TYPE Ia SUPERNOVA PROPERTIES AS A FUNCTION OF THE DISTANCE TO THE HOST GALAXY IN THE SDSS-II SN SURVEY

Lluís Galbany1,18, Ramon Miquel1,2, Linda Östman1, Peter J. Brown3, David Cinabro4, Chris B. D’Andrea5, Joshua Frieman6,7,8, Saurabh W. Jha9, John Marriner9, Robert C. Nichol3, Jakob Nordin10,11, Matthew D. Olmstead3, Masao Sako12, Donald P. Schneider13,14, Matthew Smith15, Jesper Sollerman16, Kaike Pan17, Stephanie Snedden17, Dmitry Bizyaev17, Howard Brewington17, Elena Malanushenko17, Viktor Malanushenko17, Dan Oravetz17, Audrey Simmons17, and Alaina Sheldon17

1 Institut de Física d’Altes Energies, Universitat Autònoma de Barcelona, E-08193 Bellaterra (Barcelona), Spain; lluis.galbany@ist.utl.pt
2 Institució Catalana de Recerca i Estudis Avançats, E-08010 Barcelona, Spain
3 Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
4 Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA
5 Institute of Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth PO1 3FX, UK
6 Kavli Institute for Cosmological Physics, The University of Chicago, 5640 South Ellisse Avenue, Chicago, IL 60637, USA
7 Department of Astronomy and Astrophysics, The University of Chicago, 5640 South Ellisse Avenue, Chicago, IL 60637, USA
8 Center for Astrophysics, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA
9 Department of Physics and Astronomy, Rutgers the State University of New Jersey, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA
10 E.O. Lawrence Berkeley National Lab, 1 Cyclotron Rd., Berkeley, CA 94720, USA
11 Space Sciences Laboratory, University of California Berkeley, Berkeley, CA 94720, USA
12 Department of Physics and Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA 19104, USA
13 Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA
14 Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA
15 Department of Physics, University of Western Cape, Bellville 7535, Cape Town, South Africa
16 The Oskar Klein Centre, Department of Astronomy, AlbaNova, SE-106 91 Stockholm, Sweden
17 Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349, USA

Received 2012 January 24; accepted 2012 June 8; published 2012 August 2

ABSTRACT

We use Type Ia supernovae (SNe Ia) discovered by the Sloan Digital Sky Survey-II SN Survey to search for dependencies between SN Ia properties and the projected distance to the host-galaxy center, using the distance as a proxy for local galaxy properties (local star formation rate, local metallicity, etc.). The sample consists of almost 200 spectroscopically or photometrically confirmed SNe Ia at redshifts below 0.25. The sample is split into two groups depending on the morphology of the host galaxy. We fit light curves using both MLCS2k2 and SALT2, and determine color ($A_V$, $c$) and light-curve shape ($\Delta$, $\tau_1$) parameters for each SN Ia, as well as its residual in the Hubble diagram. We then correlate these parameters with both the physical and the normalized distances to the center of the host galaxy and look for trends in the mean values and scatters of these parameters with increasing distance. The most significant (at the 4$\sigma$ level) finding is that the average fitted $A_V$ from MLCS2k2 and $c$ from SALT2 decrease with the projected distance for SNe Ia in spiral galaxies. We also find indications that supernovae (SNe) in elliptical galaxies tend to have narrower light curves if they explode at larger distances, although this may be due to selection effects in our sample. We do not find strong correlations between the residuals of the distance moduli with respect to the Hubble flow and the galactocentric distances, which indicates a limited correlation between SN magnitudes after standardization and local host metallicity.

Key words: galaxies: general – galaxies: photometry – supernovae: general

Online-only material: color figures

1. INTRODUCTION

In 1998, the study of the redshift–luminosity relation (Hubble diagram) for nearby and distant Type Ia supernovae (SNe Ia; Riess et al. 1998; Perlmutter et al. 1999) provided the “smoking gun” for the accelerated expansion of the universe. Since then, several surveys have added substantial statistics to the Hubble diagram (e.g., Astier et al. 2006; Wood-Vasey et al. 2007; Hicken et al. 2009b; Kessler et al. 2009a; Conley et al. 2011) and extended it to higher redshifts (e.g., Knop et al. 2003; Riess et al. 2003; Riess et al. 2004; Barris et al. 2004; Amanullah et al. 2010; Suzuki et al. 2012), thus strengthening the evidence for the accelerating universe.

SNe Ia can serve as cosmological probes because of their ability to function as reliable and accurate distance indicators on cosmological scales. This ability rests on the empirical correlation between the supernova (SN) peak brightness and light-curve width (Phillips 1993). Several empirical techniques (Riess et al. 1996; Phillips et al. 1999; Barris & Tonry 2004; Guy et al. 2005; Prieto et al. 2006; Jha et al. 2007; Guy et al. 2007) have been developed to exploit this correlation and turn SNe Ia into standard candles, with a dispersion on their corrected peak magnitude of 0.10–0.15 mag, corresponding to a precision of ~5%–7% in distance.

As both the quantity and quality of SN observations have increased, limitations of the homogeneity of SNe Ia have become apparent (Riess et al. 1996; Sullivan et al. 2006). If these inhomogeneities are not accounted for by the light-curve width and color corrections or by other means, these
variations may introduce systematic errors in the determination of cosmological parameters from SN surveys. One plausible source of inhomogeneity is a dependence of SN properties on host-galaxy features. Since the average properties of host galaxies evolve with redshift, any such dependence will impact the cosmological parameter determination. There have been many recent studies illustrating the dependence of SN properties on global characteristics of their hosts (Sullivan et al. 2006; Gallagher et al. 2008; Howell et al. 2009; Hicken et al. 2009a; Kelly et al. 2010; Sullivan et al. 2010), also by the Sloan Digital Sky Survey-II (SDSS-II) SN collaboration (Lampeitl et al. 2010; Smith et al. 2012; D’Andrea et al. 2011; Gupta et al. 2011; Nordin et al. 2011a; Konishi et al. 2011). Much has been learned from these studies. For instance, it has by now been established (Hamuy et al. 1996; Gallagher et al. 2005; Sullivan et al. 2006; Lampeitl et al. 2010) that SNe Ia in passive galaxies are, on average, dimmer than those in star-forming galaxies. These SNe also have narrower light curves, and, after applying the light-curve standardization procedure, turn out to have slightly larger corrected peak brightnesses (Lampeitl et al. 2010).

Following earlier work by Ivanov et al. (2000), Jha et al. (2006), and Hicken et al. (2009a), we present here a study of the dependency of SN Ia properties with local characteristics of their host galaxies, using the location of the SN inside the galaxy as a proxy for physically relevant parameters, such as local metallicity or local star formation rate. We use the three-year SDSS-II SN Survey sample (Friedman et al. 2008), as well as the Fall 2004 test campaign sample, restricting the redshifts to $z < 0.25$ in order to minimize observational biases. We examine the SN light-curve parameters related to color and decline rate, as well as the Hubble-diagram residuals, as a function of the projected distance between the SN and the center of its host galaxy. We use the output parameters from two light-curve fitters, MLCS2k2 (Jha et al. 2007) and SALT2 (Guy et al. 2007). For MLCS2k2 we obtain $A_V$ as a measure of the color and $\Delta$ for the light-curve width/decline rate. The corresponding parameter for SALT2 for color is $c$ and for light-curve width, $x_1$.

The outline of the paper is as follows. In Section 2, we describe the SN sample and the host-galaxy information used in the analysis. Section 3 covers the selection of SNe Ia, the procedure used for separating the host galaxies according to their morphology, and the description of the light-curve parameters studied. In Section 4, we introduce the method used to extract correlations between light-curve parameters and distance to the host galaxy, and present the results of the analysis. Finally, in Section 5 we discuss these results, and offer some conclusions.

2. DATA SAMPLE

2.1. SDSS-II Supernova Sample

The SDSS-II SN Survey (Friedman et al. 2008) has identified and measured light curves for intermediate redshift ($0.01 < z < 0.45$) SNe during the three Fall seasons of operation from 2005 to 2007, using the dedicated SDSS 2.5 m telescope at Apache Point Observatory (Gunn et al. 1998, 2006). A handful of SNe were also obtained in the Fall 2004 test campaign. The SNe are all located in Stripe 82, a 300 deg$^2$ region along the Celestial Equator in the Southern Galactic hemisphere (Stoughton et al. 2002). The target selection is presented in Sako et al. (2008), the first year photometry in Holtzman et al. (2008), the first year spectroscopy in Zheng et al. (2008), and the second and third year NTT/NOT spectroscopy in Östman et al. (2011). The SDSS-II SN survey has discovered and confirmed spectroscopically 559 SNe Ia, of which 514 were confirmed by the SDSS-II SN collaboration, 36 are likely SNe Ia, and nine were confirmed by other groups. We will refer to these SNe as the “Spec-Ia” sample. Besides the spectroscopically confirmed SNe, the SDSS-II SN sample has 759 SNe photometrically classified as Type Ia from their light curves, with spectroscopic redshifts of the host galaxy either measured previously by the SDSS Legacy Survey (York et al. 2000) or recently by the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS; see Eisenstein et al. 2011 for an overview and M. Olmstead 2012, in preparation for the BOSS redshifts). The classification is based on the algorithm presented in Sako et al. (2011), which compares the SN light curves against a grid of SN Ia light-curve models and core-collapse SN light-curve templates, choosing the best-matching SN type using the host-galaxy spectroscopic redshift as a prior. We designate this SN sample as the “Photo-Ia” sample. The expected contamination of non-Ia SNe in the Photo-Ia sample is $\sim 6\%$ (Sako et al. 2011). The number of SNe in the Photo-Ia sample has been significantly increased with the BOSS contribution. The entire SDSS-II SN sample, combining the Spec-Ia and Photo-Ia samples, consists of 1318 SNe Ia. Note that all these SNe have spectroscopically determined redshifts, either from the host galaxy or from the SN spectrum.

Several host-galaxy analyses have been performed using the SDSS-II SN sample. Nordin et al. (2011a, 2011b) and Konishi et al. (2011) studied the relations between spectral lines and light-curve and host-galaxy properties using different spectroscopic SDSS samples. The full three-year sample was used by Lampeitl et al. (2010) to analyze the effect of global host-galaxy properties on light-curve parameters, Smith et al. (2012) studied the SN Ia rate as a function of host-galaxy properties, D’Andrea et al. (2011) correlated the Hubble residuals of SNe Ia to the global star formation rate in their host galaxies, and Gupta et al. (2011) related the ages and masses of the SN Ia host galaxies to SN properties.

In this analysis we restrict the sample to redshifts $z < 0.25$, where the detection efficiency of the SDSS-II SN survey remains reasonably high ($\gtrsim 0.5$; Smith et al. 2012). This constraint provides a sample of 608 SNe Ia, of which 376 have been confirmed spectroscopically and 232 are photometrically classified SNe Ia.

2.2. Host-galaxy Identification

We have matched every SN Ia in our sample to the closest galaxy within an angular separation of 20′′ using the SDSS Data Release 7 (DR7) data set (Abazajian et al. 2009), which contains imaging of more than 8 000 deg$^2$ of the sky in the five SDSS optical bandpasses $ugriz$ (Fukugita et al. 1996) including the 300 deg$^2$ of Stripe 82 where the SDSS-II SN sample is located. The matching was done through the SDSS Image Query Form.19 Out of the 608 SNe in the redshift range of this analysis, 17 SNe did not have a visible galaxy within 20′′ and were consequently excluded from the following analysis, leaving 591 SNe Ia (363 Spec-Ia and 228 Photo-Ia).

3. MEASUREMENTS

3.1. Light-curve Parameters

We fit the SN Ia light curves with two light-curve fitters (MLCS2k2 and SALT2) using the implementation in the

19 http://cas.sdss.org/astrodr7/en/tools/search/IQS.asp
publicly available Supernova Analyzer package (SNANA, Kessler et al. 2009b).

For the MLCS2k2 fitter we use $R_V = 2.2$ for the reddening law and an AV prior of $P(A_V) = \exp(-A_V/\tau)$ with $\tau = 0.33$, as described in Kessler et al. (2009b). We have checked that using $R_V = 3.1$ instead does not qualitatively change the results. The fitter provides four parameters for each SN: epoch of maximum brightness ($t_0$), light-curve extinction ($A_V$), decline rate of the light curve ($\Delta$), and distance modulus ($\mu_{\text{MLCS}}$).

In the SALT2 light-curve fitter the epoch of maximum brightness ($t_0$), the color variability of the SN ($c$), the stretch of the light curve ($\chi_1$), and the apparent magnitude at maximum brightness in the $B$ band ($m_B$) are determined from the fit to the light curve. The distance modulus can be calculated by

$$\mu_{\text{SALT}} = m_B - M + \alpha x_1 - \beta c,$$

where $M$, $\alpha$, and $\beta$ are obtained by minimizing the Hubble diagram residuals. For the average absolute magnitude at peak brightness ($M$), we use $-19.41 \pm 0.04$ (Guy et al. 2005, where $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ was used). For $\alpha$ and $\beta$ we use the values obtained from the three-year SDSS-II SN sample, independent of cosmology ($\alpha = 0.135 \pm 0.033$ and $\beta = 3.19 \pm 0.24$; Marriner et al. 2011).

Both $\Delta$ and $x_1$ are related to the width of the SN light curve. However, while $\Delta$ increases for narrower light curves, $x_1$ decreases. The $A_V$ and $c$ parameters are both measurements of color variability. MLCS2k2 assumes that the color variations not included in $\Delta$ can be described by a Milky-Way-like dust extinction law and an $AV$ parameter in the rest frame after the date of $B$-band maximum.

We assign an elliptical morphology to a galaxy when it has at least one measurement earlier than 2 days (0 days) in the rest frame before the date of $B$-band maximum. 2. At least one measurement earlier than 2 days (0 days) in the rest frame before the date of $B$-band maximum. 3. At least one measurement later than 10 days (9.5 days) in the rest frame after the date of $B$-band maximum. 4. At least one measurement with a signal-to-noise ratio greater than 5 for each of the $g$, $r$, and $i$ bands (not necessarily from the same night). 5. A light-curve fit probability of being an SN Ia, based on the $\chi^2$ per degree of freedom, greater than 0.001.

These cuts were designed to remove objects with questionable classification, uncertain determination of the time of maximum brightness, or peculiar or badly constrained light curves.

Out of the 591 objects, there are 248 that fail the selection cuts for MLCS2k2, leaving 343 SNe (228 Spec-Ia and 115 Photo-Ia). For SALT2, there are 249 objects that fail, leaving 342 SNe (217 Spec-Ia and 125 Photo-Ia). Note that the MLCS2k2 and SALT2 samples are studied separately. The majority of the remaining SNe are present in both samples, but some are retained in one but not the other.

Furthermore, we remove all SNe with extreme values of the light-curve parameters, in order to have a sample unaffected by peculiar objects. We follow the empirically determined cuts in Lampeitl et al. (2010), which define the location in the light-curve parameter space for the majority of SNe in the SDSS-II SN sample. For MLCS2k2 we restrict the sample to $-0.4$, removing 30 SNe, while for SALT2 the allowed ranges are set to $-0.3 < c < 0.6$ and $-4.5 < x_1 < 2.0$, removing 22 SNe. After the cuts on light-curve parameters, 313 SNe (203 Spec-Ia and 110 Photo-Ia) remain in the MLCS2k2 sample, and 320 (209 Spec-Ia and 111 Photo-Ia) in the SALT2 sample.

### 3.2. Host-galaxy Typing

We split the SN sample into two groups depending on the morphology of the host galaxy determined using two photometric parameters: the inverse concentration index and the comparison of the likelihoods for two different Sérsic brightness profiles (Sérsic 1963).

The inverse concentration index (e.g., Strateva et al. 2001; Shimasaku et al. 2001) is defined as the ratio between the radii of two circles, centered on the core of the galaxy, containing respectively 50% and 90% of the Petrosian flux (see Blanton et al. 2001). These radii are obtained in the $r$ band for all our host galaxies from SDSS DR7 (Abazajian et al. 2009).

The Sérsic brightness profile is described by

$$I(r) = I_0 \exp \left[ -a_n \left( \frac{r}{r_e} \right)^{1/n} \right],$$

where $r$ is the distance from the galaxy center, $I_0$ is the intensity at the center ($r = 0$), and $r_e$ is the radius which contains half of the luminosity. From SDSS DR7, we obtain the $r$-band profiles of all host galaxies for two specific patterns: a pure exponential profile ($n = 1$, $a_1 = 1.68$) and a de Vaucouleurs profile ($n = 4$, $a_4 = 7.67$; see Ciotti 1991; Graham & Driver 2005, and references therein). We also extract from SDSS DR7 the likelihoods for the two fits. The exponential profile is better at describing the decrease in brightness for spiral galaxies, while the de Vaucouleurs profile is better at describing elliptical galaxies (de Vaucouleurs 1948; Freeman 1970).

We assign an elliptical morphology to a galaxy when it has both an inverse concentration index lower than 0.4 (Dilday...
Figure 1. Determination of the morphology of the host galaxies using the inverse concentration index and the comparison of the likelihoods for the fits to a de Vaucouleurs and an exponential S´ersic brightness profile. The vertical axis shows the ratio of the logarithmic likelihoods. The dashed lines show the separation points between elliptical and spiral galaxies. The two methods must agree in order for a galaxy to be classified as either elliptical (red symbols) or spiral (blue symbols). Galaxies with unknown morphology are marked in black. SNe in the MLCS2k2 sample are marked with up-pointing triangles, while for SNe in SALT2 inverted triangles are used. Those SNe that belong to both samples have the two triangles superimposed.

(A color version of this figure is available in the online journal.)

et al. 2008), and the likelihood for the de Vaucouleurs profile fit is larger than for the exponential fit. A galaxy is classified as a spiral if the inverse concentration index is above 0.4, and the likelihood for the exponential profile fit is larger than for the de Vaucouleurs fit. Figure 1 illustrates this separation in morphology. SNe for which the two morphological indicators for their host galaxy disagree are removed from the analysis. There are 74 host galaxies that cannot be classified within our system as spiral or elliptical galaxies, leaving 239 SNe Ia in the MLCS2k2 sample and 246 in the SALT2 sample.

3.3. Galactocentric Distances

From the position of the SN and the center of the host galaxy, we measure the angular separation between the SN and its host, and calculate the projected physical distance using the redshift. We use the same flat cosmology assumed in the calculation of the Hubble residuals, and a value for the Hubble constant of $70 \pm 4$ km s$^{-1}$ Mpc$^{-1}$ taken from the Wilkinson Microwave Anisotropy Probe (WMAP) 7 year results. The distribution of physical distance of all SNe Ia in our sample is shown in the top panel of Figure 2.

Galaxies vary in morphology and size, thus it makes sense to normalize the SN–galaxy separation in order to be able to compare the light-curve parameters for SNe in the entire host-galaxy sample. We use the normalization derived from the shape of the galaxy described by an elliptical S´ersic profile, taking into account the orientation of the galaxy. We distinguish between elliptical galaxies, which are fitted with a de Vaucouleurs (DEV) profile, and spiral galaxies, which are fitted with a pure exponential (EXP) profile (see Section 3.2 for the definitions). We have repeated the analysis using two other normalizations, one based on the Petrosian 50 radius, defined as the radius of a circle containing 50% of the flux in the $r$ filter, and another using the ellipse estimated from the 25 mag arcsec$^{-2}$ isophote in the $r$ band. The results agree qualitatively with those found using the S´ersic profile normalization, which are the only ones we will discuss in the following.

The necessary quantities, the major and minor axes, and orientation are obtained from the SDSS DR7 catalog (Abazajian et al. 2009). The $r$ band is used for all of them. We exclude the SNe for which any of these quantities is missing. In the bottom panel of Figure 2, we show the distribution of the normalized distances.

A possible concern may arise from the fact that we use a normalization based on $r$-band galaxy sizes at all redshifts. Thus, since the observer $r$ band will sample bluer rest-frame...
wavelengths with increasing redshift, the apparent galaxy sizes, of spiral galaxies in particular, may increase at larger redshifts, resulting in a lower normalized distance. We have found that, indeed, the average spiral galaxy Sérsic size increases by about 35% for galaxies above $z = 0.1$, compared with lower redshift galaxies, and then it stabilizes beyond $z = 0.1$. We have checked that correcting for this has little effect on the correlations with distance that we are trying to detect and have elected to keep using the uncorrected galaxy sizes obtained from the $r$-band photometry.

All measurements of the distance here are lower limits of the true separation from the center of the host galaxy due to the unknown inclination of the galaxy with respect to the observer. We therefore refer to these distances as projected galactocentric distances (GCDs).

We exclude all SNe where the normalized GCD is greater than 10, since these SNe are too far from the center of the closest galaxy for the galaxy to be considered as its host with certainty. We also remove all SNe where the normalizing distance (the radius of the galaxy in the direction of the SN) has a large uncertainty; i.e., if the radius estimate has a fractional error larger than 100% or an absolute error larger than 0.5. We also apply a cut on the SN–galaxy distance if the uncertainty in the distance is larger than the actual distance, or if the uncertainty in the distance is larger than either 0.5 or 1 kpc. The cuts were motivated by the distribution of errors for the full sample.

There are 49 SNe in the MLCS2x2 sample and 51 in the SALT2 sample which are excluded from the analysis because the matched host galaxy lack one or more of the parameters needed for the distance calculation, because the SN is too far from the center of the matched host, or because the uncertainty in the galaxy size or galaxy–SN distance is too large.

Finally, after all cuts are applied, the analysis of the light-curve parameters as a function of the separation to the center of the SN host is performed with 190 SNe for MLCS2x2 and 195 for SALT2. In Table 1, we present the number of SNe before and after each selection cut. The list of all SNe used in this analysis is given in Table 2, where we indicate whether the SN is present only in the MLCS2x2 or SALT2 samples or in both. The redshift, the estimated GCDs, and host type will be released in M. Sako (2012, in preparation), together with all the SDSS-II SN sample data, and the SDSS-III SN redshifts will be released in M. Olmstead (2012, in preparation). In Figure 3, the redshift distribution of the SNe is shown. The final sample consists of 64 SNe in elliptical host galaxies and 126 SNe in spiral galaxies for the MLCS2x2 sample. For the SALT2 sample there are 65 SNe in elliptical galaxies and 130 in spiral galaxies.

### Table 1

| Spec-Ia | Photo-Ia | Total |
|---------|----------|-------|
| MLCS    | SALT2    | MLCS  |
| SN Ia sample ($z < 0.45$) | 559 | 759 | 1318 |
| Redshift < 0.25 | 376 | 232 | 608 |
| Identified host galaxy | 363 | 228 | 591 |
| LC quality cuts | 228 | 217 | 115 | 125 | 343 | 320 |
| LC parameter cuts | 203 | 209 | 110 | 111 | 313 | 320 |
| Determined host type | 160 | 164 | 79 | 82 | 239 | 246 |
| Distance cuts | 127 | 131 | 63 | 64 | 190 | 195 |

### Table 2

| IDa In Sampleb | IDa In Sampleb | IDa In Sampleb | IDa In Sampleb |
|----------------|----------------|----------------|----------------|
| 2004Hz both 2006ku both 2007zo | SALT2 |
| 2004ie both 2006kw both 2007af both | SALT2 |
| 2005eg both 2006kx both 779 both | SALT2 |
| 2005ez both 2006ky SALT2 both 911 both | SALT2 |
| 2005fa SALT2 2006kz both 1415 both | SALT2 |
| 2005ff both 2006la both 2057 both | SALT2 |
| 2005fn both 2006lb SALT2 both 2162 both | SALT2 |
| 2005fp both 2006lj both 2639 both | SALT2 |
| 2005fu both 2006lo both 3049 both | SALT2 |
| 2005fv both 2006lp both 3426 both | SALT2 |
| 2005fw both 2006md both 3959 both | SALT2 |
| 2005fy MLCS2x2 2006mt both 4019 both | SALT2 |
| 2005ga both 2006mv both 4690 MLCS2x2 | SALT2 |
| 2005gb both 2006mz both 5199 both | SALT2 |
| 2005gc both 2006nb both 5486 both | SALT2 |
| 2005gd both 2006nc both 5689 both | SALT2 |
| 2005ge both 2006ni both 5785 SALT2 | SALT2 |
| 2005gf both 2006mn SALT2 both 5859 both | SALT2 |
| 2005gp both 2006no both 5963 both | SALT2 |
| 2005gt both 2006ed both 6274 both | SALT2 |
| 2005gh both 2006ef SALT2 both 6326 both | SALT2 |
| 2005hn both 2006ey MLCS2x2 6530 both | SALT2 |
| 2005hv both 2006pa SALT2 6614 both | SALT2 |
| 2005hx both 2007hx both 6831 both | SALT2 |
| 2005by SALT2 2007ih both 6861 both | SALT2 |
| 2005hz both 2007ik both 7350 MLCS2x2 | SALT2 |
| 2005if both 2007jd MLCS2x2 7600 both | SALT2 |
| 2005ij both 2007jk both 8254 both | SALT2 |
| 2005ir both 2007jt both 8555 both | SALT2 |
| 2005is both 2007ju both 9740 both | SALT2 |
| 2005je SALT2 2007iw MLCS2x2 9817 MLCS2x2 | SALT2 |
| 2005jh both 2007jz both 10106 MLCS2x2 | SALT2 |
| 2005jk both 2007kb both 11172 SALT2 | SALT2 |
| 2005jl both 2007kj both 12804 both | SALT2 |
| 2005jm MLCS2x2 2007ks both 13323 both | SALT2 |
| 2005kn MLCS2x2 2007kt both 13545 both | SALT2 |
| 2005kt both 2007kx both 13897 both | SALT2 |
| 2005ni SALT2 2007lc both 13907 both | SALT2 |
| 2006cr both 2007lg both 14113 SALT2 | SALT2 |
| 2006cx both 2007li SALT2 14317 both | SALT2 |
| 2006cy both 2007lk MLCS2x2 14389 both | SALT2 |
| 2006fa both 2007lo both 14445 SALT2 | SALT2 |
| 2006fb both 2007lp both 14525 both | SALT2 |
| 2006fc MLCS2x2 2007iq both 14554 MLCS2x2 | SALT2 |
| 2006fd both 2007lr SALT2 14784 both | SALT2 |
| 2006fe both 2007ly MLCS2x2 15033 both | SALT2 |
| 2006fx both 2007ma both 15343 both | SALT2 |
| 2006fy MLCS2x2 2007nb both 15587 both | SALT2 |
| 2006gy both 2007mc both 15748 both | SALT2 |
| 2006gp SALT2 2007mh both 15823 both | SALT2 |
| 2006gx MLCS2x2 2007mi SALT2 15829 both | SALT2 |
| 2006he SALT2 2007nj both 15850 both | SALT2 |
| 2006hh both 2007nz SALT2 15866 both | SALT2 |
| 2006hl both 2007ne both 16052 both | SALT2 |
| 2006hp both 2007af both 16103 both | SALT2 |
| 2006hr MLCS2x2 2007ni SALT2 16163 both | SALT2 |
| 2006hw both 2007nj both 16452 SALT2 | SALT2 |
| 2006iy both 2007nt both 16462 both | SALT2 |
| 2006ja both 2007oj both 16467 both | SALT2 |
| 2006jn both 2007ok both 17206 both | SALT2 |
| 2006jp MLCS2x2 2007om both 17408 SALT2 | SALT2 |
| 2006jq SALT2 2007or MLCS2x2 17434 both | SALT2 |
| 2006jr both 2007ow both 17748 both | SALT2 |
| 2006jw both 2007ox both 17908 both | SALT2 |
| 2006jy SALT2 2007oy both 17928 both | SALT2 |
| 2006jz both 2007pc both 18362 both | SALT2 |
Table 2
(Continued)

| ID     | In Samplea | ID     | In Sampleb | ID     | In Sampleb |
|--------|------------|--------|------------|--------|------------|
| 2006ka | both       | 2007pt | both       | 19317  | MLCS2x2    |
| 2006kd | both       | 2007qq | both       | 19987  | both       |
| 2006kl | both       | 2007qh | both       | 20088  | MLCS2x2    |
| 2006kq | MLCS2x2    | both   | 2007iq    | both   | 20232      |
| 2006ka | both       | MLCS2x2| both       | 20480  | both       |
| 2006kt | both       | 2007kq | both       | 20721  | both       |

Notes. There remain 190 SNe for MLCS and 195 for SALT2.

a IAU name when exists; otherwise internal SDSS name.
b Indicates if SN is present only in the MLCS2x2 or SALT2 samples, or in both.

Figure 3. Redshift distribution for the 1318 SNe Ia in the full SDSS-II SN sample (z < 0.45; top panel) and for the sample used in this analysis after all cuts have been applied (bottom panel), divided into spectroscopically confirmed SNe Ia and photometrically identified SNe Ia. The bottom panel shows the 190 SNe Ia in the sample used with the MLCS2x2 fitter. The corresponding figure for the SALT2 fitter is similar.

(A color version of this figure is available in the online journal.)

4. RESULTS

We have searched for trends in SN Ia light-curve parameters with GCD. The photometric and the spectroscopic sub-samples were analyzed together since no significant differences were detected between them. The results obtained hold for both sub-samples. We examined correlations for the complete sample, as well as when dividing the sample according to host-galaxy morphology (spiral and elliptical).

We correlate four light-curve parameters (MLCS2x2: $A_V$, $\Delta x_1$, $c$ and SALT2: $x_1$, $c$) and the Hubble residuals with two different measurements of the distance to the center of the host galaxy (physical GCD, and normalized GCD expressed in Sérsic (DEV/EXP) radius). For every combination of light-curve parameter and distance measurement, we bin the SNe in distance and calculate the mean, both for the light-curve parameter and the distance. In each bin, the uncertainty in the mean light-curve parameter is calculated as the rms in the bin divided by the square root of the number of SNe in the bin. The uncertainty in the distance is taken as the width of the bin. For the physical GCD, we use a bin width of 0.5 kpc, while for the normalized GCD we use bins of width 0.25. When a bin contains less than five SNe, this bin is joined with the next one until there are at least five SNe in the bin. We then perform a linear fit to the binned measurements taking into account their uncertainties. The reduced $\chi^2$ is calculated, as well as the significance of the slope (the slope divided by the uncertainty of the slope as obtained from the linear fit). Figure 4 shows the MLCS2x2 parameters for each SN as a function of the projected separation in kiloparsecs and in Sérsic units, together with the binned mean values and the best-fit lines. Figure 5 shows the corresponding plots for SALT2. The results from these correlation studies are presented in the upper panels of Tables 3–14. For these linear fits to multiple bins, we focus on the results where a dependence with distance is preferred with more than 2$\sigma$ and the reduced $\chi^2$ is lower than 2. A cut in $\chi^2$ is necessary since some of the light-curve parameters might be correlated with distance, but with a correlation that cannot be modeled with a simple linear fit. For these scenarios we solely study the two-bin analysis (described below), which is model independent.

We also search for the same correlations but using only two bins, “Near” and “Far,” with equal number of objects in each. Note that this means that the distance where the near/far split is made depends on whether we study all galaxies, spiral galaxies only, or elliptical galaxies only. We then calculate the mean values for the two bins, as well as their uncertainties (the rms of the distribution in the bin divided by the square root of the number of objects in it). We study the significance of the difference in the two means by taking the difference divided by the uncertainty. Finally, we calculate the difference in the scatter for the two bins and compare it with its uncertainty to obtain the significance. The results from the correlation studies with two bins are presented in the lower panels of Tables 3–14. For the two-bin analysis, we focus on results where the difference between the two means or two scatters is greater than 2$\sigma$.

As a cross-check of the fit method, we also fit the measurement points, without binning, with a straight line. The errors on the individual points are increased to include the intrinsic spread in the values, by adding in quadrature a term giving a reduced $\chi^2$ of 1.

In order to study the effect of non-Ia contamination in the Photo-Ia sample, we repeated the fitting process, removing from the Photo-Ia sample all possible combinations of two
Figure 4. MLCS2k2 parameters and Hubble residuals as a function of projected distance in kiloparsecs and Sérsic normalization. SNe in elliptical galaxies are marked in red and SNe in spiral galaxies in blue. Each individual supernova is shown as a small dot, and the bold points indicate the mean values in each bin. Note that the error bars in distance for the binned data show the extent of the bin, and not the standard deviation of the points. The dotted lines show the best fit to the mean values. The values for spiral galaxies and elliptical galaxies in the plots for the Sérsic profile cannot be directly compared since they have different normalizations (EXP and DEV) and thus there is no black line showing the combined result.

(A color version of this figure is available in the online journal.)

SNe in elliptical hosts and two in spiral hosts, which roughly corresponds to the expected 6% non-Ia contamination. The distribution of the fitted slopes for all the combinations looked consistent with the expectations for no background, within the errors quoted below. Furthermore, we repeated all fits using only the SNe in the Spect-Ia sample (with negligibly small non-Ia contamination) and found the results to be qualitatively similar to the results with the full sample, which are the ones we will present in the following.

We find two (related) trends with high significance and good fit quality: Both $A_V$ and $c$ decrease with increasing physical GCD, with the slopes of the linear fits being, respectively, 4.8 and 4.4σ away from zero. These and other correlations with lower significance are presented in detail in the following.
4.1. Correlations between Projected Distance and Supernova Color ($A_V, c$)

4.1.1. MLCS2k2

When studying all SNe Ia, regardless of host-galaxy type, we find that the fitted $A_V$ from MLCS2k2 decreases with SN–galaxy distance (see Tables 3 and 4). In the multi-bin analysis we find a deviation from a non-evolving $A_V$ with a 4.8σ significance for physical distances, with a good quality fit (reduced $\chi^2$ of 0.6). Using a two-bin analysis, we confirm the sign of the slope, but with lower significance of only 1.0σ, due to the loss of precision in using only two bins. Using the linear fit to the unbinned data, we find trends of similar significance.

When splitting the sample into SNe in elliptical and spiral galaxies we find indications that the trend of decreasing $A_V$ with distance is driven by the SNe in spiral galaxies, where the deviation from a non-evolving $A_V$ is 0.6σ and 2.4σ, respectively, when using physical and normalized distances. Similar significances (1.6, 2.4) are found in the two-bin analysis.
restricted to SNe in spiral galaxies. This result is also confirmed with the linear fit to the unbinned data. In all cases, the sample of SNe in elliptical galaxies is consistent with an $A_V$ not evolving with physical distance.

A potentially confusing result from the multi-bin analysis of $A_V$ is that the fit to the full sample, for distances measured in kpc, has a steeper slope than for the samples of SNe in elliptical and spiral galaxies separately. Naively one would expect a slope for the full sample between that of the elliptical and spiral samples. The reason for this seemingly contradictory result is the different binning, e.g., the sample of all SNe has the center of the last bin at a significantly larger distance than the two other samples, thus increasing the lever arm. As a consistency check, we redid the binned analysis, using the same binning for spiral galaxies and the full sample as for the elliptical sample (which is the smallest of the three). Using equal binning, we obtained a fitted line for the full sample which was in between the lines for elliptical and spiral galaxies. We still see a non-zero slope, but with decreased significance because of the lower sensitivity of the fit with fewer bins.

| Distance Unit | Host Type | Slope | Significance | $\chi^2$/dof | dof |
|---------------|-----------|-------|--------------|-------------|-----|
| kpc           | All       | $-0.0081 \pm 0.0017$ | $-4.8$ | 0.6 | 17 |
|               | Elliptical| $0.0008 \pm 0.0031$  | 0.3    | 0.9 | 7  |
|               | Spiral    | $-0.0024 \pm 0.0043$ | $-0.6$ | 1.4 | 13 |
| deV           | Elliptical| $-0.0020 \pm 0.012$  | $-1.6$ | 0.8 | 5  |
| exp           | Spiral    | $-0.0037 \pm 0.015$  | $-2.4$ | 1.2 | 9  |

Note. $^a$ Significance of non-zero result, value divided by uncertainty.

| Distance Unit | Host Type | Mean $A_V$ | Scatter of $A_V$ |
|---------------|-----------|------------|-----------------|
| kpc           | All       | $3.92 \pm 0.33$ | $0.034 \pm 0.023$ | $-0.037 \pm 0.038$ | $-1.0$ | $0.299 \pm 0.037$ | $0.224 \pm 0.019$ | $-0.075 \pm 0.041$ | $-1.8$ |
|               | Elliptical| $3.08 \pm 0.050$ | $0.238 \pm 0.036$ | $-0.033 \pm 0.062$ | $-0.5$ | $0.285 \pm 0.082$ | $0.206 \pm 0.039$ | $-0.079 \pm 0.091$ | $-0.9$ |
|               | Spiral    | $4.45 \pm 0.038$ | $0.322 \pm 0.028$ | $-0.073 \pm 0.047$ | $-1.6$ | $0.299 \pm 0.039$ | $0.222 \pm 0.022$ | $-0.078 \pm 0.045$ | $-1.7$ |
| deV           | Elliptical| $1.03 \pm 0.033$ | $0.274 \pm 0.052$ | $0.039 \pm 0.062$ | $0.6$ | $0.189 \pm 0.044$ | $0.295 \pm 0.078$ | $0.106 \pm 0.090$ | $1.2$ |
| exp           | Spiral    | $1.34 \pm 0.038$ | $0.303 \pm 0.027$ | $-0.110 \pm 0.046$ | $-2.4$ | $0.298 \pm 0.038$ | $0.216 \pm 0.022$ | $-0.082 \pm 0.044$ | $-1.8$ |

Notes.

$a$ Significance of non-zero result, value divided by uncertainty.

$b$ The distance where the “near” and “far” bins were separated.

| Distance Unit | Host Type | Slope | Significance | $\chi^2$/dof | dof |
|---------------|-----------|-------|--------------|-------------|-----|
| kpc           | All       | $-0.0032 \pm 0.0007$ | $-4.4$ | 0.9 | 18 |
|               | Elliptical| $-0.0008 \pm 0.0022$ | $-0.4$ | 1.0 | 6  |
|               | Spiral    | $-0.0031 \pm 0.0020$ | $-1.5$ | 0.6 | 11 |
| deV           | Elliptical| $-0.007 \pm 0.008$  | $-0.9$ | 0.5 | 6  |
| exp           | Spiral    | $-0.008 \pm 0.007$  | $-1.2$ | 3.4 | 10 |

Note. $^a$ Significance of non-zero result, value divided by uncertainty.
Table 7
Results when Correlating MLCS2k2-A with Distance Binned in Multiple Bins of Equal Size

| Distance Unit | Host Type  | Slope       | Significance | $\chi^2$/dof | dof |
|---------------|------------|-------------|--------------|--------------|-----|
| kpc           | All        | $-0.0064 \pm 0.0031$ | $-2.1$ | 1.8 | 17 |
|               | Elliptical | $0.0231 \pm 0.0092$   | $2.5$   | 2.4 | 7  |
|               | Spiral     | $-0.0072 \pm 0.0047$ | $-1.5$  | 0.5 | 13 |
| deV           | Elliptical | $0.104 \pm 0.043$    | $2.4$   | 1.3 | 5  |
| exp           | Spiral     | $-0.015 \pm 0.021$   | $-0.7$  | 2.1 | 9  |

Notes. a Significance of non-zero result, value divided by uncertainty.

Table 8
Results when Correlating MLCS2k2-A with Distance Binned in a Near and a Far Sample, with Equal Number of Events in Each Bin

| Distance Unit | Host Type  | Near $\bar{\Delta}$ | Far $\bar{\Delta}$ | Difference $\bar{\Delta}$ | Significance | Near $\sigma_n$ | Far $\sigma_f$ | Difference $\sigma_f$ | Sig. | $\chi^2$/dof | dof |
|---------------|------------|----------------------|--------------------|---------------------------|--------------|-----------------|-----------------|---------------------|------|--------------|-----|
| kpc           | All        | $-0.010 \pm 0.032$   | $0.009 \pm 0.039$ | $0.019 \pm 0.050$         | $0.4$        | $0.311 \pm 0.033$ | $0.379 \pm 0.048$ | $0.069 \pm 0.058$            | $1.2$ |              |     |
|               | Elliptical | $0.067 \pm 0.060$    | $0.253 \pm 0.076$ | $0.186 \pm 0.096$         | $1.9$        | $0.337 \pm 0.068$ | $0.428 \pm 0.069$ | $0.091 \pm 0.097$            | $0.9$ |              |     |
|               | Spiral     | $-0.077 \pm 0.033$   | $-0.088 \pm 0.039$ | $-0.011 \pm 0.051$        | $-0.2$       | $0.262 \pm 0.028$ | $0.308 \pm 0.064$ | $0.046 \pm 0.070$            | $0.7$ |              |     |
| deV           | Elliptical | $0.094 \pm 0.062$    | $0.226 \pm 0.075$ | $0.132 \pm 0.098$         | $1.4$        | $0.353 \pm 0.064$ | $0.425 \pm 0.073$ | $0.072 \pm 0.097$            | $0.7$ |              |     |
| exp           | Spiral     | $-0.059 \pm 0.038$   | $-0.106 \pm 0.034$ | $-0.047 \pm 0.051$        | $-0.9$       | $0.302 \pm 0.059$ | $0.267 \pm 0.038$ | $-0.036 \pm 0.070$           | $-0.5$|              |     |

Notes. a Significance of non-zero result, value divided by uncertainty. b The distance where the “near” and “far” bins were separated.

Table 9
Results when Correlating SALT2-$x_1$ with Distance Binned in Multiple Bins of Equal Size

| Distance Unit | Host Type  | Slope       | Significance | $\chi^2$/dof | dof |
|---------------|------------|-------------|--------------|--------------|-----|
| kpc           | All        | $0.0120 \pm 0.0140$ | $0.9$        | 1.6 | 18 |
|               | Elliptical | $-0.0016 \pm 0.0201$ | $-0.1$       | 1.4 | 6  |
|               | Spiral     | $0.0195 \pm 0.0177$ | $1.1$        | 0.8 | 11 |
| deV           | Elliptical | $-0.013 \pm 0.097$  | $-0.1$       | 0.5 | 6  |
| exp           | Spiral     | $0.018 \pm 0.069$   | $0.3$        | 1.1 | 10 |

Notes. a Significance of non-zero result, value divided by uncertainty.

Table 10
Results when Correlating SALT2-$x_1$ with Distance Binned in a Near and a Far Sample, with Equal Number of Events in Each Bin

| Distance Unit | Host Type  | Near $\bar{x}_1$ | Far $\bar{x}_1$ | Difference $\bar{x}_1$ | Sig. | Near $\sigma_n$ | Far $\sigma_f$ | Difference $\sigma_f$ | Sig. | $\chi^2$/dof | dof |
|---------------|------------|------------------|-----------------|---------------------|------|-----------------|-----------------|---------------------|------|--------------|-----|
| kpc           | All        | $-0.164 \pm 0.107$ | $-0.084 \pm 0.108$ | $0.080 \pm 0.152$ | $0.5$ | $1.059 \pm 0.064$ | $1.064 \pm 0.070$ | $0.005 \pm 0.095$ | $0.1$ |              |     |
|               | Elliptical | $-0.701 \pm 0.181$ | $-0.830 \pm 0.185$ | $-0.129 \pm 0.259$ | $-0.5$| $1.041 \pm 0.089$ | $1.049 \pm 0.128$ | $0.008 \pm 0.156$ | $0.1$ |              |     |
|               | Spiral     | $0.112 \pm 0.118$  | $0.280 \pm 0.107$ | $0.168 \pm 0.160$ | $1.1$ | $0.955 \pm 0.092$ | $0.866 \pm 0.095$ | $-0.089 \pm 0.133$ | $-0.7$|              |     |
| deV           | Elliptical | $-0.775 \pm 0.178$ | $-0.754 \pm 0.190$ | $0.021 \pm 0.260$ | $0.1$ | $1.021 \pm 0.089$ | $1.072 \pm 0.124$ | $0.051 \pm 0.153$ | $0.3$ |              |     |
| exp           | Spiral     | $0.199 \pm 0.114$  | $0.192 \pm 0.114$ | $-0.007 \pm 0.161$ | $-0.0$| $0.915 \pm 0.092$ | $0.915 \pm 0.097$ | $-0.000 \pm 0.133$ | $-0.0$|              |     |

Notes. a Significance of non-zero result, value divided by uncertainty. b The distance where the “near” and “far” bins were separated.

Examine Figure 4, we can see that the most dimmed explosions are close to the center of their host galaxies. A natural consequence of this result is that the scatter diminishes with distance. This correlation is particularly visible when studying the full set of galaxies, comparing the near and far sub-samples split in physical distance (1.8σ). We also find that SNe Ia with high values of $A_V$ preferentially explode in spiral galaxies. Out of the 64 elliptical host galaxies only 6 (9%) have SNe with an $A_V > 0.5$, while there are 29 (23%) in the 126 spiral hosts. The mean value of $A_V$ for the SNe in elliptical galaxies was found to be $\langle A_V^{\text{elliptical}} \rangle = 0.26 \pm 0.03$ mag, while for SNe in spiral galaxies it was $\langle A_V^{\text{spiral}} \rangle = 0.36 \pm 0.02$ mag.

4.1.2. SALT2

We now turn to the color term $c$ from the SALT2 analysis to determine if we reproduce similar trends (see Tables 5 and 6). For the linear fit to multiple bins, we also find that $c$ decreases, with 4.4σ significance, for the full sample

10
with increasing physical distances. The corresponding number when only studying spiral galaxies is 1.5σ for the slope with increasing physical distance and 1.2σ with normalized distance. For SNe in elliptical galaxies, the fit is consistent with a non-evolving c.

Using the two-bin analysis we confirm the results, but with lower significances, the largest being when using the normalized distance with spiral galaxies (2σ). The same result is found when using a linear fit to unbinned data, with significances of similar strengths.

Just as for the MLCS2k2 $A_V$ parameter, we find a trend between $c$ and host-galaxy type. The mean $c$ for SNe Ia in spiral galaxies is $(c_{spiral}) = 0.040 \pm 0.010$, while it is $(c_{elliptical}) = 0.016 \pm 0.013$ for elliptical galaxies.

We find no significant differences between the near and far samples when examining the scatter of the color term $c$.

### Table 11
Results when Correlating MLCS2k2 Hubble Residuals with Distance Binned in Multiple Bins of Equal Size

| Distance Unit | Host Type | Slope Mean | Significance$^a$ | $\chi^2$/dof | dof |
|---------------|-----------|------------|------------------|--------------|-----|
| kpc           | All       | $0.0006 \pm 0.0027$ | 0.2             | 1.3          | 17  |
|               | Elliptical| $0.0006 \pm 0.0055$ | 0.1             | 0.6          | 7   |
|               | Spiral    | $-0.0004 \pm 0.0037$ | $-0.1$         | 1.4          | 13  |
| deV           | Elliptical| $0.006 \pm 0.020$ | 0.3             | 0.9          | 5   |
| exp           | Spiral    | $0.017 \pm 0.014$ | 1.2             | 0.9          | 9   |

Note. $^a$ Significance of non-zero result, value divided by uncertainty.

### Table 12
Results when Correlating MLCS2k2 Hubble Residuals with Distance Binned in a Near and a Far Sample, with Equal Number of Events in Each Bin

| Distance Unit | Host Type | Slope Mean | Significance$^a$ | $\chi^2$/dof | dof |
|---------------|-----------|------------|------------------|--------------|-----|
| kpc           | All       | $-0.010 \pm 0.026$ | $0.007 \pm 0.022$ | $0.017 \pm 0.034$ | 0.5 | 0.255 ± 0.029 | 0.217 ± 0.021 | $-0.037 \pm 0.036$ | $-1.0$ |
|               | Elliptical| $-0.088 \pm 0.041$ | $-0.104 \pm 0.033$ | $-0.016 \pm 0.053$ | $-0.3$ | 0.233 ± 0.030 | 0.187 ± 0.030 | $-0.046 \pm 0.042$ | $-1.1$ |
|               | Spiral    | $0.054 \pm 0.033$ | $0.039 \pm 0.025$ | $-0.015 \pm 0.042$ | $-0.4$ | 0.264 ± 0.037 | 0.201 ± 0.025 | $-0.063 \pm 0.044$ | $-1.4$ |
| deV           | Elliptical| $-0.090 \pm 0.039$ | $-0.102 \pm 0.036$ | $-0.012 \pm 0.053$ | $-0.2$ | 0.218 ± 0.028 | 0.205 ± 0.033 | $-0.013 \pm 0.043$ | $-0.3$ |
| exp           | Spiral    | $0.056 \pm 0.034$ | $0.037 \pm 0.024$ | $-0.018 \pm 0.042$ | $-0.4$ | 0.273 ± 0.038 | 0.188 ± 0.015 | $-0.085 \pm 0.041$ | $-2.1$ |

Notes. $^a$ Significance of non-zero result, value divided by uncertainty. $^b$ The distance where the “near” and “far” bins were separated.

### Table 13
Results when Correlating SALT2 Hubble Residuals with Distance Binned in Multiple Bins of Equal Size

| Distance Unit | Host Type | Slope Mean | Significance$^a$ | $\chi^2$/dof | dof |
|---------------|-----------|------------|------------------|--------------|-----|
| kpc           | All       | $-0.0019 \pm 0.0022$ | $-0.0008 \pm 0.0024$ | $-0.0021 \pm 0.0031$ | $-0.7$ | 0.9 | 1.0 | 18 |
| deV           | Elliptical| $-0.010 \pm 0.016$ | $-0.7$ | 0.8 | 6 |
| exp           | Spiral    | $0.033 \pm 0.008$ | 4.0 | 1.0 | 10 |

Note. $^a$ Significance of non-zero result, value divided by uncertainty.

### Table 14
Results when Correlating SALT2 Hubble Residuals with Distance Binned in a Near and a Far Sample, with Equal Number of Events in Each Bin

| Distance Unit | Host Type | Slope Mean | Significance$^a$ | $\chi^2$/dof | dof |
|---------------|-----------|------------|------------------|--------------|-----|
| kpc           | All       | $0.029 \pm 0.022$ | $0.009 \pm 0.019$ | $-0.020 \pm 0.029$ | $-0.7$ | 0.215 ± 0.022 | 0.183 ± 0.014 | $-0.032 \pm 0.026$ | $-1.2$ |
|               | Elliptical| $-0.014 \pm 0.028$ | $-0.046 \pm 0.037$ | $-0.032 \pm 0.046$ | $-0.7$ | 0.160 ± 0.022 | 0.208 ± 0.027 | 0.048 ± 0.035 | 1.4 |
|               | Spiral    | $0.047 \pm 0.029$ | $0.040 \pm 0.020$ | $-0.007 \pm 0.035$ | $-0.2$ | 0.235 ± 0.028 | 0.163 ± 0.014 | $-0.071 \pm 0.032$ | $-2.2$ |
| deV           | Elliptical| $-0.037 \pm 0.028$ | $-0.022 \pm 0.037$ | $0.015 \pm 0.046$ | 0.3 | 0.162 ± 0.023 | 0.207 ± 0.027 | 0.046 ± 0.035 | 1.3 |
| exp           | Spiral    | $0.038 \pm 0.030$ | $0.049 \pm 0.019$ | $0.011 \pm 0.035$ | 0.3 | 0.240 ± 0.029 | 0.156 ± 0.012 | $-0.084 \pm 0.031$ | $-2.7$ |

Notes. $^a$ Significance of non-zero result, value divided by uncertainty. $^b$ The distance where the “near” and “far” bins were separated.
4.2. Correlations between Projected Distance and light-curve Shape (Δ, 〈x1〉)

When examining the correlations between the GCD and the MLCS2xk2 Δ (Tables 7 and 8) we find a weak relationship for elliptical galaxies, using the multi-binning method, where larger Δ are found at larger GCD. The significance of an evolving Δ 2.5σ and 2.4σ when using physical and normalized distance, respectively. Note that the fit to Δ as a function of physical distance is of limited quality, with a reduced χ^2 of 2.4. The trend is also visible in the two-bin data, but with lower significance: 1.9σ and 1.4σ. In the fit to unbinned data the correlation is only seen for normalized distances.

When studying the sample of spiral galaxies, we find only very weak correlations of the opposite trend as for the SNe in elliptical galaxies. The most significant correlation is with physical distances (1.5σ). However, using a two bin analysis and the fit to unbinned data this correlation is even less significant.

Looking at the full sample we see similar trends to what we found for the SNe in spiral galaxies (Δ diminishes with distance), since there are more SNe in spiral galaxies than in elliptical galaxies in our sample. The trend is visible when studying physical distances in the multi-bin analysis (2.1σ), but not in the two-bin analysis.

The SALT2 〈x1〉 parameter provides another measurement of the light-curve width. Since 〈x1〉 is inversely proportional to the decline rate of the light curve we would expect a correlation with the opposite sign compared with the correlation with MLCS2xk2–Δ. We find no correlations with 2σ or larger significance in either the multi-bin or the two-bin analyses (see Tables 9 and 10), the highest significance of a deviation from a constant 〈x1〉 being only 1.1σ.

Leaving aside the dependence with distance, we confirm the results that faint SNe Ia with narrow light curves favor passive host galaxies (Hamuy et al. 1996; Gallagher et al. 2005; Sullivan et al. 2006; Lampeitl et al. 2010). We find that SNe Ia with low Δ/high 〈x1〉 (bright SNe) explode preferably in spiral galaxies, which is visible in the middle panels of Figures 4 and 5.

We obtain 〈x1〉_{elliptical} = −0.76 ± 0.13 for elliptical galaxies compared with 〈x1〉_{spiral} = 0.20 ± 0.08 for spiral galaxies. The corresponding numbers for MLCS2xk2 are: 〈Δ_{elliptical}〉 = 0.16 ± 0.05 mag and 〈Δ_{spiral}〉 = −0.08 ± 0.03 mag.

4.3. Correlations between Projected Distance and Hubble Residuals

When correlating the projected distance with the Hubble residuals from MLCS2xk2 and SALT2 (see Tables 11–14), we only find a trend with a significance larger than 2σ, indicating that the SALT2 Hubble residuals increase with normalized distance for SNe in spiral hosts. However, the trend is only seen in the multi-bin analysis, and it is not confirmed by either the two-bin analysis or the unbinned fit. Furthermore, it is not seen for physical distances nor in the MLCS2xk2 residual.

Using the limits obtained from the Hubble residuals as a function of physical distance for the full sample of SNe, we obtain that both the MLCS2xk2 and SALT2 residuals will change by less than 0.06 (2σ) between an SN at the center of the galaxy and one which is 10 kpc away.

The difference in Hubble residual scatter between SNe in spiral galaxies close to the galaxy center and farther away is significant. Depending on light-curve fitter and distance type used, the significance varies between 1.4σ and 2.7σ, which can be seen in Tables 11–14. The scatter is larger close to the center of the galaxy. This scatter difference translates also to the complete sample, while it is not visible in the elliptical sample only.

Note that we find a difference in Hubble residuals between SNe in spiral galaxies and elliptical galaxies, most notably in the MLCS2xk2 residuals, 0.05 ± 0.02 mag in spirals, compared with −0.10 ± 0.03 mag in ellipticals.

5. DISCUSSION

Correlating the SN Ia light-curve parameters with the distance of the SN from the center of the host galaxies, we find strong indications of a decrease in AV with distance, in particular for spiral galaxies. If part of the color variations of SNe Ia is explained by dust, and dust is mainly present in spiral galaxies and decreasing with distance from the center, this would be expected. The trend is also reproduced when correlating the SALT2 color parameter c with distance. We find a moderately significant difference between the mean value of the color parameters AV and c for SNe exploding in spirals and elliptical galaxies, with (AV)_{sp} – (AV)_{ell} = 0.10 ± 0.04, and, with less significance, (c)_{sp} – (c)_{ell} = 0.024 ± 0.016. These differences would also be expected if these color parameters are related to dust, more prevalent in spiral galaxies. Due to the difficulty of observing faint SNe close to the galaxy center, we would expect fewer dust extincted SNe (with high AV) at small distances. However, this is opposite of what we find, so if we corrected for the brightness bias, the trend would most likely be stronger. Using the first-year SDSS-II/SN sample, Yasuda & Fukugita (2010) looked for a correlation of the SALT2 color parameter c with GCD, and did not find it to be significant for distances up to 15 kpc. If we restrict our study to the same region below 15 kpc, we still see a decreasing slope, but now with a smaller significance around 1σ. Therefore, our results are consistent with those in Yasuda & Fukugita (2010) and indicate that the bulk of the effect we see occurs at large distances between the SN and the center of its host galaxy.

We find some indications that SNe in elliptical galaxies tend to have narrower light curves (larger Δ) if they explode farther from the galaxy core. Since the width of the light curve is related to the SN brightness, this result would mean that SNe exploding at larger GCDs are fainter. Therefore, this finding could, at least partly, be explained by the difficulty in detecting faint SNe close to the galaxy center, where the galaxy light is strongest. Furthermore, the significances found for an evolving Δ are not very strong (<2.5σ) and the trend is mainly visible when using the Δ parameter from MLCS2xk2 as a measure of the light-curve width, compared to the homologous 〈x1〉 parameter in SALT2.

We find no strong correlations between the GCD and the Hubble residuals. Since the distance of the SN from the core of the galaxy can be used as a proxy for the local metallicity (see, e.g., Boissier & Prantzos 2009), this result can be interpreted as an indication of a limited correlation between Hubble residuals and local metallicity. Since there is also a correlation between the metallicity and the luminosity of the host galaxy, there could be a bias in our sample where there are fewer SNe detected in bright galaxies (with high metallicity) at small GCDs. However, even if we exclude the data with the smallest SN–galaxy distances, we still see no significant correlations between the GCD and the Hubble residuals. Ivanov et al. (2000) found no correlations between the GCD and both the absolute magnitude in the B band and the decline rate parameter Δm_{15} using 62 SNe at z < 0.1. Our results, with a larger SN sample that extends to z < 0.25,
agree with those. Gallagher et al. (2005) suggest that progenitor age should be a more important factor than metallicity in determining the variations in SN peak brightness. Gupta et al. (2011) found a correlation between the Hubble residuals and the mass-weighted average age of the host galaxy in SDSS data. However, a correlation between the Hubble residuals and the age should be a more important factor than metallicity in

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, Cambridge University, Casey Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

This work is based in part on observations made at the following telescopes. The Hobby–Eberly Telescope (HET) is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen. The HET is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly. The Marcardio Low-Resolution Spectrograph is named for Mike Marcardio of High Lonesome Optics, who fabricated several optics for the instrument but died before its completion; it is a joint project of the Hobby–Eberly Telescope partnership and the Instituto de Astronomía de la Universidad Nacional Autónoma de México. The Apache Point Observatory 3.5 m telescope is owned and operated by the Astrophysical Research Consortium. We thank the observatory director, Suzanne Hawley, and site manager, Bruce Gillespie, for their support in this project. The Subaru Telescope is operated by the National Astronomical Observatory of Japan. The William Herschel Telescope is operated by the Isaac Newton Group, and the Nordic Optical Telescope is operated jointly by Denmark, Finland, Iceland, Norway, and Sweden, both on the island of La Palma in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. The Italian Telescopio Nazionale Galileo (TNG) is operated on the island of La Palma by the Fundación Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories. The South African Large Telescope (SALT) of the South African Astronomical Observatory is operated by a partnership between the National Research Foundation of South Africa, Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, the Hobby–Eberly Telescope Board, Rutgers University, Georg-August-Universität Göttingen, University of Wisconsin-Madison, University of Canterbury, University of North Carolina-Chapel Hill, Dartmouth College, Carnegie Mellon University, and the United Kingdom SALT consortium.

**REFERENCES**

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543

Amanullah, R., Lidman, C., Rubin, D., et al. 2010, ApJ, 716, 743

Astier, P., Guy, J., Regnault, N., et al. 2006, A&A, 447, 31

Barris, B. J., & Tonry, J. L. 2004, ApJ, 613, L21

Barris, B. J., Tonry, J. L., Blondin, S., et al. 2004, ApJ, 602, 571

Blanton, M. R., Dalcanton, J., Eisenstein, D., et al. 2001, AJ, 121, 2358

Boissier, S., & Prantzos, N. 2009, A&A, 503, 137

Ciotti, L. 1991, A&A, 249, 99

Conley, A. J., Guy, J., Sullivan, M., et al. 2011, ApJS, 192, 1

D’Andrea, C. B., Gupta, R. R., Sako, M., et al. 2011, ApJ, 743, 172

de Vaucouleurs, G. 1948, Ann. d’Astrophys., 11, 247

Dilday, B., Kessler, R., Frieman, J. A., et al. 2008, ApJ, 682, 262

Eisenstein, D. J., Weinberg, D. H., Agol, E., et al. 2011, AJ, 142, 72

Freeman, K. C. 1970, ApJ, 160, 811

Frieman, J. A., Bassett, B. A., Becker, A. C., et al. 2008, AJ, 135, 338

Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748

Gallagher, J. S., Garnavich, P. M., Berlind, P., et al. 2005, ApJ, 634, 210

Gallagher, J. S., Garnavich, P. M., Caldwell, N., et al. 2008, ApJ, 685, 752

Graham, A. W., & Driver, S. P. 2005, PASA, 22, 118

Gunn, J. E., Carr, M., Rockosi, C., et al. 1998, AJ, 116, 3040

Gunn, J. E., Siegmund, W. A., Mannery, E. J., et al. 2006, AJ, 131, 2332

Gupta, R. R., D’Andrea, C. B., Sako, M., et al. 2011, ApJ, 740, 92

Guy, J., Astier, P., Baumont, S., et al. 2007, A&A, 466, 11

Guy, J., Astier, P., Nobili, S., Regnault, N., & Pain, R. 2005, A&A, 443, 781

Hamuy, M., Phillips, M. M., Suntzeff, N. B., et al. 1996, AJ, 112, 2391

Hicken, M., Challis, P., Jha, S., et al. 2009a, ApJ, 700, 331

Hicken, M., Wood-Vasey, W. M., Blondin, S., et al. 2009b, ApJ, 700, 1097

Holtzman, J. A., Marriner, J., Kessler, R., et al. 2008, AJ, 136, 2306

Howell, D. A., Sullivan, M., Brown, E. F., et al. 2009, ApJ, 691, 661

Ivanov, V. D., Hamuy, M., & Pinto, P. A. 2000, ApJ, 542, 588

Jha, S., Branch, D., Chornock, R., et al. 2006, AJ, 132, 189

Jha, S., Riess, A. G., & Kirshner, R. P. 2007, ApJ, 659, 122

Kelly, P. L., Hicken, M., Burke, D. L., Mandel, K. S., & Kirshner, R. P. 2010, ApJS, 175, 743

Kessler, R., Becker, A. C., Cinabro, D., et al. 2009a, ApJS, 185, 32

Kessler, R. B., Bernstein, J. P., Cinabro, D., et al. 2009b, PASP, 121, 1028

Knop, R. A., Aldering, G., Amanullah, R., et al. 2003, ApJ, 598, 1012

Konishi, K., Cinabro, D., Garnavich, P. M., et al. 2011, arXiv:1101.4269

Lampeitl, H., Smith, M., Nichol, R. C., et al. 2010, ApJ, 722, 566

Marriner, J., Bernstein, J. P., Kessler, R., et al. 2011, ApJ, 740, 72

Nordin, J., ¨Ostman, L., Goobar, A., et al. 2011, A&A, 526, 119

Nordin, J., ¨Ostman, L., Goobar, A., et al. 2011, A&A, 526, 28

Perlmuter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565

Phillips, M. M. 1993, ApJ, 413, L105

Phillips, M. M., Lira, P., Suntzeff, N. B., et al. 1999, AJ, 118, 1766

Prieto, J. L., Rest, A., & Suntzeff, N. B. 2006, ApJ, 647, 501

Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009

Riess, A. G., Press, W. H., & Kirshner, R. P. 1996, ApJ, 473, 88

Riess, A. G., Str"ogler, L.-G., Tonry, J., et al. 2004, ApJ, 600, L163

Sako, M., Bassett, B., Becker, A., et al. 2008, ApJ, 673, 348

Sako, M., Bassett, B., Connolly, B., et al. 2011, ApJ, 738, 162

Sérsic, J. L. 1963, Bol. de la Asociacion Argentina de Astron., 6, 41
Shimasaku, K., Fukugita, M., Doi, M., et al. 2001, AJ, 122, 1238
Smith, M., Nichol, R. C., Dilday, B., et al. 2012, ApJ, in press (arXiv:1108.4923)
Stoughton, C., Lupton, R. H., Bernardi, M., et al. 2002, AJ, 123, 485
Strateva, I., Ivezić, Ž., Knapp, G. R., et al. 2001, AJ, 122, 1861
Sullivan, M., Borgne, D. L., Pritchet, C. J., et al. 2006, ApJ, 648, 868
Sullivan, M., Conley, A., Howell, D. A., et al. 2010, MNRAS, 406, 782
Suzuki, N., Rubin, D., Lidman, C., et al. 2012, ApJ, 746, 85
Tonry, J. L., Schmidt, B. P., Barris, B., et al. 2003, ApJ, 594, 1
Wood-Vasey, W. M., Miknaitis, G., Stubbs, C. W., et al. 2007, ApJ, 666, 694
Yasuda, N., & Fukugita, M. 2010, AJ, 139, 39
York, D. G., Adelman, J., Anderson, J. E., et al. 2000, AJ, 120, 1579
Zheng, C., Romani, R. W., Sako, M., et al. 2008, AJ, 135, 1766