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# IS THERE AN INDICATION OF EVOLUTION OF TYPE Ia SUPERNOVAE FROM THEIR RISE TIMES?

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## ABSTRACT

We have compared the rise time for samples of nearby and high-redshift Type Ia supernovae (SNe Ia). The fiducial rise time of the nearby SNe Ia is 2.5 ± 0.4 days longer than the preliminary measurement of the rise time in 1998 by Goldhaber and by Groom for high-redshift SNe Ia from the Supernova Cosmology Project. If further analysis of the high-redshift data does not lead to a significant change in the value or uncertainty in the rise time, then the statistical likelihood that the two samples have different fiducial rise times remains high (5.8 $\sigma$) and indicates possible evolution between the samples of SNe Ia. We consider the likely effects of several sources of systematic error, but none of these resolves the difference in the rise times. Currently, we cannot directly determine the impact of the apparent evolution on previous determinations of cosmological parameters.

*Key words:* cosmology: observations — supernovae: general

## 1. INTRODUCTION

High redshift ($0.3 < z < 1.0$) Type Ia supernovae (SNe Ia) are unexpectedly dim, a phenomenon readily attributed to a cosmological constant and an accelerating universe (Riess et al. 1998; Perlmutter et al. 1999). These cosmological conclusions rely on the *assumption* that SNe Ia have not evolved. Both the High-$z$ Supernova Search team (Schmidt et al. 1998) and the Supernova Cosmology Project (SCP; Perlmutter et al. 1997) have found no indication from spectra, light curves, and various subsamples that SNe Ia have evolved between $z = 0$ and $z = 0.5$ (Riess et al. 1998; Perlmutter et al. 1999); this evidence will be considered in § 4. However, an unexpected luminosity evolution of ∼25% over a look-back time of approximately 5 Gyr would be sufficient to nullify the cosmological conclusions. Evolution is a notorious foe, plaguing previous measurements of the global deceleration parameter using brightest cluster galaxies (e.g., Sandage & Hardy 1973). While we cannot hope to *prove* that the samples of SNe Ia have not evolved, we would increase our confidence in their reliability by adding to the list of ways in which they are similar, while failing to discern any way in which they are different.

An important probe into supernova physics and possibly evolution is the rapid rise in luminosity of SNe Ia shortly after explosion. A wellspring of energy from birth, an expanding supernova releases ever dwindling resources of trapped energy from the radioactive decay of $^{56}$Ni and $^{56}$Co. The rise time (i.e., the time interval between explosion and peak) is dictated by the amount and location of synthesized $^{56}$Ni and the opacity of the intervening layers (Leibundgut & Pinto 1992; Nugent et al. 1995; Vacca & Leibundgut 1996).

Theoretical modeling indicates that expected variations in the composition of SN Ia progenitors at high redshift could be accompanied by an evolution in luminosity not accounted for by current empirical distance techniques (Höflich, Wheeler, & Thielemann 1998). One predicted signature of this evolution is an alteration of the rise time.

A preliminary measurement of the rise time using a large set of prediscovery images of high-redshift ($z \approx 0.5$) SNe Ia from the SCP was presented by Goldhaber (1998a, 1998b) and Groom (1998). Although the early SN Ia light is not strongly detected for individual objects, the statistics of ∼40 different SNe Ia have been used to meaningfully measure the fiducial rise time. The final results from this measurement will be presented by Goldhaber et al. (2000).

We have previously determined the rise time of nearby SNe Ia using a set of discovery and prediscovery images from a mix of amateur and professional supernova searches (Riess et al. 1999). A comparison of the high-redshift and low-redshift rise behavior (§ 2) should provide a valuable test of evolution. We discuss systematic errors that could bias this comparison in § 3 and the implications in § 4.

## 2. ANALYSIS

Details concerning the acquisition and photometric calibration of very early observations of nearby SNe Ia can be found in Riess et al. (1999). These observations include ∼25 new measurements of SNe Ia between 10 and 18 days before $B$ maximum. The final analysis of the high-redshift data set and the details of the SCP's methods of analysis will be presented in Goldhaber et al. (2000).

It is clear from the observations of nearby SNe Ia that there is considerable inhomogeneity in the rise times of SNe Ia (Riess et al. 1999). However, individual SN Ia rise times are well correlated with the postrise light-curve shape (Goldhaber 1998a, 1998b). Therefore, one can determine both a fiducial rise time and the correlation between the rise time and the postrise light-curve shape. Riess et al. (1999) explored multiple techniques to quantify the fiducial SN Ia rise time, all with consistent results.

To reliably compare the fiducial rise times, it is essential to apply the *same method* of analysis to the high-redshift and low-redshift SN Ia data sets. For this reason, we emulated the stated methodology of Goldhaber (1998a, 1998b) and Groom (1998) in analyzing the low-redshift data.

We used the "stretch" method (Perlmutter et al. 1997) to normalize the $B$-band light curves of 10 nearby SNe Ia from Riess et al. (1999), using the same fiducial template—a modified Leibundgut (1989) template—employed by Goldhaber (1998a, 1998b) and Groom (1998). (This template is very similar to the Leibundgut [1989] template.) We

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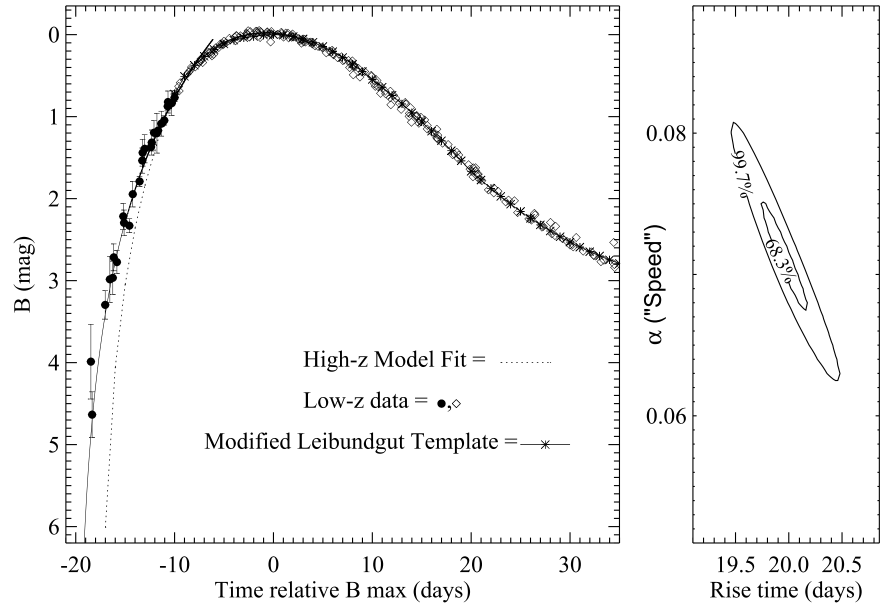

FIG. 1.—*B*-band data of nearby SNe Ia normalized by the "stretch" method to the same modified Leibundgut (1989) template used to normalize the high-redshift SNe Ia (Goldhaber 1998a, 1998b) and the inferred rise-time parameters. The observation times of the individual SNe Ia are dilated to provide the best fit of the postrise (i.e., after 10 days before maximum) data (*diamonds*) to the modified Leibundgut (1989) template (*asterisks*). Fitting a quadratic rise model to the nearby rise data (*filled circles*) yields confidence intervals for the fiducial speed and rise time to *B* maximum. The preliminary best fit of the same model to the high-redshift data is shown as a dashed line. The best estimate of rise time of nearby SNe Ia is 19.98 ± 0.15 days, significantly longer and statistically inconsistent with the preliminary measurement of the rise time of high-redshift SNe Ia of 17.5 ± 0.4 days (Goldhaber 1998a, 1998b).

performed this normalization using only observations later than 10 days before maximum. To emulate the lack of significant measurements of high-redshift SNe Ia at late times, we discarded observations past 35 days after *B* maximum. The normalization parameters were then applied to the rise data (i.e., the observations earlier than 10 days before *B* maximum). As noted by Riess et al. (1999), this process results in an impressive decrease in the dispersion of the rise data from different SNe Ia.

After normalization, we fitted the same empirical model proposed by Goldhaber (1998a, 1998b) and Groom (1998) to the rise data. This model is motivated by the description of a young SN Ia as a homologously expanding fireball whose initial luminosity is most sensitive to its changing radius (and relatively insensitive to the fractionally smaller changes in photospheric velocity and temperature). The luminosity is

$$L = \alpha(t + t_r)^2 , \tag{1}$$

where $t$ is the time elapsed relative to maximum, $t_r$ is the rise time, and $\alpha$ is the "speed" of the rise.

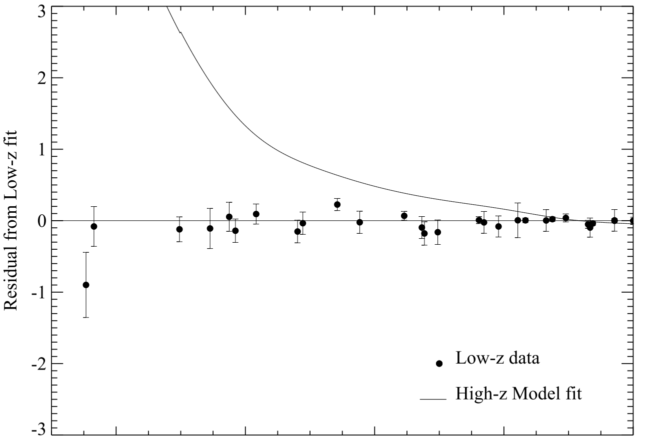

FIG. 2.—Residuals from the best fit rise model of the nearby SNe Ia. Individual observations of nearby SNe Ia are shown as filled circles, and the preliminary best model fit to the high-redshift data is shown as a solid line.

The two free parameters, $t_r$ and $\alpha$, were determined by finding the best match between the model and data, i.e., when the standard $\chi^2$ statistic is minimized. The minimum $\chi^2_\nu$ was 0.82, indicating a good concordance between model and data. This fit and confidence intervals of the parameters are shown in Figure 1. Like Goldhaber (1998a, 1998b) and Groom (1998), we identified the time of maximum as the time when the SCP template reaches its brightest magnitude. (Uncertainties in determining the fiducial time of maximum do not affect a consistent comparison.) The resulting parameters from this fit were $t_r = 19.98 \pm 0.15$ days and $\alpha = 0.071 \pm 0.005$. Because the SCP template is a good match to the Leibundgut (1989) template, it is not surprising that this rise time is quite similar to the value found by Riess et al. (1999) using the Leibundgut template as the fiducial template. Besides the 29 detections of SNe Ia between explosion and 10 days before maximum (relative to the SCP template), Riess et al. (1999) also provide four nondetection limits of SNe Ia in the temporal vicinity of explosion. Unfortunately, these nondetections provide negligible additional constraints; in all cases they are more than 3 mag above the expected luminosity of the SNe Ia (based on the fit to the detections).

As seen in Figure 1, the postrise low-redshift data are well fitted by the same modified Leibundgut (1989) template used to normalize the high-redshift data, verifying that the two data sets have indeed been normalized to the same light-curve shape. The light curve shown for the high-redshift SNe Ia prior to 10 days before maximum is the best fit of equation (1) to the preliminary SCP data (Goldhaber 1998a, 1998b). This model fit clearly departs from the low-redshift data as seen in the residuals from the fit to the nearby rise in Figure 2. By 13.8 days before maximum, the difference is 0.5 mag. At 15.5 days before maximum, the difference rises to 1 mag.

The low-redshift rise time of 19.98 ± 0.15 days is significantly longer than the preliminary measurement of the rise time of 17.50 ± 0.40 days found for high-redshift SNe Ia from the SCP (Goldhaber 1998a, 1998b; Goldhaber et al. 2000 will present final results). The statistical likelihood that these rise-time measurements are discrepant is greater than 99.99% (5.8 $\sigma$).

## 3. BIASES AND SYSTEMATIC ERRORS

### 3.1. *Low Redshift*

Most of the earliest observations of nearby SNe Ia were recorded with unfiltered CCDs and transformed to the *B* band. Riess et al. (1999) described in detail a number of systematic tests they performed to appraise the influence of the transformation process on the estimate of the fiducial rise time. Employing different methods to calibrate the observations onto the standard passband system had little effect on the inferred rise time. In addition, the rise time was found to be insensitive to the shape or color of the young SN Ia spectral energy distribution. A comparison between transformed magnitudes and coeval magnitude measurements observed through standard passbands shows excellent agreement with no evidence for systematic departures.

However, the discrepancy between the low-redshift and high-redshift rise times is independent of *any* systematic uncertainties in the transformation of unfiltered CCD observations to a standard passband. The reason is that the two earliest (in the "dilated" time frame of the SCP template) unfiltered SN Ia detections, SN 1998bu and SN 1997bq, were recorded nearly one full day *before* the explosion time inferred from the SCP data (see Fig. 3). Moreover, it is not possible to detect SNe Ia outside the Local Group of galaxies less than ~0.5 days after explosion with small-aperture telescopes (in this case the Beijing Astronomical Observatory and the amateur telescope of C. Faranda). Therefore, we conclude that the fiducial rise time of the low-redshift SNe Ia must be *at least* 1.5 days longer than the preliminary rise-time measurement inferred by Goldhaber (1998a, 1998b) and Groom (1998) for the high-redshift SNe Ia, independent of the reliability of photometric transformations described in Riess et al. (1999). This difference alone is significant at the 99.99% (3.8 $\sigma$) confidence level.

Riess et al. (1999) discussed the possibility that an intrinsic dispersion in rise time (for a given light-curve shape) can lead to the preferential inclusion of slowly rising SNe in our nearby sample and a bias in the inferred rise time. Although the best fit $\chi_\nu^2$ does not support additional intrinsic dispersion, Riess et al. (1999) considered a subsample of SNe Ia whose membership is independent of the rise. From the unbiased set, we infer a rise time of 20.42 ± 0.34 days, inconsistent with the SCP preliminary measurement of the rise time at the 99.99% (5.6 $\sigma$) confidence level.

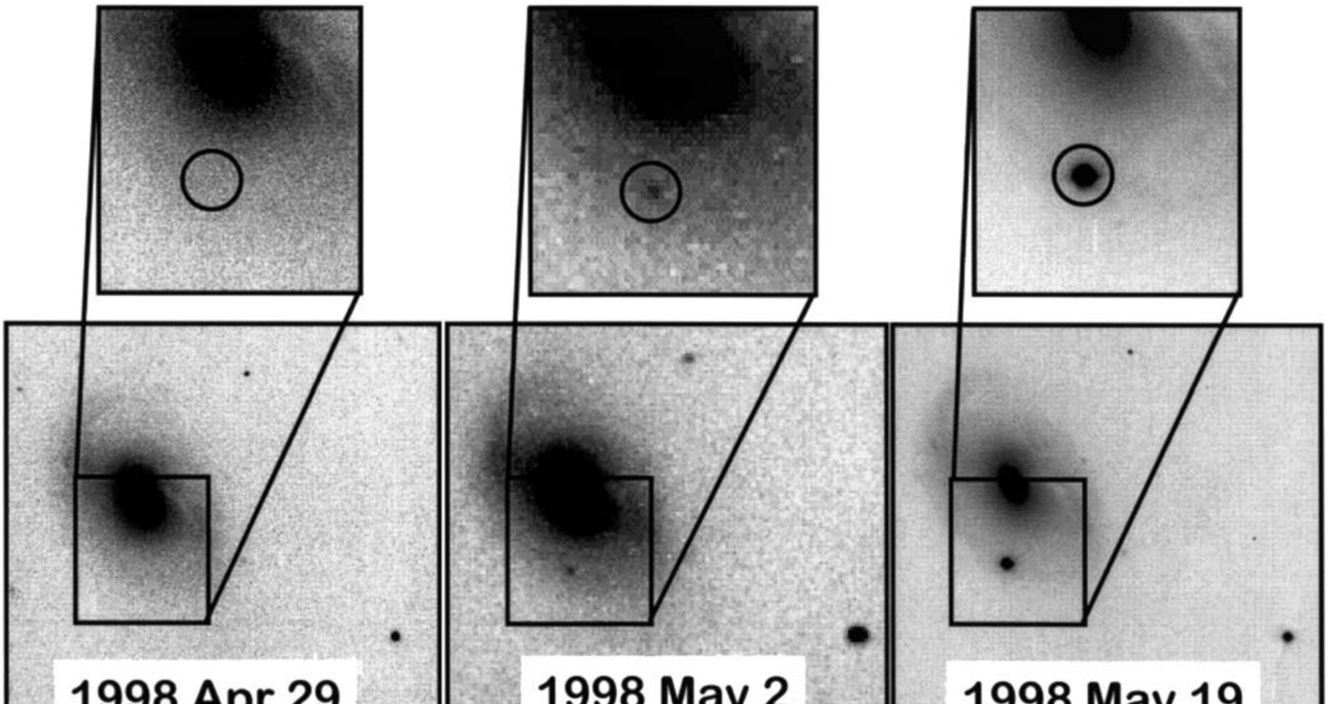

FIG. 3.—Preexplosion, postexplosion, and maximum-light observations of SN 1998bu. After dilating to match the modified Leibundgut template, the detection by Faranda of SN 1998bu (*middle*) is 18.5 days before *B* maximum and 1 day *before* the explosion time expected from the high-redshift SNe Ia. The existence of this detection is strong evidence that the rise time to *B* maximum is *at least* 1.5 days greater than the preliminary value inferred by Goldhaber (1998a, 1998b) and Groom (1998) for high-redshift SNe Ia. The image at maximum light is from Jha et al. (1999).

The difference in rise times does not seem to be a result of the stretch method. Even if this method were to distort the true rise time, this should not affect the rise-time *comparison*, because the light-curve shapes represented in the nearby sample span the range of light-curve shapes of the SCP sample. The SCP sample of SN Ia light curves has a narrow distribution of stretch factors around unity (Perlmutter et al. 1999). The average light-curve shape for our sample is 94% ± 9% of the mean width of the SCP light curves. SN Ia light curves in the nearby sample have stretch factors that are both smaller and larger than unity.

### 3.2. *High Redshift*

Correctly measuring the rise of faint SNe Ia at high redshift is a great technical challenge that must be convincingly overcome before we can trust the implications of the comparison with the low-redshift rise behavior. The differences in the rising curve of the low-redshift and high-redshift SNe Ia are only significant at 12 days before *B* maximum and younger, when SNe Ia are more than 2 mag below their peak brightness. For SNe Ia with redshifts of 0.4 to 0.5, this corresponds to observed *R*-band magnitudes of 24.0 to 24.3 (Garnavich et al. 1998), which are *K*-corrected to *B* magnitudes of 24.8 to 25.1. Even larger differences between the low- and high-redshift rises are evident when the SNe Ia are 3 mag below maximum, requiring observations of high-redshift SNe Ia at *R*-band magnitudes of 25.0 to 25.3. These faint fluxes push the limits of what can be accomplished with 4 m–class telescopes under reasonable conditions and moderate integrations. Many of these individual observations of SNe Ia at high redshift have a signal-to-noise ratio near unity, a regime where careful data analysis is required to avoid systematic errors in photometry.

The SCP observations of high-redshift SNe Ia on the rise (i.e., those 10 to 25 days before *B* maximum) originate from reference images. These are observations taken 3 to 4 weeks before a subsequent set of "search" observations and are used to measure host-galaxy brightnesses without SN light. SNe Ia found during the search phase are preferentially discovered near maximum brightness. Because of time dilation, the reference observations therefore contain the light of SNe ∼14 to 18 days before maximum. The SCP has taken great care to obtain "final" reference images years after (or before) the SN Ia explosions to accurately assess the amount of SN Ia light in the original reference images (Perlmutter et al. 1999). They also employ light curves of SNe Ia to determine the amount of any residual light remaining in the final reference images (S. Perlmutter 1999, private communication). Consequently, we expect the SCP measurement of the rise time of high-redshift SNe Ia to be accurate and comparisons with the low-redshift rise time to be meaningful.

However, a very powerful cross-check of systematic errors on the SCP's faint photometry of young high-redshift SNe Ia comes from examining their data of SNe Ia well past maximum, when the SNe Ia are again of similar brightness. In the age range of 35 to 45 days past maximum, the nearby SNe Ia are 2.7 to 3.1 mag below their maximum brightness. This is the same flux range at which differences of 0.6 to 0.8 mag are evident in the similarly normalized low- and high-redshift rising SN Ia light curves. Figure 4 shows a comparison of the low- and high-redshift behavior of SNe Ia (normalized to the composite light curve of the high-redshift SNe Ia) on the rising and declining sides of maximum at identical magnitudes. This comparison demonstrates a high degree of concurrence of the declining light curves *at the same magnitude levels* where the disparity occurs on the rising light curves. The difference in the mean between the high-redshift and low-redshift magnitudes on the decline and in this magnitude range is less than 0.02 mag, indicating that conspicuous systematic errors in the faint SCP photometry cannot explain the differences in the rise behavior. It is important to note that the data in the age range of 35 to 45 days past maximum were not used in the process of

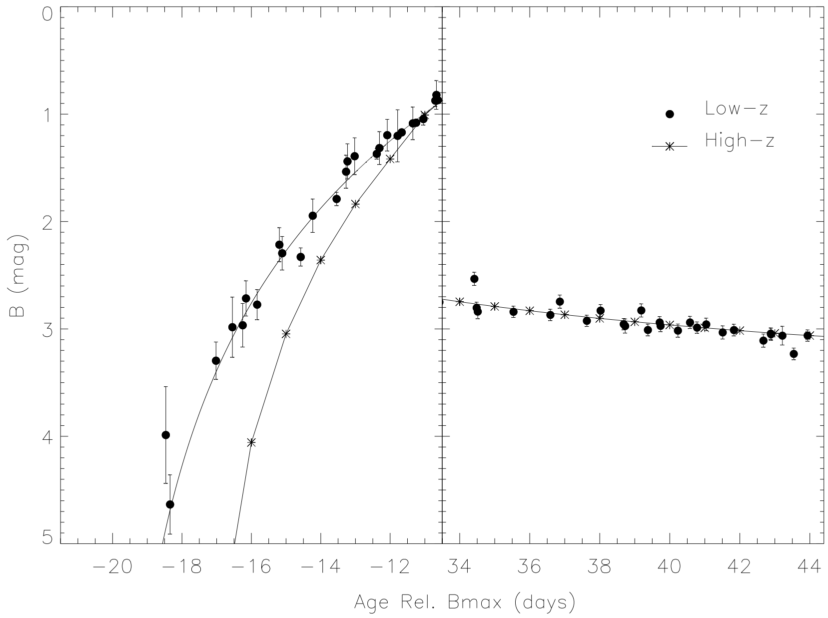

FIG. 4.—Comparison of nearby and high-redshift SNe Ia at similar magnitudes below maximum on the rise and decline. The excellent agreement between the two samples on the decline is strong evidence that systematic errors incurred in measuring faint SNe at high redshift on the rise are not the cause of the apparent difference between fits to the rise of the samples.

normalizing the light curves, making this an independent test.

As discussed in § 3.1, an intrinsic dispersion in SN Ia rise time (for SNe Ia with the same postrise light-curve shape), together with a selection criterion related to the brightness of SNe Ia on the rise, could also bias the high-redshift measurement. Because high-redshift SNe Ia are discovered by their appearance in differenced images, SNe Ia that are fainter than average in the reference observations will display a larger change in the "search" images. This effect would seem to favor the discovery of SNe Ia that are faster or have shorter rise times than the average for a given light-curve shape. However, the individual measurement uncertainties in the SCP reference observations are larger than the differences in the low-redshift and high-redshift rises (Goldhaber 1998a, 1998b). Therefore the criterion used to discover a SN Ia, the signal-to-noise ratio of the change in flux, is unaltered by changes in flux at this level. Because SNe Ia in the high-redshift sample and the unbiased subset of the nearby sample were not discovered during the early rise, the apparent difference in the samples' rise times is not simply a result of a selection bias.

The transformation of observed high-redshift SN Ia magnitudes to rest-frame magnitudes requires the application of cross-filter *K*-corrections (Kim, Goobar, & Perlmutter 1996). Systematic errors in these corrections are likely at the 0.03 to 0.05 mag level (Perlmutter et al. 1999; Kim et al. 1996; Schmidt et al. 1998) but cannot explain the observed differences of ~0.7 mag at 14–15 days before *B* maximum. Additional sources of systematic errors in the SCP measurement of the SN Ia high-redshift rise time are best considered by Goldhaber et al. (2000).

Despite the above tests, it would be desirable to have an additional cross-check in the form of an independent measurement of the high-redshift rise time. Although the data of the SCP are currently the most extensive available on the rise of high-redshift SNe Ia, early detections were made by the High-$z$ team of SN 1995K at $z = 0.48$ (Schmidt et al. 1998) and SN 1996K at $z = 0.38$ (Riess et al. 1998). Unfortunately, with only two data points, it is not possible to derive an independent, meaningful comparison with the rise-time measurements. More early rise data are needed from the High-$z$ team to yield an accurate measurement of the rise time.

## 4. DISCUSSION

Our measurement of the rise time from nearby SNe Ia is inconsistent with the preliminary measurement of the rise time of high-redshift SNe Ia inferred by the SCP (Goldhaber 1998a, 1998b; Groom 1998; see Goldhaber et al. 2000 for final results) with high statistical confidence (5.8 $\sigma$). The sense of the difference is that the low-redshift rise-time measurement is $2.5 \pm 0.4$ days longer than the high-redshift measurement. This difference must be either the result of a systematic error in the measurements or intrinsic to SNe Ia. No compelling source of systematic error was found in § 3 that could bring the low-redshift and high-redshift rise times into concordance. However, systematic errors in the preliminary high-redshift measurement are best addressed by Goldhaber et al. (2000).

We attempted to follow the methodology of Goldhaber (1998a, 1998b) and Groom (1998) in making this comparison, and *if* they have correctly followed their stated methodology, we believe the difference reported here is significant. This difference can only be rendered insignificant if future analysis of the high-redshift data concludes that a substantial error was made in determining the high-redshift rise time *or its uncertainty*. The significantly higher quality of the low-redshift photometry and the existence of strong early detections of nearby SNe Ia make it highly unlikely that a systematic error in the low-redshift rise-time measurement could alone bring the disparate rise times into concordance. A further comparison between the data sets cannot be made at this time because of the unavailability of the SCP photometry.

It is surprising, considering the relatively low signal-to-noise ratio of the high-redshift SN Ia photometry, that a measurement of the rise time could be made to within the stated precision (1 $\sigma = 0.4$ days; Groom 1998). Indeed, further careful analysis of the high-redshift data could result in a larger measurement uncertainty. For example, if the precision of the high-redshift rise-time measurement decreased significantly to 1 $\sigma = 1$ to 1.5 days, the significance of the difference in the measured rise times would reduce to only ~95% (i.e., 2 $\sigma$). If further analysis indicates an extreme increase in the uncertainty of the high-redshift rise-time measurement, the current precision of the comparison of the rise times as a test of evolution might become insufficient to reach a robust conclusion.

If the difference in the rise-time behavior is intrinsic to the SNe Ia, this would likely indicate an evolution of the characteristics of SN Ia explosions. Synonymous with evolution is the existence of a previously unknown, additional parameter not included in the current one-parameter empirical description of SN Ia light curves, whose typical value evolves with redshift. What would be the implications of an evolution of SNe Ia between $z = 0$ and $z = 0.5$?

An evolution of SNe Ia may reveal a redshift-dependent variation in the composition of SN Ia progenitors (Ruiz-Lapuente & Canal 1998; Livio 1999; Kobayashi et al. 1998). The construction of SN Ia progenitors is limited by the time required for stars to reach their degenerate end states and for transfer of sufficient material from the donor star. Because white dwarfs born from low-mass stars will be absent at high redshifts, some evolution of SNe Ia may be expected. The apparent evolution of SNe Ia may augment our currently limited understanding of the nature of SN Ia progenitors.

SNe Ia have also been employed as a powerful tool for measuring cosmological parameters. In this role, the observed faintness of high-redshift SNe Ia has been taken as evidence for a current acceleration of the universe because of a cosmological constant (Riess et al. 1998; Perlmutter et al. 1999). If SNe Ia are evolving, how are previous measurements of cosmological parameters from SNe Ia affected?

The observed evolution of SNe Ia during their rise could only impact distance measurements if this evolution extends to the postrise development. Only observations of the brightness and colors of SNe Ia near peak and a few weeks thereafter have been used to estimate their distances.

The observation of different rise times for SNe with similar subsequent light-curve shapes may signal a departure of the viability of previous one-parameter empirical models. Unfortunately, we cannot yet *directly* infer the size or direction of the effect on the cosmological parameters.

A pure empiricist could be guided simply by Ockham's razor to conclude that the two unexpected characteristics of high-redshift SNe Ia (that they appear to rise more quickly and to be systematically dimmer than expected) are most economically explained by a single hypothesis: they have evolved. Such evolution might be expected between high and low redshifts, where variations in metallicity and progenitor ages must occur. This hypothesis would obviate the need for a cosmological constant.

However, as noted by Schmidt et al. (1998), Riess et al. (1998), and Perlmutter et al. (1999), the sample of nearby SNe Ia already spans an impressive range of environments and stellar populations. SNe Ia hosted by early-type, late-type, and starburst galaxies show no systematic differences in their distance estimates. The relative reliability of SN Ia distance measurements across expected variations in progenitor properties in the nearby universe is arguably the best evidence that evolution since $z \approx 0.5$ should not affect cosmological measurements. Yet it has not been determined whether the *specific* environments of progenitors in different host-galaxy types vary substantially. The individual environments of SNe Ia in the nearby universe must be investigated before we can infer whether or not their *assumed* variability provides evidence against evolution. It is important to note that none of the host galaxies used to measure the low-redshift rise time are early-type galaxies. The complete distribution of host-galaxy types used to measure the high-redshift rise time is not yet known (Perlmutter et al. 1999).

Semiempirical methods used to calibrate the maximum luminosity of SNe Ia suggest that the peak luminosity may be affected by a change in the rise time, but without additional information these methods give opposite indications of the direction of the change in peak luminosity (Nugent et al. 1995). Treating a SN Ia as an expanding photosphere with all other variables unaffected, a shorter rise time results in a dimmer SN Ia at peak. Alternately, a determination of the peak luminosity from the instantaneous rate of radioactive energy deposition indicates that a shorter rise time yields a brighter peak. Because the expanding photosphere determination of the peak luminosity is a steeper function of the rise time, the methods together suggest that a shorter rise time yields a somewhat dimmer peak (Nugent et al. 1995).

Because the perceived differences are only apparent when the SNe Ia are very young, we might conclude that physical differences exist only on the surface or outer layer of the SNe. This conclusion resonates with the observation that spectroscopic differences among normal and overluminous SNe Ia are most apparent at early times (e.g., Filippenko et al. 1992; Phillips et al. 1992; Li et al. 1999). These superficial differences may be related to an aspect of the material recently accreted (but not thoroughly processed) onto the progenitor. If this parameter were the metallicity of the accreted material, it would not be surprising that the opacity and hence the rise time could be affected. A lower surface metallicity, expected at high redshift, would produce a faster or shorter rise time, in concordance with our results. However, modeling indicates that the photosphere of a SN Ia may recede below the surface layer of unprocessed material in only a few days (Höflich et al. 2000; see also Lentz et al. 2000).

If the only source of the observed rise time difference is the surface of the SN Ia, how would the peak luminosity be affected? As a fraction of the peak output, the difference in the total energy lost during a short or long rise is negligible. If the conditions necessary for explosion are dictated by the progenitor mass or properties near the center, the variations in the surface chemistry would not affect the size of the energy source (i.e., the $^{56}$Ni mass). Once the photosphere receded beneath the surface, the subsequent evolution of the SN Ia, including the peak luminosity, may be unaltered.

Because the rise time is a function of the diffusion time of energy from the decay of $^{56}$Ni to the surface, the observed difference in rise times could indicate a variation in the initial location of the synthesized $^{56}$Ni. Longer rise times would result from SNe Ia that have a greater depth of intermediate-mass elements covering the $^{56}$Ni. If this variation is caused only by mixing, the differences in the diffusion times at peak should be negligible, resulting in little or no variation in peak luminosity (P. Pinto 1999, private communication).

Yet, it is also possible that the rise time difference could be indicative of a deeper evolution of the SN Ia explosion that is only observable at the surface, where the unburnt material resides. If the change in the rise time results from a more complex alteration of the SN Ia physics, we cannot easily infer the effect on the postrise light curve.

We might hope to employ detailed modeling of SN Ia explosions to gauge the effect that the observed evolution has on measurements of the cosmological parameters. However, the inability of current theory to adequately model many of the observed characteristics of SNe Ia engenders little faith that theory alone can be used to predict the consequences of the observed evolution. Specifically, the value of the fiducial rise time and the trend between rise time and peak luminosity (or decline rate) is in poor concordance with most available theoretical models (Riess et al. 1999).

Theoretical models have indicated that differences in white dwarf carbon-to-oxygen ratios (C/O) should produce variations in SN Ia explosions (Höflich et al. 1998). The similarity between stellar and cosmological timescales leads to the conclusion that the white dwarfs that produce high-redshift SNe Ia originate, on average, in younger and hence more massive stars than today's SNe Ia (von Hippel, Bothun, & Schommer 1997). Variations in the C/O ratio may be a natural consequence of white dwarfs that evolved from different stellar masses.

Höflich et al. (1998) predict that decreasing the progenitor's C/O ratio by 60% produces a SN Ia with the same decline rate, yet is 30% brighter and requires 3 days longer to reach maximum brightness. If low-redshift SNe Ia have C/O ratios that are significantly smaller than those of high-redshift SNe Ia, the direction and size of this effect obviates the need for a cosmological constant or an accelerating universe to explain the observations of low and high-redshift SNe Ia. However, Höflich et al. (2000) also expect that more massive stars would yield white dwarfs with lower C/O ratios. At higher redshifts, lower mass stars have not yet had time to become white dwarfs. Therefore, the theoretical prediction would be for higher redshift progenitors to give rise to more slowly rising SNe Ia, which is opposite of the observed trend reported here. In addition, others suggest an inverse relation to that of Höflich et al. (1998) between the C/O ratio and luminosity (Umeda et al. 1999). More work is needed to understand this complicated process.

Observations at high and low redshifts can directly test for rise-time evolution and its cosmological implications. An exploration of the rise behavior of nearby SNe Ia born in a wide range of environments may reveal objects more similar to those at high redshift; by determining the relative luminosity of "fast" and "slow" rising SNe Ia in the nearby universe, we could directly evaluate the impact of the apparent evolution on cosmological inferences. Comparisons of the spectra of high- and low-redshift SNe Ia observed during the early rise, for example, may indicate systematic differences. A measurement of the rise behavior of SNe Ia at $z \approx 0.2$ should yield results that are between those presented here and the preliminary SCP measurement. Finally, the most challenging but potentially most fruitful way to explore the role of evolution in the current cosmological measurements is by extending the measurement of high-redshift SNe Ia to $z > 1.0$, where the effect of luminosity evolution is likely to diverge from that of a vacuum energy density. As seen in Figure 5, a simple linear luminosity evolution of SNe Ia mimics the effects of a cosmological constant and mass density only in a specific redshift range. Continued degeneracy between evolution and cosmology at additional redshifts can only be envisioned by the most imaginative (and sadistic) minds.

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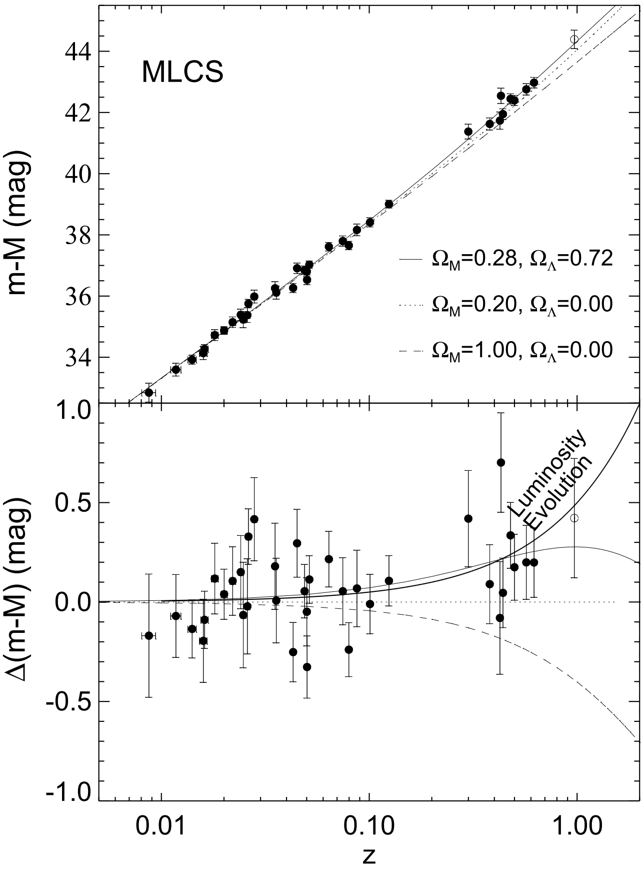

FIG. 5.—Degeneracy between simple linear evolution and cosmological parameters on the Hubble diagram of nearby and high-redshift SNe Ia. The possible confusion between the effect of evolution and a cosmological constant on SN Ia distances could be resolved by additional measurements of SNe Ia at redshifts greater than 1. The data shown are from Riess et al. (1998).

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