

## HUBBLE DIAGRAMS OF TYPE Ia SUPERNOVAE IN THE NEAR-INFRARED

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### ABSTRACT

From observations of seven Type Ia supernovae obtained during the last 4 years at the Las Campanas and Cerro Tololo Inter-American Observatories, along with previous published data for nine supernovae, we present *JHK* Hubble diagrams and derive absolute magnitudes at maximum light of 16 objects out to a redshift of 0.038. On the scale of  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$  we find mean absolute magnitudes of  $-18.57$ ,  $-18.24$ , and  $-18.42$  for *J*, *H*, and *K*, respectively, with  $1 \sigma$  uncertainties of the distributions of values of  $\pm 0.14$ ,  $0.18$ , and  $0.12 \text{ mag}$ . The data indicate no significant decline rate relations for the infrared. Thus, Type Ia supernovae at maximum brightness appear to be *standard candles* in the infrared at the  $\pm 0.20 \text{ mag}$  level or better. The minimum requirements for obtaining the distance to a Type Ia supernova are reasonably accurate values of  $\Delta m_{15}(B)$  and  $T(B_{\text{max}})$ , and one night of infrared data in the  $-12$  to  $+10$  day window with respect to  $T(B_{\text{max}})$ .

*Subject headings:* distance scale — supernovae: general

*On-line material:* color figures

### 1. INTRODUCTION

Type Ia supernovae (SNe) are the most precise distance indicators for extragalactic astronomy at redshift  $z \gtrsim 0.01$ . Since the discovery that the absolute magnitudes at maximum light were related to the decline rates (Pskovskii 1977, 1984; Phillips 1993), Type Ia SNe have been considered standardizable candles. The intrinsically brighter ones have wider *B*- and *V*-band light curves, along with stronger and later secondary humps in the *I*-band light curves. The three principal schemes for characterizing the light curves are the  $\Delta m_{15}$  method (Hamuy et al. 1996; Phillips et al. 1999), the multicolor light curve shape (MLCS) method (Riess, Press, & Kirshner 1996; Riess et al. 1998), and the “stretch method” of Perlmutter et al. (1997).

Elias et al. (1981, 1985) were the first to publish any extensive infrared (IR) photometry of Type Ia SNe. In their Figure 6, they presented the first *H*-band Hubble diagram of Type Ia SNe and commented, “the dispersion in their absolute magnitude near maximum is small, making them potentially useful distance indicators.” After this, with the exception of SN 1986G (Frogel et al. 1987), very few IR observations were made of Type Ia SNe until the appearance of SN 1998bu (Jha et al. 1999; Hernandez et al. 2000). A summary of IR data available 4 years ago is given by Meikle (2000).

It is well known that light is less extinguished by dust at infrared wavelengths compared with optical wavelengths. According to Cardelli, Clayton, & Mathis (1989),  $A_{\lambda}/A_V = 0.282$ ,  $0.190$ , and  $0.114$ , for the near-IR *JHK* bands. In principle, the near infrared bands should be less subject to systematic errors due to dust extinction along the line of sight. Until recently, it has been difficult to test this hypothesis because few Type Ia SNe have been observed early enough to overlap the times of infrared maximum, which generally occur about 3 days prior to the *B*-band maximum.

Simple experimentation on the data showed us that the rest

frame light curves could be fitted by template *JHK* light curves (Krisciunas et al. 2004, § 3.1) using the stretch technique of Perlmutter et al. (1997), provided that the fits were made in the window of time  $-12$  to  $+10$  days with respect to  $T(B_{\text{max}})$ . To create the near-IR templates, the data were transformed to the SN rest frame by applying *K*-corrections to the observed magnitudes and time dilation corrections to the time from maximum light. Since we did not have the Perlmutter templates or the code to calculate the stretch factors directly, we estimated the optical stretch factors using the relationships of Jha (2002, Fig. 3.8), which relate the *B*- and *V*-band stretch factors to the Phillips parameter  $\Delta m_{15}(B)$ . We have very few IR light curves that are well sampled and cover the maxima. To bring all the data to a standard  $s = 1$  stretch, we used the inverse stretch factors  $s^{-1}$  (averaging the *B*- and *V*-band values) to scale the time axis of the IR light curves. The final templates, shown in Figure 1, represent the averaged behavior in *JHK* for a supernova with  $s = 1$ .<sup>4</sup> Our *JHK* templates exhibit rms deviations of  $\sigma_J = \pm 0.062$ ,  $\sigma_H = \pm 0.080$ , and  $\sigma_K = \pm 0.075 \text{ mag}$  around a cubic fit. Except at  $t' \gtrsim +7$  days in the *H*-band diagram, these uncertainties seem to be bona fide measures of the rms errors, rather than evidence for systematic differences between objects. For *RIJHK* the stretch method does not work beyond  $t \approx +10$  days because the secondary humps do not scale like the maxima.

We then used the adopted maximum apparent magnitudes of eight of the nine template SNe, estimates of the *V*-band extinction appropriate to each object, and the ratios of IR extinction to  $A_V$  of Cardelli et al. (1989) to obtain extinction-corrected maxima. For the seven objects with sparser data, we used the templates and appropriate extinction corrections to determine their extinction-corrected maxima. Finally, we include the unusual SN 1999ac (Phillips et al. 2003), which was reasonably well sampled at the time of its IR maxima.

In this Letter we present the *JHK* Hubble diagrams and absolute magnitudes at maximum light based on the data in Krisciunas et al. (2004).

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<sup>4</sup> We shall define “stretched time” ( $t'$ ) to be the number of days with respect to  $T(B_{\text{max}})$ , multiplied by the inverse stretch factor  $s^{-1}$  and divided by  $(1+z)$ .

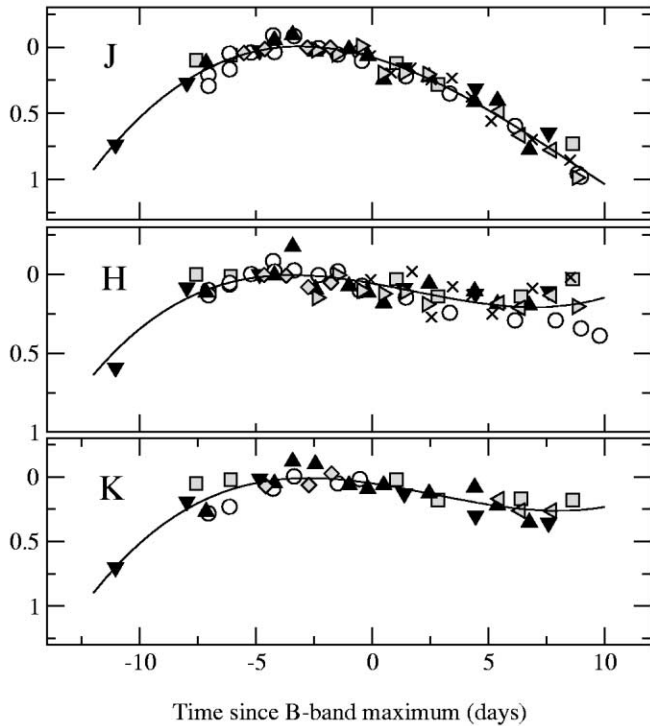


FIG. 1.—*JH* templates based on eight Type Ia SNe and *K*-band template based on six objects. The time axis is “stretched time” (in days), which has been corrected for time dilation and scaled to a fiducial  $s = 1$  stretch factor. Third-order fits to the data are shown. The symbols for various supernovae are 1980N (triangles, pointing left), 1986G (squares), 1998bu (triangles, pointing up), 1999aw (crosses), 1999ee (circles), 2000ca (triangles, pointing right), 2001el (triangles, pointing down), and 2001ba (diamonds). [See the electronic edition of the *Journal* for a color version of this figure.]

## 2. THE DATA

We consider the following Type Ia SNe:

*SN 1980N* (Elias et al. 1981).—For this SN and its host, NGC 1316, we use the weighted mean of the two distance moduli given by Ajhar et al. (2001, Table 3),  $m - M = 31.44 \pm 0.14$ . This distance modulus is based on surface brightness fluctuations (SBFs) of the host and is on the Cepheid scale of Freedman et al. (2001), with  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

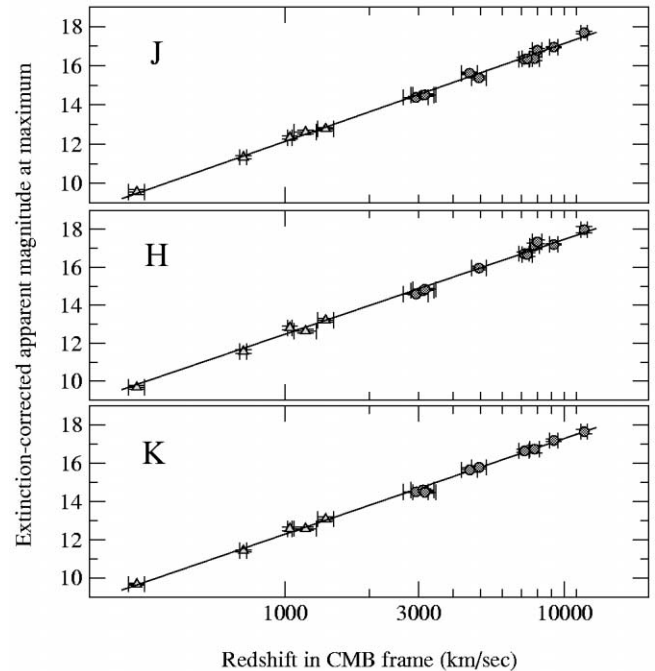


FIG. 2.—Hubble diagrams of Type Ia SNe. We plot the extinction-corrected *J*-, *H*-, and *K*-band maxima vs. the logarithm of the redshifts in the CMB frame. The round dots have velocities taken from NED. We have added horizontal error bars corresponding to typical peculiar velocity of  $\pm 300 \text{ km s}^{-1}$ . The points represented by triangles have “equivalent” CMB velocities derived from direct measures of the distances to the hosts, on the  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$  scale of Freedman et al. (2001). The straight lines given in each plot have a slope of exactly 5 and correspond to the mean absolute magnitudes in each filter on an  $H_0 = 72$  scale. [See the electronic edition of the *Journal* for a color version of this figure.]

*SN 1981B* (Elias et al. 1981, 1985; Rafanelli, Birkie, & Heffele 1981; Salinari & Moorwood 1981).—Freedman et al. (2001) give a Cepheid distance modulus of  $\mu_0 = 30.80 \pm 0.04$  for the host (NGC 4536).

*SN 1994D*.—This object was observed by Richmond et al. (1995) in the IR on only one night near maximum. Ajhar et al. (2001, Table 3) give an SBF distance modulus of  $m - M = 31.08 \pm 0.20$ .

TABLE 1  
DATA FOR TYPE Ia SUPERNOVAE

SN	$\Delta m_{15}(B)$	$v_{\text{CMB}}$ ( $\text{km s}^{-1}$ )	$A_V$	$J_{\text{max}}$	$J_{\text{corr}}$	$H_{\text{max}}$	$H_{\text{corr}}$	$K_{\text{max}}$	$K_{\text{corr}}$	$N_{J,H,K}^a$
1980N <sup>b</sup>	1.28 (04)	1397 <sup>c</sup>	0.22 (06)	12.84 (08)	12.78 (08)	13.24 (10)	13.20 (10)	13.10 (10)	13.08 (10)	3, 3, 3
1981B	1.10 (07)	1041 <sup>c</sup>	0.40 (09)	12.44 (08)	12.33 (08)	12.88 (10)	12.81 (10)	12.61 (09)	12.57 (09)	3, 3, 3
1986G <sup>b</sup>	1.73 (07)	295 <sup>c</sup>	1.56 (40)	10.00 (03)	9.56 (12)	9.96 (03)	9.66 (10)	9.85 (03)	9.67 (06)	5, 6, 6
1994D	1.31 (08)	1184 <sup>c</sup>	0.12 (02)	12.65 (09)	12.62 (09)	12.65 (10)	12.63 (10)	12.59 (10)	12.58 (10)	1, 1, 1
1998bu <sup>b</sup>	1.01 (05)	710 <sup>c</sup>	1.13 (20)	11.65 (06)	11.33 (08)	11.77 (10)	11.56 (11)	11.55 (05)	11.42 (06)	11, 11, 11
1999aa	0.81 (04)	4572	0.12 (01)	15.65 (07)	15.62 (07)	...	...	15.66 (10)	15.65 (10)	1, 0, 1
1999ac	1.34 (08)	2943	0.51 (20)	14.53 (03)	14.39 (06)	14.68 (03)	14.58 (05)	14.56 (03)	14.50 (04)	14, 14, 14
1999aw <sup>b</sup>	0.81 (03)	11750	0.10 (02)	17.71 (06)	17.68 (06)	18.00 (16)	17.98 (16)	17.65 (11)	17.64 (11)	9, 8, 9
1999cp	0.87 (10)	3115	0.07 (01)	14.55 (02)	14.53 (02)	14.78 (02)	14.77 (02)	14.61 (06)	14.60 (06)	2, 2, 2
1999ee <sup>b</sup>	0.94 (06)	3163	0.94 (16)	14.78 (04)	14.52 (06)	15.02 (04)	14.84 (05)	14.62 (03)	14.51 (04)	17, 18, 6
1999gp	1.00 (10)	7806	0.17 (03)	16.41 (09)	16.36 (09)	17.16 (15)	17.13 (15)	16.75 (18)	16.73 (18)	1, 1, 2
2000bh	1.16 (10)	7181	0.21 (09)	16.39 (08)	16.33 (08)	16.75 (09)	16.71 (09)	16.66 (09)	16.64 (09)	5, 5, 5
2000bk	1.63 (10)	7976	0.28 (20)	16.87 (07)	16.79 (09)	17.39 (09)	17.34 (10)	...	...	2, 2, 0
2000ca <sup>b</sup>	0.98 (05)	7352	0.21 (09)	16.41 (03)	16.35 (04)	16.71 (09)	16.67 (09)	...	...	7, 7, 0
2000ce	0.99 (10)	4946	1.67 (20)	15.85 (07)	15.38 (09)	16.27 (08)	15.95 (09)	15.97 (09)	15.78 (09)	1, 1, 1
2001ba <sup>b</sup>	0.97 (05)	9152	0.32 (09)	17.04 (03)	16.95 (04)	17.26 (03)	17.20 (03)	17.22 (06)	17.18 (07)	5, 5, 3

<sup>a</sup> Number of data points prior to  $t' = +10$  days in “stretched time.”

<sup>b</sup> Objects used for *JHK* templates. SN 2001el was also a template object. See text for further comments.

<sup>c</sup> See text for comments on “equivalent” velocities.

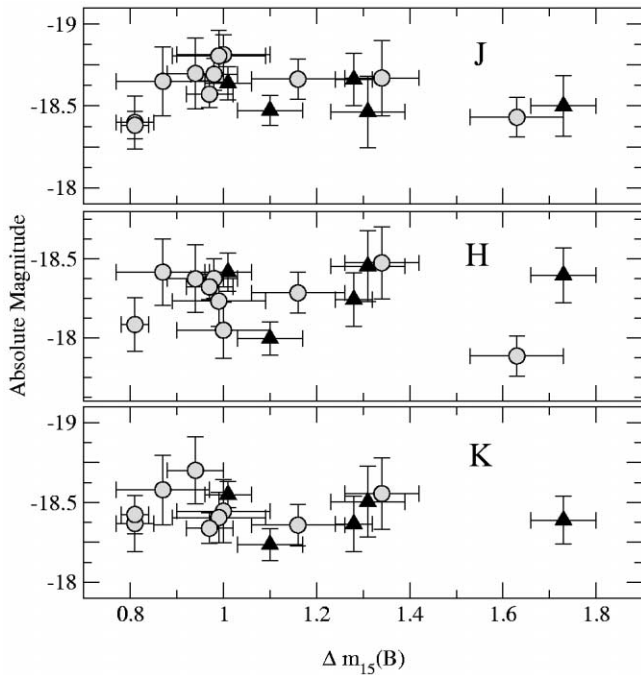


FIG. 3.—Absolute magnitudes of Type Ia SNe at maximum on the  $H_0 = 72$  km s $^{-1}$  Mpc $^{-1}$  scale. Symbols: Dots are objects in the Hubble flow ( $v \geq 3000$  km s $^{-1}$ ); triangles are SNe 1980N, 1981B, 1986G, 1994D, 1998bu, which have Cepheid or SBF distances. The uncertainties in the absolute magnitudes take into account the random errors of the photometry, template fitting, extinction corrections, and the determination of the distance moduli. [See the electronic edition of the Journal for a color version of this figure.]

*SN 1986G* (Frogel et al. 1987).—Phillips et al. (1999) indicate that  $E(B-V)_{\text{host}} = 0.50$  mag. The Schlegel, Finkbeiner, & Davis (1998) Galactic reddening is  $E(B-V)_{\text{Gal}} = 0.115$ . From polarimetry Hough et al. (1987) indicate that  $R_V \equiv A_V/E(B-V) = 2.4 \pm 0.13$  for the dust in the host galaxy, NGC 5128, much less than the nominal Galactic value of  $R_V = 3.1$ . For this object  $A_V = 3.1 \times 0.115 + 2.4 \times 0.50 = 1.56$ , to which we assign a large uncertainty. Ajhar et al. (2001, Table 3) give a distance modulus of  $m-M = 28.06 \pm 0.14$  on the basis of SBFs.

*SN 1998bu* (Suntzeff et al. 1999; Jha et al. 1999; Hernandez et al. 2000).—We exclude the data of Mayya, Puerari, & Kuhn (1998), which we consider uncertain. Freedman et al. (2001, Table 4) give a distance modulus of  $\mu_0 = 29.97 \pm 0.06$  for the host, NGC 3368, on the basis of their final Cepheid calibrations.

*SN 1999aa* (Krisciunas et al. 2000) and *SN 1999gp* (Krisciunas et al. 2001).—We assume that they are unreddened in their hosts. We use a corrected decline rate of  $\Delta m_{15}(B) = 0.81 \pm 0.04$  for SN 1999aa (J. L. Prieto 2003, private communication), which is based on the photometry of Krisciunas et al. (2000) and Jha (2002). SN 1999aa at optical wavelengths was similar in many ways to SN 1999aw.

*SN 1999ac* (Phillips et al. 2003).—This object was spectroscopically peculiar, and its  $B-V$  colors were unusual in the tail of the color curve. Because of the peculiarities of SN 1999ac, we have not used it as a template object, but the  $K$ -band data in particular are very similar to our  $K$ -band template.

*SN 1999aw* (Strolger et al. 2002).—The  $H$ - and  $K$ -band photometry has lower S/N owing to the higher redshift ( $z = 0.038$ ) of the object. We did not use the  $K$ -band data of this object for the construction of our  $K$ -band template. The host galaxy is of very low surface brightness, and we assume no

TABLE 2

MEAN ABSOLUTE MAGNITUDES OF TYPE Ia SUPERNOVAE AT MAXIMUM

Filter	$\langle M \rangle$	$\sigma_x$	$\chi^2_\nu$	$N$
<i>J</i> .....	-18.57 (03)	$\pm 0.138$	1.27	16
<i>H</i> .....	-18.24 (04)	$\pm 0.183$	1.67	15
<i>K</i> .....	-18.42 (04)	$\pm 0.121$	0.77	14

host reddening. This object was similar to SN 1999aa. Both were slow decliners and exhibited spectroscopic peculiarities.

*SN 1999cp* (Krisciunas et al. 2000).—MLCS fits indicate that this object was unreddened in its host. Analysis of  $\Delta m_{15}$  gives  $E(B-V)_{\text{host}} = 0.04 \pm 0.03$ . We adopt the MLCS value of  $T(B_{\text{max}})$  because the MLCS fitting is able to include the earliest photometric points in the fit and is therefore able to constrain  $T(B_{\text{max}})$  more precisely.

*SN 1999ee*.—Stritzinger et al. (2002) give  $A_V = 0.94 \pm 0.16$  from optical data. Krisciunas et al. (2004) give extensive IR data.

*SN 2000bh*.—Krisciunas et al. (2004) give IR data on 23 nights starting at  $t' = +5.5$  days. The sparser optical data begin 1 day later.

*SN 2000bk* (Krisciunas et al. 2001).—Minimally reddened in its host.

*SN 2000ce*.—This object is considerably reddened in its host. MLCS gives  $A_V = 1.67 \pm 0.20$  mag (Krisciunas et al. 2001, their Table 14 and § 3.2).

*SN 2000ca* and *SN 2001ba*.—See Krisciunas et al. (2004). Neither is highly reddened in its host.

*SN 2001el* (Krisciunas et al. 2003).—Though this object had normal light curves and was well sampled, it is not far enough to be in the quiet Hubble flow. Lacking a directly measured distance to the host galaxy via Cepheids or SBFs, we reluctantly eliminate it from further consideration in this Letter.

The uncertainties of the magnitudes at maximum light are given by the photometry alone for the objects with well-sampled light curves at maximum. For the other objects the uncertainties of the apparent magnitudes at maximum were taken to be the square root of the quadratic sum of the typical uncertainties of the photometry and the uncertainties of our template rms values ( $\sigma_x$ ,  $\sigma_H$ ,  $\sigma_K$ ).

In order to make Hubble diagrams we need corresponding velocities in the frame of the cosmic microwave background (CMB). Ideally, we would only consider objects in the Hubble flow ( $v \geq 3000$  km s $^{-1}$ ) to reduce the effects of peculiar velocities on the dispersion in the flow. Five of our objects are closer than this.

For two of the nearest objects (SNe 1981B and 1998bu) we used the Cepheid distances of Freedman et al. (2001). For SNe 1980N, 1986G, and 1994D we used SBF distances on the Cepheid scale of Freedman et al. (2001) and simply multiplied the distances by  $H_0 = 72$  km s $^{-1}$  Mpc $^{-1}$  to get “equivalent” velocities in the CMB frame.<sup>5</sup> For the other 11 objects we used the redshifts in the CMB frame.

In Table 1 we give the values of  $\Delta m_{15}(B)$ , the velocities in the CMB frame or their equivalents, values of  $A_V$  derived from optical light curves, the adopted  $JHK$  maxima of the SNe, and their maxima corrected for extinction along the line of sight.

<sup>5</sup> We also employed the flow model of Tonry et al. (2000) to calculate the equivalent distances of the five nearest objects in our sample that give flow velocities equal to the CMB velocities from NED. This gave equivalent distances of SNe 1986G, 1980N, and 1998bu in reasonable agreement with the directly determined values. However, the model is too simplistic in the cases of SNe 1981B and 1994D, which are found in the direction of the Virgo cluster itself.

For those objects assumed unreddened in their hosts, we adopted the values of Galactic reddening  $E(B-V)$  of Schlegel et al. (1998) and assumed  $R_V = 3.1$ . To correct the observed IR maxima for dust extinction we assumed the  $A_\lambda/A_V$  ratios of Cardelli et al. (1989).

### 3. RESULTS

In Figure 2 we show the Hubble diagrams of Type Ia SNe for the near-IR *JHK* bands, plotting the extinction-corrected apparent magnitudes versus the logarithm of the redshifts in the CMB frame. For the five objects with directly measured distances, we plot the “equivalent” redshifts.

It is obvious from an inspection of Figure 2 that our sample of Type Ia SNe may be regarded as excellent standard candles in the IR. SNe 1999ee and 1999cp, one well sampled and reddened, the other sparsely sampled and unreddened, with nearly identical velocities, fall on top of each other in all three subdiagrams. We note that, while SNe 1999aa, 1999ac, and 1999aw are “peculiar” in some ways at optical wavelengths, there seems to be nothing peculiar about their IR luminosities compared with other objects.

The next question to ask is clearly: are the deviations from the Hubble lines in Figure 2 a function of  $\Delta m_{15}(B)$ ? In other words: are there decline rate relations for the IR bands? To answer this we derive the absolute magnitudes of the objects in our sample.

All of our absolute magnitudes were determined on the Freedman et al. (2001) scale of  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . For distances, we used either the directly measured distances for the hosts of SNe 1980N, 1981B, 1986G, 1994D, and 1998bu or CMB-frame velocities converted to distances via Hubble’s Law. In Figure 3 we show the *JHK* absolute magnitudes of our sample. The uncertainties in the absolute magnitudes include the random errors of the photometry, template fitting, extinction corrections, and also the distance moduli. For those objects in the Hubble flow we assumed a representative peculiar motion of  $\pm 300 \text{ km s}^{-1}$ . This translates to an uncertainty in the distance modulus of 0.222 mag for SN 1999ac, but only 0.055 mag for SN 1999aw. From Figure 3 we deduce that there are no obvious decline rate relations in the near-IR.

In Table 2 we give the weighted mean values and dispersions of the absolute magnitudes at maximum. The third column of this table contains the  $1 \sigma$  Gaussian widths of the distributions of the absolute magnitudes. In Table 2 we also give the reduced

$\chi^2$ -values, which (since they are close to 1) demonstrate that we have assumed sensible uncertainties for the adopted distance moduli and photometry and that the absolute magnitudes are constant within the errors.

Figures 2 and 3 also demonstrate the soundness of the assumption that a single Hubble constant is applicable out to a redshift of 0.04. Otherwise, there would be a shift with respect to the lines of slope 5 in Figure 2, and the points corresponding to nearby objects and those in the Hubble flow in Figure 3 would exhibit some kind of systematic difference.

While Type Ia SNe are *standardizable* candles in the optical bands, they apparently are *standard* candles in the near-IR, at the  $\pm 0.20$  mag level or better ( $\pm 9\%$  in distance), depending on the filter.

In this Letter we have outlined a new method of determining distances to Type Ia SNe. Of course, the use of highly nonstandard *JHK* filters is to be avoided. Our method requires a minimum of one night’s IR data in the window  $-12$  to  $+10$  days with respect to  $T(B_{\text{max}})$ , and reasonably accurate values of  $T(B_{\text{max}})$  and  $\Delta m_{15}(B)$ . This exploits the nature of the IR light curves, which are well behaved and obey the stretch model *at maximum light*. By focusing on IR light curves we employ extinction corrections whose values and uncertainties are much smaller than in the optical. Not only does this lead to very small scatter in the near-IR Hubble diagrams, but it underscores the standard candle nature of Type Ia SNe in the IR.

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