotted is the best-fitting cosmology assuming a cosmological constant (i.e., $\omega = -1$). We find a scatter of 0.176 mag for the entire sample. Objects are colour coded by the sample to which they belong. Plotted in the bottom panel are the residuals as a function of redshift. We define the Hubble residual as $\Delta H(z) = H(z) - H(z_{\text{model}})$, where $H(z)$ is the observed Hubble constant at redshift $z$ and $H(z_{\text{model}})$ is the model Hubble constant at the same redshift.

No significant trend is found as a function of redshift (see Section 4.1.2 for further discussion on tensions between data sets).

We measure cosmological parameters in the context of the recent advances in the field, such as the Planck satellite results (2013) and the NASA/ESA Hubble Space Telescope (2012).
two scenarios. First, we consider a flat Universe dominated by matter and DE. We fit for $\Omega_m$ and the DE equation-of-state parameter, $w$. Second, we relax the assumption of flatness and consider a Universe with matter and a cosmological constant, $\Lambda$. We fit for $\Omega_m$ and $\Omega_\Lambda$. We present the results of both scenarios in Tables 4 and 5. Results for both $\chi^2$ minimisation and marginalisation are shown, and they are consistent within 1σ uncertainties. In the results that follow, we present our $\chi^2$ marginalisation results which produce more reliable uncertainty estimates.

Assuming a flat Universe dominated by matter and DE, we find using only SN Ia data that $\Omega_m = 0.159^{+0.077}_{-0.086}$ and $w = -0.855^{+0.125}_{-0.164}$. We are able to reject a Universe without DE at the >4σ level (99.999% confidence) using the SN Ia dataset. Including BAO measurements from Percival et al. (2010) and measurements of anisotropy in the CMB from Komatsu et al. (2011), we find significantly tightened constraints on cosmological parameters, as expected. Our results are within the 1σ confidence interval of $w = -1$.

In Figure 3, we show two-dimensional probability contours in the $\Omega_m$–$w$ plane for SNe Ia in blue, WMAP7 + BAO in green, and the joint constraints from SNe Ia + WMAP7 + BAO in grey. Contours indicate the 68.3%, 95.4%, and 99.7% confidence levels. Overplotted as a black solid line is the expectation from a cosmological constant. This is in excellent agreement with recent results from Conley et al. (2011) and Suzuki et al. (2012).

Next, we allow for a Universe with curvature and DE powered by a cosmological constant. From our SN fits, we...
Figure 4. Probability contours for $\Omega_m$ and $w$ assuming a flat Universe. Contours represent 68.3%, 95.4%, and 99.7% confidence levels. Constraints from SNe Ia and WMAP7 + BAO are labeled accordingly. The combined constraints lie in the intersection of the two sets of confidence intervals. Overplotted as a solid line is the expected equation-of-state parameter for a Universe with a cosmological constant. Our combined SN Ia + WMAP7 + BAO results are consistent with the concordance ΛCDM cosmology.

Figure 5. Probability contours for $\Omega_m$ and $\Omega_\Lambda$ from SNe Ia. Overplotted as a solid line is the expectation for a flat Universe.

Figure 6. Comparison of probability contours for $\Omega_m$ and $w$ assuming a flat Universe using the entire low-z sample with other samples versus using LOSS with other samples. Constraints from using the entire low-z sample are plotted in grey-scale while constraints from LOSS are outlined in red. If we restrict our low-z sample to LOSS data with good consistency with LOSS + SDSS + SNLS + HST.

Table 4. Best-fitting cosmological parameters, flat Universe.

|          | Minimisation | Marginalisation |
|----------|--------------|-----------------|
| $\Omega_m$ | 0.159$^{+0.077}_{-0.086}$ | 0.159$^{+0.077}_{-0.086}$ |
| $w$      | $-0.855^{+0.125}_{-0.164}$ | $-0.855^{+0.125}_{-0.164}$ |
| $\alpha$ | 0.147$^{+0.010}_{-0.006}$ | 0.147$^{+0.010}_{-0.006}$ |
| $\beta$  | $3.2288^{+0.070}_{-0.070}$ | $3.2288^{+0.070}_{-0.070}$ |

Table 5. Best-fitting cosmological parameters if $w = -1$.

|          | Minimisation | Marginalisation |
|----------|--------------|-----------------|
| $\Omega_m$ | 0.161$^{+0.079}_{-0.074}$ | 0.161$^{+0.079}_{-0.074}$ |
| $\Omega_\Lambda$ | 0.641$^{+0.117}_{-0.113}$ | 0.641$^{+0.117}_{-0.113}$ |
| $\alpha$ | 0.147$^{+0.007}_{-0.006}$ | 0.147$^{+0.007}_{-0.006}$ |
| $\beta$  | $3.229^{+0.070}_{-0.070}$ | $3.229^{+0.070}_{-0.070}$ |

find $\Omega_m = 0.161^{+0.079}_{-0.074}$ and $\Omega_\Lambda = 0.641^{+0.117}_{-0.113}$. When combined with constraints from WMAP7 + BAO, we recover concordance cosmology values of $\Omega_m = 0.264^{+0.019}_{-0.011}$ and $\Omega_\Lambda = 0.738^{+0.012}_{-0.011}$.

In Figure 6 we show probability contours in the $\Omega_m$-$\Omega_\Lambda$ plane from only SNe Ia. Our results are consistent with a flat, $\Lambda$-dominated Universe as indicated by the solid black line.

If we restrict our low-z sample to LOSS data with good fits (104 SNe) in addition to SDSS + SNLS + HST, we lose only a small degree of statistical leverage. From our fits with just SNe Ia, we find $\Omega_m = 0.151^{+0.008}_{-0.007}$ and $w = -0.835^{+0.087}_{-0.178}$. The only slight increase in statistical error is a strong indication that we are reaching the statistical limit.
achievable by current low-\(z\) data sets. Future improvements will be gained by eliminating systematic errors.

In Figure 6, we compare the probability contours in the \(\Omega_m-\Omega_{DE}\) plane using our entire low-\(z\) sample to those using only LOSS. The blue shaded contours represent constraints from using all of our low-\(z\) + SDSS + SNLS + \(HST\) data. The red outline indicates constraints from LOSS + SDSS + SNLS + \(HST\) data. The contours from using just LOSS are slightly larger than with the entire low-\(z\) sample. Comparing the area in the innermost contours, the LOSS contour is \(\sim 18\%\) larger than the low-\(z\) contour.

### 4.2 Tension between data sets

As a measure of systematic differences between the data sets, we calculate the error-weighted mean residual and its uncertainty in Table 6 for the samples used in this study. We fix \(\alpha\) and \(\beta\) to their best-fitting values. Overall, we do not see any significant residuals between the data sets. The SNLS dataset shows a slightly higher mean residual, but not at a significant level (\(\sim 2\sigma\)). The slight trend with increasing redshift is not statistically significant.

Within the low-\(z\) data sets, the Lit sample shows the largest mean residual of \(-0.062 \pm 0.023\) mag at the 2.7\(\sigma\) level. The LOSS, CfA3, and CSP samples, all of which are fit in their natural system, do not show significant mean offsets.

### 4.3 Residuals with SALT2 Parameters

In Figure 7, we plot the Hubble residual as a function of \(x_1\) (top panel) and \(c\) (the bottom panel). Recall that we define the residual as \(\mu_{SN} - \mu(x_1, \Omega_m, \Omega_{DE}, w)\). A negative residual indicates a SN that is too bright (post light-curve correction) for its luminosity distance. Our binned error-weighted mean residual is plotted as red squares and individual measurements are grey points. The bins are constructed such that each bin is of equal width with the point centred on the midpoint of the bin. The error bar along the abscissa extends across the length of the bin. The error bar along the ordinate is the standard error in the weighted mean.

We do not see any trend between \(x_1\) and Hubble residual, indicating that our single \(\alpha\) value represents the entire range of \(x_1\) values. A slight deviation is seen in our final \(x_1\) bin, but it is not statistically significant (\(< 2\sigma\)).

In the bottom panel, we do find a linear trend with \(c\) and the Hubble residual. SNe with \(c < -0.05\) have a negative slope with respect to Hubble residual, implying that our best-fitting \(\beta\) value is not applying an appropriate linear correction in this range of SN color. This trend corresponds to a preference for a smaller \(\beta\) for low \(c\) values. We find a slight deviation in our final \(c\) bin, but it is not statistically significant (\(< 2\sigma\)).

Sullivan et al. (2011) found a similar trend between \(c\) and Hubble residual in their analysis of SNLS3 data. The authors attribute the trend in Hubble residual to a dependence of \(\beta\) on the stellar mass of the galaxy. When splitting their sample based on host-galaxy mass, they found strong evidence (\(\sim 4.5\sigma\)) that low-mass galaxies prefer a higher \(\beta\) value than high-mass galaxies. Since many of our bluest, least reddened SNe are found preferentially in early-type (and presumably massive) galaxies (see Section 5.2), this may explain the trend we see in Figure 7. A similar result is found by Lampeitl et al. (2010) in a study of the SDSS sample (\(\sim 3.5\sigma\)). In a future paper, we will further explore trends between our sample and host-galaxy properties.

Alternatively, the different \(\beta\) values may be the result of two different SN Ia populations that prefer different \(\beta\) values. Wang et al. (2009a) and Silverman et al. (2012c) found that objects with high-velocity (HV) \(\text{Si II} \lambda 6355\) features in their spectra near maximum brightness have an observed distribution of \((B-V)_{\text{max}}\) colours that is redder compared to that of spectroscopically normal objects. Wang et al. (2009a) found that when separating SNe into two classes by Si II velocity, the two classes preferred different reddening laws (i.e., different \(\beta\) values). The HV objects with a redder colour distribution preferred a smaller beta compared to normal objects. This runs counter to what we observe in our data, where the bluest objects appear to prefer a smaller \(\beta\). We note, however, that making a cut on \(c\) differs from making a cut by spectroscopic subclass since the two observed colour distributions are offset by only \(\sim 0.10\) mag and overlap considerably. Future observing programs that include spectroscopic follow-up observations may be able to disentangle these effects. We explore this further in Section 5.3 using a subset of the low-\(z\) sample that also has spectral measurements.

### 4.4 Systematic Uncertainties

Thus far, we have only treated the statistical error associated with our SN fits. In this section, we investigate the important role of systematic uncertainties. We consider a systematic error to be an error that affects multiple SNe in a correlated manner. In a recent analysis by the SNLS team, Conley et al. (2011) found that the most significant contribution to their systematics was the lack of a \(\beta\) term in their analysis of SNLS3 data. The authors attribute the trend in Hubble residual to a dependence of \(\beta\) on the stellar mass of the galaxy. When splitting their sample based on host-galaxy mass, they found strong evidence (\(\sim 4.5\sigma\)) that low-mass galaxies prefer a higher \(\beta\) value than high-mass galaxies. Since many of our bluest, least reddened SNe are found preferentially in early-type (and presumably massive) galaxies (see Section 5.2), this may explain the trend we see in Figure 7. A similar result is found by Lampeitl et al. (2010) in a study of the SDSS sample (\(\sim 3.5\sigma\)). In a future paper, we will further explore trends between our sample and host-galaxy properties.

Alternatively, the different \(\beta\) values may be the result of two different SN Ia populations that prefer different \(\beta\) values. Wang et al. (2009a) and Silverman et al. (2012c) found that objects with high-velocity (HV) \(\text{Si II} \lambda 6355\) features in their spectra near maximum brightness have an observed distribution of \((B-V)_{\text{max}}\) colours that is redder compared to that of spectroscopically normal objects. Wang et al. (2009a) found that when separating SNe into two classes by Si II velocity, the two classes preferred different reddening laws (i.e., different \(\beta\) values). The HV objects with a redder colour distribution preferred a smaller beta compared to normal objects. This runs counter to what we observe in our data, where the bluest objects appear to prefer a smaller \(\beta\). We note, however, that making a cut on \(c\) differs from making a cut by spectroscopic subclass since the two observed colour distributions are offset by only \(\sim 0.10\) mag and overlap considerably. Future observing programs that include spectroscopic follow-up observations may be able to disentangle these effects. We explore this further in Section 5.3 using a subset of the low-\(z\) sample that also has spectral measurements.

Table 6: Tension between SN samples

| Sample | Weighted mean (mag) | Uncertainty (mag) |
|--------|---------------------|-------------------|
| Low-\(z\) | -0.005 | 0.012 |
| SDSS | -0.011 | 0.015 |
| SNLS | 0.023 | 0.010 |
| \(HST\) | 0.035 | 0.073 |
| LOSS | 0.024 | 0.016 |
| CfA3 | 0.035 | 0.022 |
| CSP | -0.007 | 0.028 |
| Lit | -0.062 | 0.023 |
Ganeshalingam et al. (2011) found differences of 0.03 mag in the $B$ and $V$ bands. These comparisons did not include S-corrections to place the SNe on a common photometric system.

As a measure of systematic errors between data sets, we compare SALT2 light-curve parameters for overlapping SNe in Table 7. SALT2 measures parameters in SED space using transmission curves for each photometry system which should alleviate any concerns about S-corrections. We find an excellent level of agreement among the 11 overlapping objects in the LOSS and CSP data sets for measurements of $m_B$ and $c$. There are indications of a $\sim 0.02$ mag offset between LOSS and the other two samples at significant levels ($2.4\sigma$ for Lit and $4\sigma$ for CfA3).

Comparing the LOSS $x_1$ values with the CfA3 and CSP samples, we find differences of $\sim 0.1$, which translate to differences of $\sim 0.01$ mag for typical $\alpha$ values (0.12–0.15). LOSS $x_1$ values best agree with the Lit sample. All of our samples have the same $c$ values to within $1\sigma$. We do not see a significant trend of the differences between LOSS and another sample with time which would indicate an issue with one of the KAIT filter/CCD combinations (KAIT[1–4]).

A similar comparison between nine objects in both the CfA3 and CSP samples shows somewhat large offsets in $m_B$ of $0.054 \pm 0.012$ mag and in $x_1$ of $0.115 \pm 0.032$ (error-weighted mean and uncertainty). The $c$ values of the two samples agree to within uncertainties.

We have also performed SALT2 fits for the LOSS photometry on the Landolt system (without S-corrections) and find overall that the results agree well. We do note, however, that we find an error-weighted mean difference of $0.014 \pm 0.004$ mag in $m_B$. Differences in $c$ and $x_1$ are consistent with no difference. Comparing our fits in the standard system to the CfA and Lit improves the offset to $\sim 0.01$ mag, but worsens the comparison to CSP to $\sim 0.04$ mag. The weighted mean residuals for $x_1$ and $c$ mostly remain the same.

The level of disagreement between the different data sets is somewhat alarming, but it is also within the systematic uncertainties attributed to the photometric zero-points associated with each sample. However, when combined with the other higher-redshift samples, the cumulative effect can alter best-fitting cosmological parameters and the associated uncertainties.

To model the effect of these uncertainties, we perform a Monte Carlo simulation focusing on the effects of the zero-
and δΩ from the uncertainty of the low-z parameter estimates. However, they found only fitting cosmological parameters.

fit by SALT2 for new light-curve parameter estimates and all of the photometry samples. Each dataset realization is realization of a dataset includes perturbed photometry for increases the systematic error from SNe alone. Bernstein et al. (2005) used a BAO prior from Eisenstein et al. (2005) which de-

Table 7. SALT2 light-curve parameter comparison

|          | Mean  | Std. Dev | WMean (σWM) | N |
|----------|-------|----------|-------------|---|
| LOSS - LIT | −0.021 | 0.039 | −0.024 (0.010) | 18 |
| LOSS - CFA3 | −0.024 | 0.058 | −0.024 (0.006) | 47 |
| LOSS - CSP | 0.001 | 0.037 | 0.002 (0.011) | 11 |
| CFA3 - CSP | 0.054 | 0.037 | 0.054 (0.012) | 9 |

5 PHYSICAL SYSTEMATICS IN THE LOW-REDSHIFT SAMPLE

In this section, we focus exclusively on looking for physical systematics inferred from the low-z samples. The low-z samples have the advantage of often having complementary spectroscopic coverage and publicly available data on host galaxies. We fix our cosmological parameters to concordance cosmology values of (Ω_m, Ω_DE, w) = (0.27, 0.73, −1) and our fitting coefficients (α, β) = (0.146, 3.169). We note that these values of (α, β) are consistent with the values found if we fix (Ω_m, Ω_DE, w) = (0.27, 0.73, −1) and fit for the coefficients using only the low-z sample; we find α = 0.154 ± 0.011 and β = 3.132_{−0.113}^{+0.113}.

5.1 Is There a Hubble Bubble?

Zehavi et al. (1998) and Jha et al. (2007) presented evidence for a monopole in the peculiar velocity field of galaxies in the local Universe. Their analyses indicated that we live in an underdense region of the Universe relative to the global average energy density, manifesting itself as a larger Hubble constant within cz < 7500 km s^{-1}. Both analyses adopted distances using the MLCS framework and found the presence of a “Hubble bubble” at ∼ 2σ confidence assuming a flat, Λ-dominated Universe with Ω_m = 0.3. Zehavi et al. (1998) used a previous version of MLCS with a smaller training set compared to the version (MLCS2k2) used by Jha et al. (2007). In a reanalysis of the data from Jha et al. (2007), Conley et al. (2007) found that the presence of the Hubble bubble may actually be an artefact of assuming that dust in other galaxies has the same extinction properties as Milky Way dust with R_V = 3.1 (β = 4.1). Conley et al. (2007) found that the Hubble bubble disappeared using lower values of R_V as preferred by the data when doing a χ^2 minimization of SALT2 parameters similar to the analysis presented here. Our best-fitting β = 3.169 corresponds to R_V = 2.169 under the assumption that the SALT2 c is an estimate of E(B − V) host-galaxy reddening.

Hicken et al. (2009a) found that the significance and partition redshift of the Hubble bubble was a function of light-curve fitter, assumption of host-galaxy extinction, and even photometry sample. They analysed departures from a single Hubble law using low-z SN distances estimated from SALT, SALT2, MLCS2k2 with R_V = 3.1, and MLCS2k2 with R_V = 1.7. Hicken et al. found the most significant detection of a Hubble bubble at the ∼ 5σ confidence level at cz = 8400 km s^{-1} with MLCS2k2 and R_V = 3.1. The significance of the void decreased substantially to 1.3σ confidence if SNe with A_V > 0.5 mag are excluded. Hicken et al. did not find evidence of a Hubble bubble using distances derived from SALT or SALT2.

Following previous analyses, we work in the more convenient units of km s^{-1} for distances. SN distance moduli, μ_SN, are translated by converting to distance (Mpc) and multiplying by H_0. The luminosity distance to z_CMB in units of km s^{-1} for a given cosmology is

H_0d_L(z_CMB) = c(1 + z_CMB) \int_0^{z_CMB} \frac{dz'}{\Omega_m(1 + z')^3 + \Omega_N} \frac{dz'}{(1 + z')^{3/2}}

(5)

The peculiar velocity of a galaxy, u, with respect to the CMB rest frame is given by u = H_0d_L(z_CMB) − H_0d_SN. We
note that c in the above equation refers to the speed of light. The fractional deviation from a Hubble flow is \( \delta H/H = u/u_0 \). We plot \( \delta H/H \) for our low-z sample in the top panel of Figure 8. For the most part, deviations from Hubble expansion appear randomly distributed, consistent with a single value of \( H_0 \).

We estimate the void amplitude signal by partitioning our low-z sample into two subsamples based on redshift. Starting at \( z_{\text{partition}} = 0.0106 \), we compute \( H_0 \) in the inner subsample \( (z \leq z_{\text{partition}}) \) and in the outer subsample. We define the void amplitude as \( \delta V = (H_{\text{inner}} - H_{\text{outer}}) / H_{\text{outer}} \). We calculate the void amplitude as a function of \( z_{\text{partition}} \) with the constraint that the minimum number of points in a subsample is \( \geq 6 \). We estimate the void significance by weighting the void amplitude by its uncertainty given by Equation 3 of Zehavi et al. (1998). We plot the void amplitude significance in the middle and lower panels of Figure 8 respectively.

We do not see a significant void amplitude in the entire sample of low-z SNe. The largest void amplitude of \(-0.04\) is detected at \( z_{\text{CMB}} = 21,000 \text{ km s}^{-1} \), although the significance of this detection is relatively low and likely caused by a small number of objects in our outer subsample. We do not find a significance larger than 1.64\( \sigma \), indicating that our data are consistent with a single value of \( H_0 \). Our maximum void detection occurs at \( z_{\text{CMB}} = 5300 \text{ km s}^{-1} \).

We further investigate whether we detect a Hubble bubble in each of our low-z data sets. The LOSS dataset has a peak void amplitude of 1.28\( \sigma \) at \( z \approx 6000 \text{ km s}^{-1} \), which is marginally consistent with what is found for the entire sample. However, the CfA3 and CSP samples show peak void signatures in the opposite direction and in the region \( z \approx 3900–4200 \text{ km s}^{-1} \), although also at a low significance (\(< 1.5\sigma \)). The most significant void detection is from the Lit sample with a void significance of 2.4\( \sigma \) at \( z_{\text{CMB}} = 4200 \text{ km s}^{-1} \), but in the opposite direction of the CfA3 and CSP samples.

A list of our results is given in Table 8.

To summarize, in agreement with Hicken et al. (2009a), we find that our analysis is consistent with no Hubble bubble. Our measurement of a void signal depends on the photometry sample, but for each sample the detection is mostly at low significance. Our sample excluded extremely reddened objects which likely have different reddening properties than normal SNe Ia. We find it likely that previous detections of an apparent Hubble bubble were due to the way in which reddening was treated, consistent with the conclusions of Conley et al. (2007) and Hicken et al. (2009a).

Table 8. Peak Hubble bubble significance

| Sample  | Partition Redshift (km s\(^{-1}\)) | Void Amplitude | Void Significance |
|---------|----------------------------------|----------------|-----------------|
| Low-z   | 5306                            | 0.023          | 1.638           |
| LOSS    | 6025                            | 0.022          | 1.281           |
| CfA3    | 4406                            | -0.040         | 1.757           |
| CSP     | 4047                            | -0.038         | 1.600           |
| Lit     | 4167                            | 0.058          | 2.408           |

5.2 Host Galaxies

With our large sample of low-z SNe, we can look for trends as a function of host-galaxy properties. Previous studies comparing Hubble residuals to host-galaxy properties have found that after correcting the SN luminosity for light-curve width and SN colour, SNe in more massive galaxies appear brighter than SNe in their less massive counterparts Kelly et al. (2010), Sullivan et al. (2010), Lampeitl et al. (2010). The physical interpretation of this result remains elusive, but it could be caused by a dependence on the progenitor metallicity which would be a function of host galaxy mass (Kasen et al. 2006). In this section, we study our Hubble residuals and light-curve parameters as a function of galaxy morphology (as a proxy for galaxy mass) and projected galactocentric distance (PGCD) to look for trends in our data. Again, we restrict our analysis to low-z objects where discovery information regarding galaxy morphology and offsets from the host-galaxy nucleus are easily available in the International Astronomical Union Circulars (IAUCs) and the NASA/IPAC Extragalactic Database^6. In

^6 http://nedwww.ipac.caltech.edu/.
cases where host-galaxy offsets are not available, we calculate the offset from the difference between the host-galaxy coordinates and the SN coordinates; examples include objects found by the SNFactory (Aldering et al. 2002).

We caution that the low-z sample suffers from a bias to more massive galaxies because of targeted surveys such as LOSS (Filippenko et al. 2001; Li et al. 2003a; Leaman et al. 2011), which account for a vast majority of the discoveries in the nearby Universe after 1998. LOSS preferentially monitors more-massive galaxies to maximize the number of discovered SNe (Leaman et al. 2011; Li et al. 2011a,b). The low-z set is not a complete sample, and it is likely not an accurate representation of the true host-galaxy demographics. We continue with that caveat in mind.

### 5.2.1 Morphology

In the top panel of Figure 9 we plot Hubble residual as a function of host-galaxy morphology. If more-massive galaxies have brighter SNe post-correction. While this agrees with previous results, our result is significant only at the ∼1.6σ confidence level.

If we bin the data into early (E–S0), mid (S0a–Sbc), and late (Sbc/Sd/Irr) galaxy bins, we find a difference between the late- and early galaxy bins of 0.050 ± 0.046 mag, consistent with no difference. We find a more significant difference between mid and late galaxies of 0.059 ± 0.029 mag. The consistency between our early and mid galaxy bins indicates that there may be more to gain by either excluding late galaxies or treating them separately. We caution that there are only 19 objects in our late bin, and the rather large weighted mean residual may be a result of small-number statistics. The full set of Hubble residuals as a function of host-galaxy morphology can be found in Table 9.

Sullivan et al. (2003) found that the Hubble residual scatter was minimized by using only SNe in early-type hosts, while Hicken et al. (2009b) found that the scatter was reduced by using late-type galaxies. Our analysis finds that both of these galaxy bins produce a scatter that is slightly lower compared to that of mid galaxies. Early galaxies do slightly better (σ = 0.167 mag) than late galaxies (σ = 0.171 mag), although the difference is statistically insignificant. mid galaxies have σ = 0.189 mag, but they also have twice the number of objects in the early and late galaxy bins combined.

In the middle panel we plot the SALT2 $x_1$ distribution as a function of host-galaxy morphology. SNe in early-type galaxies have a smaller weighted $x_1$ average (narrower light curves, corresponding to underluminous SNe) compared to SNe in mid- and late-type galaxies. This observation has been noted in previous studies (Della Valle & Livio 1994; Hamuy et al. 1996a; Howell 2001; Hicken et al. 2009a).

The presence of SNe Ia in both passive elliptical galaxies and in spirals with active star formation has led to speculation that SNe Ia may come from at least two progenitor populations (Mannucci et al. 2005; Scannapieco & Bildsten 2003; Sullivan et al. 2004; Neill et al. 2006; Maoz et al. 2011). SNe Ia in late-type...
galaxies are typically brighter and occur at \( \sim 10 \) times the rate (per unit mass) of SNe Ia in elliptical galaxies, leading to the suggestion that these SNe may be linked to young stellar progenitors. SNe Ia in early-type galaxies, on the other hand, more likely track the total mass of the galaxy. This has led rate studies to adopt a two-component model: a “prompt” component proportional to the star-formation rate and a “tardy” component proportional to the total mass. Recently, in an analysis of SN rates from LOSS, Li et al. (2011b) found intriguing evidence of a rate-size relation across all galaxy classes, indicating that the SN Ia rate is not linearly proportional to galaxy mass. Specifically, the SN rate per unit mass is larger in smaller galaxies compared to larger galaxies. Our analysis hints that different galaxy morphologies host different distributions of SN properties. However, we again caution that our distributions are likely biased and may not reflect the true distribution of SN properties.

In the bottom panel of Figure 10 we plot the SALT2 c distribution as a function of galaxy morphology. The reddest SNe occur in Sd/Irr galaxies and the bluest in E–S0. This result is somewhat counterintuitive given the above result that early galaxies host underluminous SNe that are intrinsically redder (Riess et al. 1996; Jha et al. 2007). This may instead reflect the distribution of host-galaxy extinction values. Early-type galaxies are expected to have a lower dust content and minimal amounts of star formation compared to late-type galaxies which generally exhibit more star formation. The bluer colours in early-type galaxies may reflect the lack of host-galaxy extinction. SNe in our middle galaxy bins show a larger distribution of \( c \) values.

5.2.2 Projected Galactocentric Distance

Similar to the above discussion of host-galaxy morphology, we now turn to an analysis with projected galactocentric distance (PGCD). In Figure 10 we plot Hubble residual (top panel), \( x_1 \) (middle panel), and \( c \) (bottom panel) as a function of PGCD. Points are colour coded by their host-galaxy morphology as either early (red squares), mid (grey circles), or late (blue triangles) galaxies using the definition of the previous subsection.

We do not see any significant trends of Hubble residual with PGCD or with host-galaxy classification. There is a noticeable lack of SNe in late-type galaxies at a PGCD > 20 kpc which was also noticed by Hicken et al. (2009a). Partitioning our sample into two subsamples using a cut of 10 kpc in PGCD, we find that the inner sample has \( \sigma = 0.186 \) mag and the outer sample has \( \sigma = 0.156 \) mag. The larger Hubble residual from SNe within 10 kpc may be the result of systematic uncertainties due to the difficulty in galaxy template subtraction or the increased effects of host-galaxy extinction. Future SN Ia samples may be able to reduce the scatter in Hubble diagrams by only using SNe at a PGCD > 10 kpc.

In the middle panel of Figure 10 we plot \( x_1 \) against PGCD. As mentioned in the previous subsection, SNe Ia are primarily underluminous (small \( x_1 \)) in early-type galaxies and overluminous (larger \( x_1 \)) in late-type galaxies. Mid-type galaxies show a rather uniform distribution within the inner 20 kpc of the host. However, at distances > 20 kpc, the error-weighted \( x_1 \) mean increases from \(-0.473 \pm 0.092\) to \(0.345 \pm 0.284\) (standard error of the mean), corresponding to a \( 2.7\sigma \) difference.

In the bottom panel of Figure 10 we plot \( c \) versus PGCD. As one might naively expect, the reddest SNe are located primarily within the inner 10 kpc where host-galaxy reddening will likely affect SN colour. Moving out to larger PGCD, SN colour becomes increasing bluer for all of our galaxy classes.

5.3 Silicon Velocity

Recent attention has been drawn to incorporating velocity information into distance fits. Wang et al. (2009a) found that separating SNe Ia into normal and high-velocity (HV) classifications based on Si II \( \lambda 6355 \) velocity near maximum light significantly improved distance estimates. Wang et al. (2009a) found that the two classes have different observed \( B_{\text{max}} - V_{\text{max}} \) distributions while having similar \( \Delta m_{15}(B) \) distributions. Performing a \( \chi^2 \) minimisation fit in the same vein as Equation 4, the authors found that the HV SNe preferred a lower \( \beta \) than the normal SNe, indicating either a difference in the intrinsic colour distribution and/or differences in the reddening law for the two samples.

In this section, we look for trends between our derived light-curve parameters, host-galaxies properties, and Si II
velocity as measured by the minimum of the blueshifted feature of the $\lambda6355$ line within 5 days of maximum light. Previous studies by Blondin et al. (2011) and Silverman et al. (2012) found that including velocity information along with light-curve parameters did not substantially improve distance estimates. We match objects in our low-$z$ photometry sample presented here to the Berkeley Supernova Ia Program (BSNIP) spectroscopic sample (Silverman et al. 2012). We also apply the software and algorithmic framework laid out by Silverman et al. (2012b) to measure Si II velocities in the near-maximum-light spectra published by Blondin et al. (2011). We have photometric and spectroscopic measurements for 65 objects. We note that LOSS light-curve parameters measured using light curves in the Landolt system were used in a similar study by Silverman et al. (2012c). Here, we use the light-curve parameters derived from the LOSS natural-photometry system.

Building upon this work, Foley & Kasen (2011) used the Wang et al. (2009a) sample and attributed the difference in $\beta$ to differences in the intrinsic reddening distribution of the two subclasses. Using the CfA spectroscopy sample, Foley et al. (2011) found that splitting objects into these two classes based on Si II velocity at maximum light improves distance measurements.

Rather than separating SNe into two classes, we seek to assess whether incorporating $v_{\text{Si}}$ as a continuous parameter along with light-curve parameters improves distance estimates. In Figure 11 we plot the Hubble residual versus the measured Si II $\lambda6355$ velocity for 65 objects in our low-$z$ sample having spectral measurements from BSNIP. There is no obvious trend between residual and velocity. Performing a Bayesian Monte Carlo linear regression (Kelly 2004), we find a slope consistent with 0, indicating no statistically significant correlation between the two variables (dashed line). We find a Pearson linear-correlation coefficient of $-0.044\pm0.084$, consistent with no correlation.

Foley & Kasen (2011) found that distance estimates to SNe Ia may be improved by taking advantage of a relationship between Si II velocity at maximum light and “intrinsic colour” (Foley et al. 2011; Foley 2012). Foley et al. (2011) reported an 3.4\,$\sigma$ relationship between “intrinsic colour” and Si II velocity that, when accounted for, decreases the dispersion in distance estimates. However, their definition of intrinsic colour assumed a somewhat simplistic offset from the observed $B_{\text{max}}-V_{\text{max}}$ pseudocolour. Blondin et al. (2012) performed a more sophisticated measurement of intrinsic $B_{\text{max}}-V_{\text{max}}$ colour with rigorous handling of uncertainties and found a significantly reduced correlation at the 2\,$\sigma$ level. Their intrinsic colour estimates were derived from BayeSN (Mandel et al. 2009, 2011), which incorporates population correlations between intrinsic absolute magnitudes, intrinsic colours, light-curve shape, and host-galaxy properties. While our work makes use of the SALT2 $c$ parameter which is more closely related to the $B_{\text{max}}-V_{\text{max}}$ observed colour, we do not see evidence that including a linear correction for Si II velocity improves distance estimates.

In Figure 12 we plot the Hubble residual versus $c$ (similar to the bottom panel of Figure 7) colour coded by Si II velocity. In Section 4.3 we noted a trend between Hubble residual and $c$ indicating that the bluest objects preferred a smaller $\beta$ value. The linear trend is still visible with fewer objects (65 here versus 586 in Section 4.3). Wang et al. (2009a) and Foley & Kasen (2011) find that objects classified as high $v_{\text{Si}}$ ($v_{\text{Si}} > 11,800$ km s$^{-1}$) have a redder colour distribution compared to normal objects. This is not evident in our plot, indicating that the linear trend between $c$ and Hubble residual does not correspond to a correlation with $v_{\text{Si}}$.

In Figure 13 we plot the Si II velocity for 56 objects having spectroscopic and host-galaxy information. We use the same colour code as in the bottom panel of Figure 10 with red squares representing early galaxies (E-S0), grey circles as mid galaxies (S0a–Sc), and blue triangles for late galaxies (Sed/Sd/Irr). We do not see an obvious trend re-
of SNe by disentangling contributions from host-galaxy reddening is required to better test how velocities may improve distance estimates.

Figure 13. Si II velocity versus projected galactocentric distance. Objects are colour-coded by galaxy type. Early-type galaxies (E–S0) are red squares, mid-type galaxies (S0a–Sbc) are grey circles, and late-type galaxies (Scd/Sd/Irr) are blue triangles. We do not see a significant difference between velocity and galaxy type, although the average Si II velocity appears to slightly decrease with PGCD.

For the above analysis, we used SNe with velocities taken within 5 d of maximum light in the B band. We have also performed our analysis using the family of velocity evolution curves presented by Foley et al. (2013), derived from the CFA spectral sample (Blondin et al. 2012) to extrapolate our velocities at various phases to velocity at maximum light in the B band. The family of curves is derived for SNe with $1.0 < \Delta m_{15}(B) < 1.5$ mag with velocity measurements made within a week of maximum light under the assumption that a Si II velocity is proportional to its time gradient. Using this relation does not change any of the results presented here.

Previous work by Wang et al. (2009a) and Foley & Kasen (2011) found that separating objects into two classes with different reddening laws improved distance estimates. We do not find any evidence that including Si II velocity as a continuous parameter improves distance estimates or correlates to trends seen in SALT2. A more detailed analysis that can infer the intrinsic colour of SNe by disentangling contributions from host-galaxy reddening is required to better test how velocities may improve distance estimates.

We do not find evidence that including the Si II $\lambda 6355$ observables.
velocity near maximum light as a continuous parameter improves distance estimates. This confirms the results of Blondin et al. (2011) and Silverman et al. (2012c).

Improvements to measurements of cosmological parameters with SNe Ia rest on our ability to limit systematic uncertainties. Our analysis shows that zero-point calibration uncertainties between the various low-z samples contribute a sizable fraction to the error budget. Future data sets taken with a single telescope system, such as Pan-STARRS, LSST, and DES, will greatly advance our ability to test cosmological models.

ACKNOWLEDGMENTS

We thank the Lick Observatory staff for their assistance with the operation of KAIT. We are grateful to the many students, postdocs, and other collaborators who have contributed to KAIT and LOSS over the past two decades, and to discussions concerning the results and SNe in general — especially S. Bradley Cenko, Ryan Chornock, Ryan J. Foley, Saurabh W. Jha, Jesse Leaman, Maryam Modjaz, Dovi Poznanski, Frank J. D. Serduke, Jeffrey M. Silverman, Nathan Smith, Thea Steele, and Xiaofeng Wang. We also thank Alex Conley for many of the cosmology fitting routines used in this work. This research, which took many years, was completed after the untimely and tragic death of our close friend, colleague, and coauthor Weidong Li, who led the nightly operation of KAIT and conducted numerous scientific studies with it; we miss him dearly.

The work of A.V.F.’s supernova group at UC Berkeley has been generously supported by the US National Science Foundation (NSF; most recently through grants AST-0908886 and AST-1211916), the TABASGO Foundation, the Christopher R. Redlich Fund, US Department of Energy SciDAC grant DE-FC02-06ER41453, and US Department of Energy grant DE-FG02-08ER41563. KAIT and its ongoing operation were made possible by donations from Sun Microsystems, Inc., the Hewlett-Packard Company, AutoScope Corporation, Lick Observatory, the NSF, the University of California, the Sylvia & Jim Katzman Foundation, the Christopher R. Redlich Fund, the Richard and Rhoda Goldman Fund, and the TABASGO Foundation. We give particular thanks to Russell M. Genet, who made KAIT possible with his initial special gift to A.V.F.; Joseph S. Miller, who allowed KAIT to be placed at Lick Observatory and provided staff support; Jack Borde, who provided invaluable advice regarding the KAIT optics; Richard R. Treffers, KAIT’s chief engineer; and the TABASGO Foundation, without which this work would not have been completed. We made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

REFERENCES

Abazajian, K. N., et al. 2009, ApJS, 182, 543
Aldering, G., et al. 2002, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4836, ed. J. A. Tyson & S. Wolff, 61
Amanullah, R., et al. 2010, ApJ, 716, 712
Astier, P., et al. 2006, A&A, 447, 31
Bailey, S., et al. 2009, A&A, 500, L17
Bernstein, J. P., Kessler, R., Kuhlmann, S., et al. 2012, ApJ, 753, 152
Blondin, S., Mandel, K. S., & Kirshner, R. P. 2011, A&A, 526, A81+
Blondin, S., Prieto, J. L., Patat, F., Challis, P., Hicken, M., Kirshner, R. P., Matheson, T., & Modjaz, M. 2009, ApJ, 693, 207
Blondin, S., et al. 2012, AJ, 143, 126
Bohlin, R. C., & Gilliland, R. L. 2004, AJ, 128, 3053
Conley, A., Carlberg, R. G., Guy, J., Howell, D. A., Jha, S., Riess, A. G., & Sullivan, M. 2007, ApJ, 664, L13
Conley, A., et al. 2008, ApJ, 681, 482
—. 2011, ApJS, 192, 1
Contreras, C., et al. 2010, AJ, 139, 519
Cooke, J., et al. 2011, ApJ, 727, L35
Della Valle, M., & Livio, M. 1994, ApJ, 423, L31
Drake, A. J., Djorgovski, S. G., Mahabal, A., et al. 2009, ApJ, 696, 870
Eisenstein, D. J., et al. 2005, ApJ, 633, 560
Ellis, R. S., et al. 2008, ApJ, 674, 51
Filippenko, A. V. 2005, in White Dwarfs: Cosmological and Galactic Probes, ed. E. M. Sion, S. Vennes, & H. L. Shipman (Dordrecht: Springer), 97
Filippenko, A. V., Li, W. D., Treffers, R. R., & Modjaz, M. 2001, in Small-Telescope Astronomy on Global Scales, ed. B. Paczyński, W.-P. Chen, & C. Lemme (San Francisco: ASP), 121
Filippenko, A. V., et al. 1992, AJ, 104, 1543
Folatelli, G., et al. 2010, AJ, 139, 120
Foley, R. J. 2012, ApJ, 748, 127
Foley, R. J., & Kasen, D. 2011, ApJ, 729, 55
Foley, R. J., Narayan, G., Challis, P. J., Filippenko, A. V., Kirshner, R. P., Silverman, J. M., & Steele, T. N. 2010, ApJ, 708, 1748
Foley, R. J., Sanders, N. E., & Kirshner, R. P. 2011, ApJ, 742, 89
Foley, R. J., et al. 2012, AJ, 143, 113
Ganeshalingam, M., Li, W., & Filippenko, A. V. 2011, MNRAS, 416, 2607
Ganeshalingam, M., et al. 2010, ApJS, 190, 418
—. 2012, ApJ, 751, 142
Goldhaber, G., et al. 2001, ApJ, 558, 359
Guy, J., Astier, P., Nobili, S., Regnault, N., & Pain, R. 2005, A&A, 443, 781
Guy, J., et al. 2007, A&A, 466, 11
—. 2010, A&A, 523, A7
Hadjiyska, E., Rabinowitz, D., Baltay, C., et al. 2012, IAU Symposium, 285, 324
Hamuy, M., Phillips, M. M., Suntzeff, N. B., Schommer, R. A., Maza, J., & Aviles, R. 1999a, AJ, 112, 2398
Hamuy, M., et al. 1999b, AJ, 112, 2408
Hatano, K., Branch, D., & Deaton, J. 1998, ApJ, 502, 177
Hicken, M., Garnavich, P. M., Prieto, J. L., Blondin, S., DePoy, D. L., Kirshner, R. P., & Parrent, J. 2007, ApJ, 669, L17
Hicken, M., Wood-Vasey, W. M., Blondin, S., Challis, P., Jha, S., Kelly, P. L., Rest, A., & Kirshner, R. P. 2009a, ApJ, 700, 1097
Hicken, M., et al. 2009b, ApJ, 700, 331
APPENDIX A: LOSS NATURAL-SYSTEM PHOTOMETRY

Deriving SN photometry in the natural system of the telescope requires determining the natural-system magnitudes of local field standards. In Ganeshalingam et al. (2010), we...
described the process of deriving Landolt magnitudes of local standard stars on photometric nights during our observing campaign. We transform the Landolt magnitudes to natural-system magnitudes using the set of equations

\[ b = B + C_B(B - V), \quad (A1) \]
\[ v = V + C_V(B - V), \quad (A2) \]
\[ r = R + C_R(V - R), \quad \text{and} \]
\[ i = I + C_I(R - I), \quad (A4) \]

where lowercase letters present natural-system magnitudes, uppercase letters represent Landolt-system magnitudes, and \( C_X \) are the observed colour terms from Table 4 of Ganeshalingam et al. (2010) derived from observations of Landolt (1992, 2009) standards on photometric nights. Catalogs for local field stars for our 165 SNe fields can be downloaded from our website.

There is a concern that we are introducing a systematic error by transforming our Landolt magnitudes for local field stars to the natural system by simply using the averaged colour terms derived from transforming natural-system magnitudes to Landolt magnitudes. In a sense, we are taking natural-system photometry, transforming it to the Landolt system, and then transforming it back to the natural system.

A more straightforward approach would create a catalog of Landolt (1992, 2009) standards on the natural system of each telescope system by applying a linear colour correction (e.g., \( A1 - A3 \)). Then for each photometric night, solve for the photometric solution using only a zero-point and an airmass term, and apply that solution to the SN fields to get the natural magnitudes of each local field star. The disadvantage of this approach is that if a field is calibrated using observations with the Lick Nickel telescope, the local field star magnitudes will be on the Nickel photometry system and cannot be used to calibrate KAIT observations.

To ensure that our technique did not introduce a significant systematic error, we tested the two approaches on a few SN fields and found that the differences were < 0.01 mag.

Next, we calculate the zero-points of our bandpasses.

The zero-point of a photometric system is defined as

\[ ZP_X = 2.5 \log_{10} \int_0^\infty F_\lambda S_X(\lambda) \frac{\lambda}{hc} d\lambda + m_0, \quad (A5) \]

where \( S_X \) is the transmission function for the \( X \) band, \( F_\lambda \) is the SED of the standard star, and \( m_0 \) is the magnitude of the standard in the Landolt system. Vega has been a historical favourite choice for the photometric zero-point, but it has many shortcomings such as a poorly constrained Landolt magnitude, and it is too bright to be imaged on most modern telescopes (Conley et al. 2011). The Supernova Legacy Survey (SNLS) adopted BD +17° 4806, which has a known Landolt magnitude (Landolt & Uomoto 2007) and a high-quality Hubble Space Telescope spectral observation (Bohlin & Gilliland 2004).

Instead of determining the zero-point using a single star, we derive the zero-point from the catalog of spectrophotometric standard stars presented by Stritzinger et al. (2003). Adopting the transmission curves given by Ganeshalingam et al. (2010), we synthesize instrumental magnitudes using spectra of 100 spectrophotometric standards. We then fit for the zero-point of each band with the equations

\[ b = B + C_B(B - V) + ZP_B, \quad (A6) \]
\[ v = V + C_V(B - V) + ZP_V, \quad (A7) \]
\[ r = R + C_R(V - R) + ZP_R, \quad \text{and} \]
\[ i = I + C_I(R - I) + ZP_I, \quad (A9) \]

where lowercase letters are the synthesized instrumental magnitudes, uppercase letters represent Landolt-system magnitudes, \( C_X \) are colour terms from Table 4 of Ganeshalingam et al. (2010), and \( ZP_X \) are the desired zero-points of the natural-photometry system. The zero-points of the KAIT[1–4] and Nickel bandpasses can be found in Table A1.

| Telescope System | \( ZP_B \) | \( ZP_V \) | \( ZP_R \) | \( ZP_I \) |
|------------------|----------|----------|----------|----------|
| KAIT1            | 15.304   | 14.913   | 15.357   | 14.686   |
| KAIT2            | 15.361   | 14.914   | 14.975   | 14.452   |
| KAIT3            | 15.332   | 14.921   | 15.068   | 14.457   |
| KAIT4            | 15.249   | 14.922   | 14.973   | 14.439   |
| Nickel           | 15.224   | 14.828   | 14.900   | 14.703   |

\( ^a \)zero-points are given in magnitudes.

---

8 http://hercules.berkeley.edu/database .
9 Download from [http://www.das.uchile.cl/~mhamuy/SPECSTDS/](http://www.das.uchile.cl/~mhamuy/SPECSTDS/)