TESTS OF THE ACCELERATING UNIVERSE WITH NEAR-INFRARED OBSERVATIONS OF A HIGH-REDSHIFT TYPE Ia SUPERNOVA

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ABSTRACT

We have measured the rest-frame B-, V-, and I-band light curves of a high-redshift type Ia supernova (SN Ia), SN 1999Q ($z = 0.46$), using the *Hubble Space Telescope* (*HST*) and ground-based near-infrared detectors. A goal of this study is the measurement of the color excess, E_{B-I}, a sensitive indicator of interstellar or intergalactic dust, which could affect recent cosmological measurements from high-redshift SNe Ia. Our observations disfavor a 30% opacity of SN Ia visual light by dust as an alternative to an accelerating universe. This statement applies to both Galactic-type dust (rejected at the 3.4 σ confidence level) and grayer dust (grain size > 0.1 μm, rejected at the 2.3–2.6 σ confidence level) as proposed by Aguirre. The rest-frame I-band light curve shows the secondary maximum 1 month after the B maximum typical of nearby SNe Ia of normal luminosity, providing no indication of evolution as a function of redshift out to $z \approx 0.5$. An expanded set of similar observations could improve the constraints on any contribution of extragalactic dust to the dimming of high-redshift SNe Ia.

Subject headings: cosmology: observations — distance scale — supernovae: general

1. INTRODUCTION

Recent observations of high-redshift ($z > 0.3$) Type Ia supernovae (SNe Ia) provide the backbone of the body of evidence that we live in an accelerating universe whose content is dominated by vacuum energy (Riess et al. 1998; Perlmutter et al. 1999). The observational evidence for an accelerating universe is that high-z SNe Ia are $\sim 30\%$ dimmer than expected in an open universe (i.e., $\Omega_M = 0.3$, $\Omega_\Lambda = 0$). The two sources most likely to obscure distant SNe Ia and affect interpretation of them are dust and evolution.

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The telltale signature of extinction by Galactic-type dust, reddening, has not been detected in the amount required to provide $A_V = 0.3$ mag for high-z SNe Ia (Riess et al. 1998; Perlmutter et al. 1999). Yet the cosmological implications of the observed faintness of high-z SNe Ia are so exotic as to merit the consideration of dust with more unusual properties. A physical model of dust composed of larger grains (> 0.1 μm) has been posited by Aguirre (1999a, 1999b) to provide a noncosmological source of extinction with less reddening. An *interstellar* component of this so-called gray dust, if neglected, would add too much dispersion to be consistent with the observed luminosities (Riess et al. 1998). However, Aguirre (1999a, 1999b) has shown that a uniformly distributed component of *intergalactic* gray dust with a mass density of $\Omega_{dust} \approx 5 \times 10^{-5}$ could explain the faintness of high-z SNe Ia without detectable reddening and without overproducing the far-infrared (far-IR) background. Previous data do not rule out this possibility. Indeed, significant interstellar extinction in the hosts of high-z SNe Ia is still favored by some (Totani & Kobayashi 1999).

Rest-frame evolution is the other potential pitfall in using high-z SNe Ia to measure the cosmological parameters. The lack of a complete theoretical model of SNe Ia including the identification of their progenitor systems makes it difficult to access the expected evolution between $z = 0$ and 0.5 (Livio 1999; Umeda et al. 1999; Höflich, Wheeler, & Thielemann 1998). An impressive degree of similarity has been observed between the spectral and photometric properties of nearby and high-z SNe Ia (Schmidt et al. 1998; Perlmutter et al. 1998, 1999; Riess et al. 1998; A. V. Filippenko et al., in preparation; but see also Riess et al. 1999a; Drell, Loredo, & Wassermann 2000). However, it is not known what kind or degree of change in the observable properties of SNe Ia would indicate a change in the expected peak luminosity by 30%. For that reason, it has been necessary to compare a wide range of observable characteristics of

nearby and high-z SNe Ia to search for a complement to luminosity evolution.

Near-IR observations of high-z SNe Ia can provide constraints on both sources of cosmological contamination. A physical model of gray intergalactic dust, such as that proposed by Aguirre (1999a, 1999b), still induces some reddening of SN light, which can be detected in the wavelength range between optical and near-IR light. In addition, near-IR observations provide a view of the behavior of high-redshift SNe Ia in a window previously unexplored. Specifically, normal, nearby SNe Ia exhibit a second infrared maximum about a month after the initial peak. We can increase our confidence that high-z SNe Ia have not evolved by observing this second maximum; its absence would indicate a change in the physics of SNe Ia across redshift, with potentially important cosmological consequences.

We obtained ground-based J-band and space-based optical observations of SN 1999Q ($z = 0.46$) to initiate a study of the systematic effects of dust and evolution on high-z SNe Ia. In § 2 we describe our observations, in § 3 we give an analysis, and in § 4 we interpret them.

2. OBSERVATIONS

Our High-z Supernova Search Team (HZT) has an ongoing program to discover and monitor high-redshift SNe Ia (Schmidt et al. 1998). SN 1999Q was discovered on 1999 January 18, using the CTIO 4 m Blanco Telescope with the Bernstein-Tyson Camera[15] as part of a three-night program to search for high-z SNe Ia using well-established methods. High signal-to-noise ratio spectra of SN 1999Q obtained with the Keck II telescope indicated that this was a typical SN Ia at $z = 0.46$ shortly before B-band maximum (Garnavich et al. 1999; A. V. Filippenko et al., in preparation). Rest-frame B- and V-band photometry using custom filters was obtained for SN 1999Q from observatories around the world. The *Hubble Space Telescope* (*HST*) monitored the B and V light curves of SN 1999Q from ~ 10 to 35 days after B maximum (rest-frame) using the WFPC2 and the F675W and F814W filters in the course of six epochs. Combined, these data provide excellent coverage of the rest-frame B and V light curves from a few days before to 60 days after B maximum (in the rest frame; A. Clocchiatti et al., in preparation).

In addition, the SN was observed in the near-IR (J-band) for five epochs between 5 and 45 days after B maximum (in the rest frame). The first observation employed the European Southern Observatory's 3.5 m New Technology Telescope equipped with the Son of Isaac (SOFI) infrared camera spectrograph;[16] subsequent observations used the Keck II Telescope, equipped with the Near-Infrared Camera (NIRC; Matthews & Soifer 1994). Because of the high sky brightness in the IR, many dithered, short images were obtained and combined to avoid saturating the detector. Care was taken to maintain a detected sky flux level of $\sim 10,000$ counts, a regime in which both SOFI and NIRC exhibit less than 0.5% nonlinearity.[17]

Using the procedure described by Garnavich et al. (1998), we subtracted an empirical point-spread function (PSF)

scaled to the brightness of the SN from each *HST* observation. A coadded image of total length 7200 s in both F675W and F814W revealed no trace of host galaxy light to more than 5 mag below the peak brightness of the supernova (i.e., $m_B, m_V > 27$). The host of SN 1999Q is likely to be intrinsically faint or of very low surface brightness, similar to the host of SN 1997ck (Garnavich et al. 1998). Because of the negligible contribution of host galaxy light to the images, we have made no correction for contamination to the measured supernova light. Assuming that the rest-frame $V - I$ color of the host galaxy is no redder than that of early K-type dwarfs ($V - I = 1.0$ for K0), this same practice is well justified for our measurements of SN light in the J band. We conservatively adopt a systematic uncertainty of 0.03 mag in the SN photometry (and 0.02 mag uncertainty in the colors) to account for any remaining bias. The procedure described by Schmidt et al. (1998), Garnavich et al. (1998), and Riess et al. (1998) was followed to calibrate the measured magnitudes of SN 1999Q on the Johnson B and V passband system.

Similar steps were performed to calibrate the observed J-band magnitudes of SN 1999Q onto the rest-frame Cousins I-band system, although a few exceptions are noted here. On three photometric nights, we observed the secondary near-IR standards of Persson et al. (1998). Because these secondary standards are solar analogues ($0.4 < B - V < 0.8$), one can transform these stars from the " Persson system " to that of NIRC or SOFI by calculating the photometric difference of the spectrophotometry of the Sun between these systems. We found these differences to be quite small (< 0.02 mag), and this correction negligible. In practice, the true transmission curve in J is dictated by the natural opacity of atmospheric H_2O, and nightly variations are generally larger than differences between different facility J-passbands. For this reason, we observed secondary standards in close temporal proximity to the SN field.

Because of the inherent nonlinearity of air-mass extinction corrections in J, the field of SN 1999Q was observed at air masses within 0.05 of the Persson et al. (1998) standards to avoid the need for air-mass corrections. Assuming a typical J-band extinction of 0.1 mag per air mass (Krisciunas et al. 1987), errors of ~ 0.005 mag are introduced without explicit extinction corrections.

Cross-band K-corrections (Kim, Goobar, & Perlmutter 1996) were calculated using spectrophotometry of SN 1994D (which extend redward of 9100 Å; Richmond et al. 1995) to transform the J-band magnitudes of SN 1999Q to the Cousins I-band. At the redshift of SN 1999Q ($z = 0.46$), the observed J-band light is an excellent match to rest-frame Cousins I, and the K-correction was determined to be -0.93 ± 0.02 mag, with no apparent dependence on supernova phase or color. The rest-frame I photometry of SN 1999Q is given in Table 1.

Of fundamental importance is our ability to correctly transform the observed J-band photometry to rest-frame I-band. Schmidt et al. (1998) discuss the derivations of optical zero points from numerous spectrophotometric stars that also have $UBVRI$ photometry. Applying the same spectrophotometry to cross-band K-corrections removes the dependence of the transformed photometry on the observed band's zero point. Unfortunately, this type of data is not available for the J-band. We have therefore calibrated our J-band data using Persson et al. standards, which are fundamentally tied to the Elias (1982) standards,

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[15] Information on the Bernstein-Tyson Camera can be found at: http://www.astro.lsa.umich.edu/btc/btc.html.

[16] See ESO's page at: http://www.ls.eso.org.

[17] For more information, see: http://www.ls.eso.org and http://www.keck.hawaii.edu.

TABLE 1
REST-FRAME PHOTOMETRY OF SN 1999Q

JD (2451000+)	Age[a] (days)	I (mag)	$B-I$[b] (mag)
204.2	+6.2	23.93 (0.14)	−0.62 (0.15)
216.4	+14.5	23.95 (0.17)	0.11 (0.18)
239.3	+30.2	24.35 (0.14)	1.30 (0.15)
243.3	+32.9	24.16 (0.14)	1.66 (0.15)
261.3	+45.3	24.59 (0.19)	1.65 (0.20)

[a] Rest-frame age relative to B maximum.
[b] B magnitude fit from HST photometry.

and we adopt an appropriate J-band zero-point uncertainty of 1 σ = 0.05 mag.

3. ANALYSIS

3.1. Second IR Maximum

A unique photometric signature of typical SNe Ia is a resurrection of the luminosity at infrared wavelengths about a month after the initial maximum. This feature is present (with the most exquisite photometry) in the V band, grows into a "shoulder" in R, and increases to a second local maximum in I (Ford et al. 1993; Suntzeff 1996; Hamuy et al. 1996a; Riess et al. 1999b). This second maximum is also readily apparent at near-IR wavelengths (J, H, and K; Elias et al. 1981; Jha et al. 1999). No other type of SN exhibits this feature.

The secondary maximum is thought to result from the escape of radiation from the core of the supernova at long wavelengths. Resonant scattering from lines is the dominant source of opacity. At short wavelengths (i.e., < 5000 Å), line blanketing traps radiation; the resonance lines at longer wavelengths are fewer and farther between, providing escape routes for the trapped radiation (Spyromilio, Pinto, & Eastman 1994). Wheeler et al. (1998) argue that this effect in itself would not explain the nonmonotic behavior of the J-band light curve. No model as yet fully explains the shape and timing of the infrared light curves of SNe.

The location and strength of the second I-band maximum is a diagnostic of the intrinsic luminosity of SNe Ia (Riess, Press, & Kirshner 1996; Hamuy et al. 1996b). SNe Ia with typical peak luminosity (i.e., $M_V = -19.4$ mag) crest again in I about 30 days after B maximum. Dimmer SNe Ia reach their second peak earlier. For example, SN 1992bo was ~0.5 mag fainter than a typical SN Ia and reached its second peak in I ~20 days after B maximum (Maza et al. 1994). For very subluminous SNe Ia, this second maximum is completely absent, merging into the phase of the initial decline (e.g., SN 1991bg; Filippenko et al. 1992). The physics detailing the formation of this feature also indicates that its magnitude and timing are sensitive to explosion parameters (e.g., ejecta composition) that determine the peak luminosity (Spyromilio et al. 1994).

In Figure 1, the relative rest-frame I-band magnitudes of SN 1999Q ($z = 0.46$) are compared to a luminosity sequence of nearby SNe Ia. The phase of the observations of
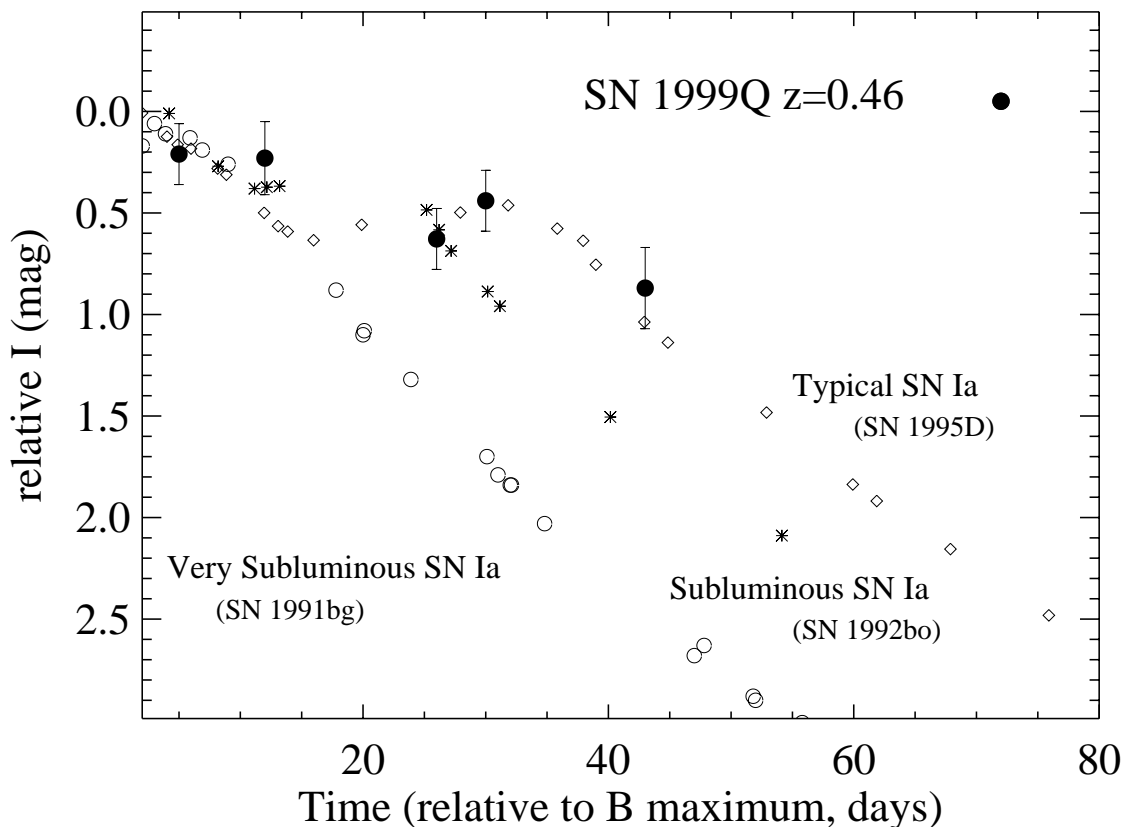

FIG. 1.—Relative rest-frame I-band light curve of a high-z SN Ia, SN 1999Q ($z = 0.46$), and a sequence of three nearby SNe Ia with different light-curve shapes and peak luminosities. The light curve of SN 1999Q is consistent with that of typical nearby SNe Ia, which reach their second maxima ~30 days after B maximum (e.g., SN 1995D, *open diamonds*, from Riess et al. 1999b). The data are inconsistent with SNe Ia that are subluminous at visual peak by ~0.5 mag and reach the second maximum ~20 days after B maximum (e.g., SN 1992bo, *asterisks*, from Maza et al. 1994). SN 1999Q bares no resemblance to the rapid decline (without a second maximum) of very subluminous SNe Ia (e.g., SN 1991bg, *open circles*, from Filippenko et al. 1992).

SN 1999Q was determined by multicolor light-curve shape (MLCS; Riess et al. 1996, 1998) fits to the B and V light curves and have an uncertainty (1 σ) of less than 2 days. The observation times were also corrected for $1 + z$ time dilation (Leibundgut et al. 1996; Goldhaber et al. 1997; Riess et al. 1997). Although the precision and sampling of the rest-frame I-band data are not high, they are sufficient to indicate that this high-z SN Ia retains significant luminosity ~ 30 days after B maximum, consistent with the phase of the second I-band peak of typical SNe Ia and inconsistent with either very subluminous or moderately subluminous SNe Ia. Using the B and V light-curve shapes of SN 1999Q as a luminosity indicator, we find its distance modulus to be $\mu_0 = 42.67 \pm 0.22$ mag, consistent with previous SNe Ia favoring a cosmological constant (Riess et al. 1998). If instead we consider the shape of the I-band light curve as an independent luminosity indicator, we find that this high-z SN Ia (and presumably other high-z SNe Ia) is not consistent with being subluminous by 0.5–0.6 mag, as needed to indicate a universe closed by ordinary matter. More precise data will be needed to differentiate between an open and a Λ-dominated universe solely on the basis of I-band light-curve shapes.

3.2. IR Color Excess

To measure the $B - I$ colors of SN 1999Q, we used the MLCS fits to the B light curve to determine the expected B magnitudes at the time of the IR observations. Because of the exquisite HST photometry in rest-frame B, this process adds little uncertainty to the $B - I$ magnitudes.

The Milky Way (MW) dust maps from Schlegel, Finkbeiner, & Davis (1998) predict a reddening of $E_{B-V} = 0.021$ mag in the direction of SN 1999Q. We subtracted the expected Galactic reddening of the rest-frame $B - I$ light (observed as $R - J$) of SN 1999Q, 0.037 mag, from the measured colors. Any remaining reddening results from extragalactic sources.

In Figure 2 the measured $B - I$ magnitudes of SN 1999Q are compared to a custom $B - I$ curve predicted from the MLCS fits to the B and V light-curve shapes (Riess et al. 1996, 1998). The smaller uncertainties shown here result from photon statistics and were determined empirically (Schmidt et al. 1998). A significant additional source of uncertainty is the intrinsic dispersion of SNe Ia $B - I$ colors around their custom MLCS model. This intrinsic dispersion is determined empirically by measuring the variance of 30 nearby SNe Ia around their MLCS fits (Riess et al. 1996, 1998) and varies from 0.1 to 0.3 mag depending on the SN Ia age. Although the observed residuals from the model prediction are correlated for time separations of less than 3 days, correlated errors are insignificant for the larger differences in time between the observations of SN 1999Q. The larger uncertainties shown in Figure 2 for the $B - I$ photometry of SN 1999Q include the intrinsic uncertainties.

The measured E_{B-I} for SN 1999Q is -0.09 ± 0.10 mag. The error includes the systematic uncertainties of the K-corrections and the zero point of the J-band system, although the dominant sources of error are the photometry noise and the intrinsic dispersion in SN Ia $B - I$ colors. This value is consistent with no reddening of this high-z SN Ia. If Galactic-type dust rather than a cosmological constant were the sole reason that $z \approx 0.5$ SNe Ia are 30% fainter than expected for an open universe (i.e., $\Omega_M = 0.3$, $\Omega_\Lambda = 0.0$), then the E_{B-I} of SN 1999Q should be 0.25 mag
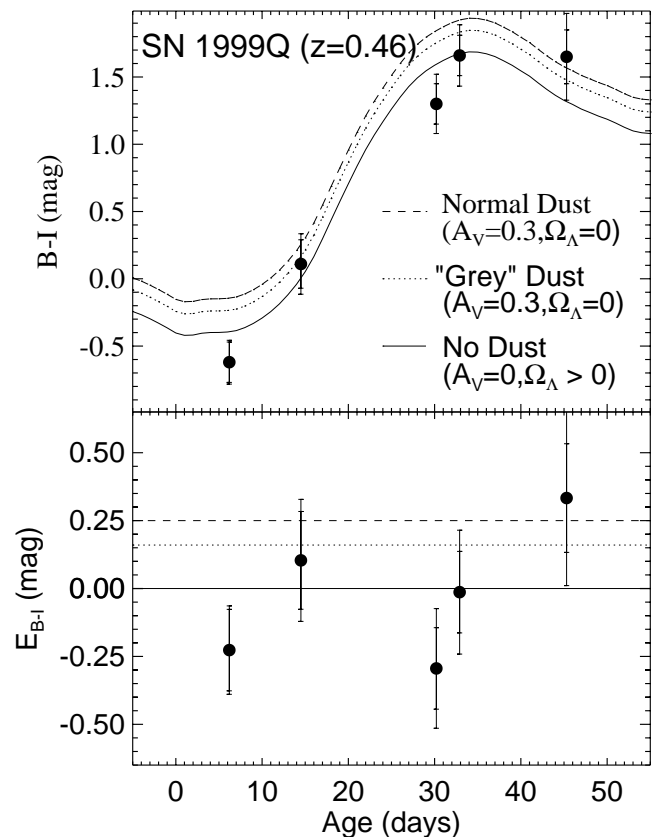

FIG. 2.—Color evolution, $B - I$, and color excess, E_{B-I}, of a high-z SN Ia, SN 1999Q, compared to the custom MLCS template curve with no dust and enough dust (either Galactic type or grayer) to nullify the cosmological constant. The smaller error bars are from photometry noise; the larger error bars include all sources of uncertainty, such as intrinsic dispersion of SN Ia $B - I$ color, K-corrections, and photometry zero points. The data for SN 1999Q are consistent with no reddening by dust, moderately inconsistent with $A_V = 0.3$ mag of gray dust (i.e., graphite dust with minimum size > 0.1 μm; Aguirre 1999a, 1999b) and $A_V = 0.3$ mag of Galactic-type dust (Savage & Mathis 1979).

(Savage & Mathis 1979). This alternative to an accelerating universe (see Totani & Kobayashi 1999) is inconsistent with the data at the 99.9% confidence level (3.4 σ). The reddening required for the SNe Ia data to be consistent with a universe closed by matter is ruled out at the $> 99.99\%$ (5.1 σ) confidence level. Despite the low precision of this data set, the wavelength range of the $B - I$ colors allows us to rule out extinction by Galactic-type dust from SN 1999Q alone with as much confidence as we can from the entire set of $B - V$ color data of Riess et al. (1998) and Perlmutter et al. (1999).

The reduced amount of reddening by "gray" dust grains (i.e., > 0.1 μm), as proposed by Aguirre (1999a, 1999b), is more difficult to detect. The amount of gray dust needed to supplant the cosmological constant as the cause of the dimming of high-z SNe Ia would result in an $E_{B-I} = 0.17$ or 0.14 mag for a composition of graphite or graphite/silicate, respectively (Aguirre 1999a, 1999b). These possibilities are moderately inconsistent with the data at the 99.0% (2.6 σ) and 97.7% (2.3 σ) confidence levels, respectively. The reddening provided by enough of such dust to change the cosmological forecast to favor a universe closed by matter is ruled out at the 99.97% (3.7 σ) and 99.90% (3.3 σ) confidence levels, respectively. The weakest constraint comes from assuming the smallest amount of the grayest type of dust, which is consistent at the 68% (1 σ) confidence level

with an open universe (i.e., $A_V = 0.2$ mag). This dust is inconsistent with the data at the 94% (1.9 σ) confidence level (although the true inconsistency of this scenario is derived from the product of the two individual likelihoods, i.e., 98% or 2.3 σ). Although these results disfavor the existence of the proposed levels of gray dust, more data are needed to strengthen this important test.

Because it is difficult to assess all sources of uncertainty in our model for the SN Ia $B-I$ color evolution, we also performed a Monte Carlo simulation of the measurement of E_{B-I} for SN 1999Q. Using all nearby SNe Ia that are not spectroscopically peculiar (see Branch, Fisher, & Nugent 1993) or photometrically extreme [$0.9 < \Delta m(B)_{15} < 1.6$; Phillips 1993)] and whose $B-I$ colors were well observed, we generated a standard, unreddened $B-I$ template curve using individual reddening estimates from Phillips et al. (1999) and Schlegel et al. (1998) for nearby SNe Ia. We then randomly selected five observations from a random member of the sample and perturbed the observations to match the photometric noise in the SN 1999Q observations. From 10,000 such synthetic measurements we generated a distribution of measured E_{B-I} whose shape should match the probability density function for the single E_{B-I} measurement of SN 1999Q. Compared to the $B-I$ template curve, SN 1999Q has an $E_{B-I} = -0.12$ mag. The distribution of synthetic E_{B-I} values is asymmetric and implies an uncertainty in the measurement for SN 1999Q of $+1 \ \sigma = 0.11$ mag and $-1 \ \sigma = 0.17$ mag (including the systematic uncertainties from K-corrections and the J-band zero point). The results are consistent with no extragalactic reddening and inconsistent with Galactic and gray dust reddening at nearly identical (although marginally higher) confidence levels as the MLCS fits. The strength of this method is that it samples real SN Ia data in the same manner as the observations of SN 1999Q and therefore incorporates the intrinsic and correlated uncertainties in the $B-I$ colors of SNe Ia.

4. DISCUSSION

Two teams have independently concluded that the observed faintness of high-z SNe Ia indicates that the expansion of the universe is accelerating and that dark energy dominates the energy density of the universe (Riess et al. 1998; Perlmutter et al. 1999). However, as a well-known adage reminds us, "extraordinary claims require extraordinary evidence." Alternative explanations, such as evolution in supernova luminosities or dust, are no more exotic than a cosmological constant and must be rigorously tested.

4.1. Dust

A $\sim 30\%$ opacity of visual light by dust is the best quantified and therefore most readily testable alternative to a cosmological constant (Aguirre 1999a, 1999b; Totani & Kobayashi 1999). Measurements of $B-V$ colors indicate that this quantity of Galactic-type dust is not obscuring high-z SNe Ia (Riess et al. 1998; Perlmutter et al. 1999), and the $B-I$ observations presented here bolster this evidence. However, observations of neither SNe Ia nor other astrophysical objects previously ruled out a similar opacity by intergalactic gray dust (Aguirre 1999a, 1999b). The observations presented here do disfavor a gray intergalactic medium providing this opacity, but additional data are needed to strengthen these conclusions. Indeed, a more

precise measurement of E_{B-I} or E_{U-I} could either constrain the total optical depth of dust in the intergalactic medium or, alternately, push the minimum size of such grains into an unphysical domain (Aguirre 1999a, 1999b). It may even be possible to use such measurements to constrain the contribution to the far-IR background by emission from the intergalactic medium (Aguirre 1999a, 1999b). Measurements of gravitational lens systems have also been used as a probe of the high-z extinction law and disfavor significant interstellar gray dust (Falco et al. 1999; McLeod 1999, except in molecular clouds).

4.2. Evolution

To date, our inability to formulate a complete theoretical description of SNe Ia makes it impossible to either predict the degree of expected luminosity evolution between $z = 0$ and 0.5 or identify an observation that would conclusively determine whether the luminosity of SNe Ia are evolving (but see Hoeflich et al. 1998). An empirical recourse is to compare all observable properties of nearby and high-z SNe Ia with the assumption that if the luminosity of a SN Ia has evolved by $\sim 30\%$, other altered characteristics of the explosion would be visible as well. The detection of such a change would cast doubt on the reliability of the luminosity distances from high-z SNe Ia. A continued failure to measure any difference between SNe Ia near and far would increase our confidence (although never prove) that evolution does not contaminate the cosmological measurements from high-z SNe Ia.

Having clearly stated our approach, it is now appropriate to review the current status of the ongoing efforts to determine whether SNe Ia are evolving.

Comparisons of high signal-to-noise ratio spectra of nearby and high-z SNe Ia have revealed remarkable similarity (Riess et al. 1998; Perlmutter et al. 1998, 1999; A. V. Filippenko et al., in preparation). Because the spectrum provides a detailed record of the conditions of the supernova in the atmosphere (i.e., temperature, abundances, and ejecta velocities), spectral comparisons are expected to be particularly meaningful probes of evolution. Furthermore, comparisons of time sequences of spectra reveal no apparent differences as the photosphere recedes in mass (A. V. Filippenko et al., in preparation), indicating that the striking resemblance between distant and nearby SNe Ia is not merely superficial, but endures at deeper layers. However, these comparisons still require the rigor of a quantitative approach to determine whether or not the two samples are statistically consistent. The distributions of light-curve shapes at high and low redshift are statistically consistent (Riess et al. 1998; Perlmutter et al. 1999). However, Drell et al. (2000) have noted that different approaches to quantifying the shape of the light curves may not be statistically consistent, so more attention needs to be focused on these light-curve shape comparisons.

The colors of prenebular supernovae should provide a useful probe of luminosity evolution, indicating changes in the approximate temperature and hence the thermal output of the explosion. The $B-V$ colors of nearby and high-z SNe Ia were found to be consistent by Perlmutter et al. (1999). The same consistency was found here for the $B-I$ colors. However, neither this work nor the $B-V$ color measurements by Riess et al. (1998) can rule out the possibility that high-z SNe Ia could be excessively blue (Falco et al. 1999); more data are needed to explore this possibility.

The time interval between explosion and maximum light (i.e., the rise time) is expected to be a useful probe of the ejecta opacity and the distribution of ^{56}Ni . The initial comparison of the rise times of nearby (Riess et al. 1999c) and high-z SNe Ia (Goldhaber 1998; Groom 1998) did not appear to be consistent (Riess et al. 1999a). Further analysis of the Supernova Cosmology Project (SCP) high-redshift data by Aldering, Nugent, & Knop (2000), however, concludes that the uncertainty in the high-z rise time found by Goldhaber (1998) and Groom (1998) was substantially underestimated and that the remaining difference in the rise time could be no more than a $\sim 2.0\,\sigma$ chance occurrence.

The weight of the evidence suggests no significant evolution of the observed SNe Ia, but more observations are needed to allay remaining reasonable doubts. Perhaps the best indication that SNe Ia provide reliable distances at high redshifts comes from SNe Ia in nearby early-type and late-type galaxies. These galaxies span a larger range of metallicity, stellar age, and interstellar environments than is expected to occur for galaxies back to $z = 0.5$. Yet after correction for the light-curve shape/luminosity relationship and extinction, no significant Hubble diagram residuals are seen that correlate with host galaxy morphology. This suggests that our distance estimates are insensitive to variations in the supernova progenitor environment (Schmidt et al. 1998). However, the evidence remains circumstantial and does not rule out the possibility that a characteristic of all progenitors of nearby SNe Ia differs for high-z SNe Ia.

Further observations, especially those in the near-IR bands, should be able to better constrain the potential contamination of the cosmological conclusions from SNe Ia posed by dust and evolution. Furthermore, rest-frame I band measurements of nearby SNe Ia show less dispersion in intrinsic luminosity and extinction, making this an attractive band for future observations (Hamuy et al. 1996b). Measurements of SNe Ia at $z > 1$ should even discriminate between the effects of a cosmological constant and those of monotonically increasing, but unidentified systematic errors (Filippenko & Riess 1999). Continuing studies of high-z SNe Ia should ultimately provide the extraordinary evidence required to accept (or refute) the accelerating universe.

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