Hubble Diagrams of Type Ia Supernovae in the Near Infrared

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ABSTRACT

From observations of 7 Type Ia supernovae obtained during the last four years at the Las Campanas and Cerro Tololo Inter-American Observatories, along with previous published data for 9 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 $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$ we find mean absolute magnitudes at maximum 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 mag. The data indicate no significant decline rate relations for the infrared. Thus, Type Ia SNe at maximum brightness appear to be standard candles in the infrared at the $\pm 0.20$ mag level or better. The minimum requirements for obtaining the distance to a Type Ia SN are: reasonably accurate values of $\Delta m_{15}(B)$ and $T(B_{\text{max}})$, and one night of infrared data in the $-12$ to $+10$ d window with respect to $T(B_{\text{max}})$.

Subject headings: supernovae, photometry; supernovae

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 Fig. 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).

Meikle (2000) gives a summary of the IR data available 4 years ago and states that “most SNe Ia are standard IR candles at a level of about 0.15 mag.” Meikle’s analysis related to the absolute magnitudes in $JHK$ at 14 days after $T(B_{\text{max}})$ and used host galaxy distance determinations via Cepheids observed with HST. In this paper we use four of the same objects considered by Meikle, namely SNe 1980N, 1981B, 1986G, and 1998bu. We key on their apparent and absolute magnitudes at maximum light. The majority of our objects are distant enough to be in the smooth Hubble flow.

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

Simple experimentation on the data showed us that the rest frame light curves could be fit by template $JHK$ light curves (Krisciunas et al. 2004a, §3.1) using the stretch technique of Perlmutter et al. (1997) provided that the fits were made in the window of time $-12$ to $+10 \text{ d with respect to } T(B_{\text{max}})$. 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 Fig. 1, represent the averaged behavior in $JHK$ for a supernova with $s = 1$.\textsuperscript{4} Our $JHK$ templates exhibit rms deviations of $\sigma_J = \pm 0.062$, $\sigma_H = \pm 0.080$, and $\sigma_K = \pm 0.075$ mag around a cubic fit. Except at $t' \gtrsim +7$ d 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 $t \approx +10$ d 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. (2004a).

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 $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$.


SN 1994D 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 $m - M = 31.08 \pm 0.20$.

SN 1986G (Frogel et al. 1987). Phillips et al. (1999) indicate that $E(B - V)_{host} = 0.50$ mag. The Schlegel, Finkbeiner, & Davis (1998) Galactic reddening is $E(B - V)_{Gal} = 0.115$. From polarimetry Hough et al. (1987) indicate that $R_V \equiv A_V / E(B - V) = 2.4 \pm 0.13$ for

\textsuperscript{4}We shall define “stretched time” ($t'$) to be the number of days with respect to $T(B_{max})$, multiplied by the inverse stretch factor $s^{-1}$ and divided by $(1 + z)$.
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 (1999), 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, 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 due 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 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 his object was unreddened in its host. $\Delta m_{15}$ analysis 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. (2004a) give extensive IR data.

SN 2000bh. Krisciunas et al. (2004a) give IR data on 23 nights starting at $t' = +5.5$ d. The sparser optical data begin one 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, Table 14 and §3.2).
SN 2000ca and SN 2001ba. See Krisciunas et al. (2004a). 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 of this paper.

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 ($\sigma_J, \sigma_H, \sigma_K$).

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 ($v \gtrsim 3000$ 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. 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. 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).

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5We also employed the flow model of Tonry et al. (2000) to calculate the equivalent distances of the five nearest objects in our sample which 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 direction of the Virgo cluster itself.
3. Results

In Fig. 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 Fig. 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 sub-diagrams. 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 to other objects.

The next question to ask is clearly: are the deviations from the Hubble lines in Fig. 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 $H_0 = 72$ km s$^{-1}$ 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 Fig. 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 $\pm 300$ 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 Fig. 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. Column 3 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.

Figs. 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 Fig. 2, and the points corresponding to nearby objects and those in the Hubble flow in Fig. 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 ± 0.20 mag level or better (± 9% in distance), depending on the filter. This confirms the prognostication of Elias et al. (1985) and the analysis of Meikle (2000), which had the benefit of Cepheid-based distance determinations of the host galaxies of 8 objects.\(^6\)

In this paper we have outlined a new method of determining distances to Type Ia SNe. Of course, the use of highly non-standard \(JHK\) filters is to be avoided. Our method requires a minimum of one night’s IR data in the window \(-12\) to \(+10\) d 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.

We gratefully made use of the NASA/IPAC Extragalactic Database (NED). This publication makes use of data products from the 2MASS Survey, funded by NASA and the NSF. KK and NBS thank STScI for their support through grants HST-GO-07505.02-96A, HST-GO-08641.07-A, and HST-GO-09118.08-A. We thank Mario Hamuy, Darren DePoy, and Peter Meikle for scientific comments on this work. We thank Pablo Candia, Sergio Gonzalez, and Jose Luis Prieto for help on the data reduction. We thank Eric Persson and Darren DePoy for providing the excellent infrared instrumentation used in this study. Some of the data used in this study were obtained at CTIO using the“Small and Moderate Aperture Research Telescope System” (SMARTS). We thank John Tonry for a copy of his flow model program and for useful discussions. KK thanks LCO and NOAO for funding part of his postdoctoral position.

REFERENCES


\(^6\)In this paper we have considered 16 objects, 11 of which are distant enough to be in the smooth Hubble flow. At the time of this update, 1 March 2004, we have 5 more objects we can add to the diagrams: SNe 1999ek, 2001bt, 2001cn, 2001cz, and 2002bo. The first 4 of these are in the smooth Hubble flow. See Krisciunas et al. (2004b) for further details. The reader could also consider the more problematic cases of SNe 2000cx (Candia et al. 2003) and 2001el (Krisciunas et al. 2003).
Jha, S. 2002, Harvard University Dissertation
Mayya, Y. D., Puerari, I., & Kuhn, O. 1998, IAU Circ., 6907

Pskovskii, Y. P. 1977, Soviet Astron., 21, 675

Pskovskii, Y. P. 1984, Soviet Astron., 28, 658

Rafanelli, P., Birkie, K., & Hefele, H. 1981, IAU Circ., 3584


Table 1. Data for Type Ia Supernovae

<table>
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<tr>
<th>SN</th>
<th>$\Delta m_{15}(B)$</th>
<th>$v_{\text{CM},B}$ (km s$^{-1}$)</th>
<th>$A_V$</th>
<th>$J_{\text{max}}$</th>
<th>$J_{\text{corr}}$</th>
<th>$H_{\text{max}}$</th>
<th>$H_{\text{corr}}$</th>
<th>$K_{\text{max}}$</th>
<th>$K_{\text{corr}}$</th>
<th>$N_a^{J\text{,}H\text{,}K}$</th>
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<td>1397$^e$</td>
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<td>12.84(08)</td>
<td>12.78(08)</td>
<td>13.24(10)</td>
<td>13.20(10)</td>
<td>13.10(10)</td>
<td>13.08(10)</td>
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<td>12.33(08)</td>
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<td>295$^c$</td>
<td>1.56(40)</td>
<td>10.00(03)</td>
<td>9.56(12)</td>
<td>9.96(03)</td>
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<td>1184$^c$</td>
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<td>710$^c$</td>
<td>1.13(20)</td>
<td>11.65(06)</td>
<td>11.33(08)</td>
<td>11.77(10)</td>
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<td>...</td>
<td>...</td>
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<td>15.65(10)</td>
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<td>0.51(20)</td>
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<td>17.68(06)</td>
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<td>2000ce</td>
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$^a$Number of data points prior to $t' = +10$ d in “stretched time”. $^b$Objects used for $JHK$ templates. SN 2001el was also a template object. See text for further comments. $^c$See text for comments on “equivalent” velocities.
Table 2. Mean Absolute Magnitudes of Type Ia SNe at Maximum

<table>
<thead>
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<th>Filter</th>
<th>( \langle M \rangle )</th>
<th>( \sigma_x )</th>
<th>( \chi^2 )</th>
<th>N</th>
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<td>(\pm 0.138)</td>
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<td>(-18.42(04))</td>
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Fig. 1.— $JH$ templates based on 8 Type Ia SNe and $K$-band template based on 6 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 (magenta triangles, pointing left), 1986G (yellow squares), 1998bu (red triangles, pointing up), 1999aw (X’s), 1999ee (blue circles), 2000ca (cyan triangles, pointing right), 2001el (green triangles, pointing down), 2001ba (orange diamonds).

Fig. 2.— Hubble diagrams of Type Ia SNe. We plot the extinction-corrected $J$-, $H$-, and $K$-band maxima versus the logarithm of the redshifts in the CMB frame. The points represented by blue circles have velocities taken from NED. We have added horizontal error bars corresponding to typical peculiar velocity of $\pm 300$ km s$^{-1}$. The points represented by red triangles have “equivalent” CMB velocities derived from direct measures of the distances to the hosts, on the $H_0 = 72$ km s$^{-1}$ 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.

Fig. 3.— Absolute magnitudes of Type Ia SNe at maximum on the $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$ scale. Symbols: blue circles are objects in the Hubble flow ($v \gtrsim 3000$ km s$^{-1}$); red 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.
Time since B-band maximum (days)

Krisciunas et al. Fig. 1
Extinction-corrected apparent magnitude at maximum

Redshift in CMB frame (km/sec)

Krisciunas et al. Fig. 2
Absolute Magnitude

$\Delta m_{15}(B)$

Krisciunas et al. Fig. 3