SCHEDULED DISCOVERIES OF 7+ HIGH-REDSHIFT SUPERNOVAE: FIRST COSMOLOGY RESULTS AND BOUNDS ON q_0

The Supernova Cosmology Project: I

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Abstract.

Our search for high-redshift Type Ia supernovae discovered, in its first years, a sample of seven supernovae. Using a "batch" search strategy, almost all were discovered before maximum light and were observed over the peak of their light curves. The spectra and light curves indicate that almost all were Type Ia supernovae at redshifts $z = 0.35 - 0.5$. These high-redshift

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supernovae can provide a distance indicator and "standard clock" to study the cosmological parameters q_0, Λ, Ω_0, and H_0. This presentation and the following presentations of Kim *et al.* (1996), Goldhaber *et al.* (1996), and Pain *et al.* (1996) will discuss observation strategies and rates, analysis and calibration issues, the sources of measurement uncertainty, and the cosmological implications, including bounds on q_0, of these first high-redshift supernovae from our ongoing search.

1. Introduction

Since the mid 1980's, soon after the identification of the supernova subclassifications Ia and Ib were recognized, Type Ia supernovae (SNe Ia) have appeared likely to be homogeneous enough that they could be used for cosmological measurements. At the time, it appeared that they could be used to determine H_0, if their absolute magnitude at peak could be measured, i.e., if some SN Ia's distance could be calibrated. They could also be used to determine q_0 from the *apparent* magnitudes and redshifts of nearby and high redshift supernovae, if high redshift SNe Ia could be found. Many of the presentations at this meeting have demonstrated significant advances in recent years in our understanding of the SN Ia homogeneity (and/or luminosity calibration), the distances to SNe Ia, and measurements of H_0. We will here discuss the search for high redshift supernovae and the measurement of q_0.

2. High Redshift Supernovae Search Strategy

We began our High Redshift Supernova Search soon after the completion of a labor-intensive search at the Danish 1.5-m in Chile, which in two years of searching had discovered one SN Ia at $z = 0.31$, approximately 18 days past maximum light (Nørgaard-Nielsen *et al.* 1989). It was apparent that SNe Ia at high redshift are difficult to work with for at least three reasons: they are rare, they are rapid, and they are random. The estimates of SN Ia rates—a few per millennium per galaxy—are daunting, if one wants a statistically useful sample of supernovae. Much of the interesting data must be obtained rapidly, since the supernova rises to maximum light within a few weeks and, at high redshifts, fades below the largest telescopes' limits within a month or two. Furthermore, it is not possible to guarantee photometry and particularly spectroscopy of randomly occurring high-redshift supernovae, since the largest, most over-scheduled telescopes are needed to observe them.

Ideally one would like to *schedule* supernova explosions on demand, and

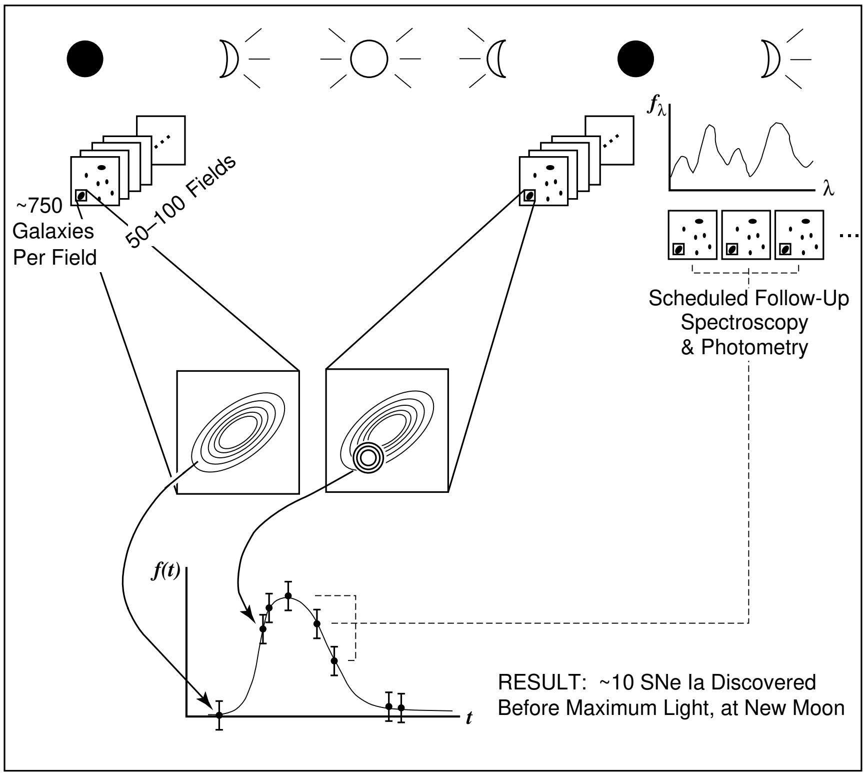

Figure 1. Search strategy designed to discover batches of ~10 high-redshift supernovae on demand, just before new moon, and while the supernovae are still brightening, i.e. before "maximum light." The follow-up spectroscopy and photometry can therefore be scheduled, and can follow the supernovae over maximum light during dark time.

then apply for the telescope time to study them, beginning at least a few days before maximum light.

To solve these problems, we developed a new search technique. Figure 1 presents a schematic outline of the strategy. Just after a new moon, we observe many tens of high-galactic-latitude fields (including known high-redshift clusters when possible) on a 2.5- to 4-meter telescope. With a wide-field camera, each image contains hundreds of galaxies at redshifts 0.3 – 0.6. Just before the following new moon, we observe the same fields again. We compare the images, thus checking tens of thousands of high redshift galaxies (including those below our detection limit) to find the ten or so showing the new light of a supernova that was not there on the previous observation. The supernovae generally do not have time to reach maximum light, with only 2.5 to 3 weeks (or approximately 11 to 14 days in the supernova rest frame) between our after- and before-new-moon comparison images. In order to begin the follow-up photometry and spectroscopy immediately, we have developed extensive software to make it possible to complete the analysis of all the images within hours of the observations.

In short, this search technique allows "batches" of pre-maximum-light supernova discoveries to be *scheduled* just before new moon, the ideal time to begin follow-up spectroscopy and photometry. This follow-up can now be scheduled as well, on the largest telescopes.

3. Supernova Discoveries and Follow Up

As of this meeting in June 1995, we had used this "batch" search technique several times at the Isaac Newton Telescope and the Kitt Peak 4-meter telescope to discover 9 supernovae. Seven of these were found within the standard 2.5 – 3 week search interval and were followed with photometry and spectroscopy (Perlmutter *et al.* 1994, 1995a, 1995b). (Since these were the demonstration runs of the project, not all of the follow up was scheduled.) We observed light curves for all of the supernovae in at least one filter (usually R band), and spectra for all of the host galaxies and three of the supernovae.

[Since the Aiguablava meeting, we have now completed another search run using the CTIO 4-meter telescope. This yielded 11 supernovae at redshifts between 0.39 and 0.65 (Perlmutter *et al.* 1995c).]

The results of the batch search strategy can be seen in Figure 2, which shows a preliminary analysis of the R-band light curves as of June 1995. For each of the supernovae, there is the 2.5 – 3 week gap in the observations leading up to the discovery just before maximum light. (There is also a gap during the following full moon.) Figure 3a shows the distribution of discovery dates spread over the week before maximum light. In the case of SN 1994am, the discovery was just after maximum light, but in this case the very first observations provide data points before maximum light.

Whenever possible, photometry was also obtained in other bands in addition to R. The light curve of SN 1994G shows an example with more extensive coverage in both I and R. Several of the supernovae were observed in the B band, although these points are not plotted in Figure 2. B-band photometry near maximum light is particularly important, because it gives an indication of rest-frame ultraviolet flux, as discussed below.

The redshift distribution of the supernova discoveries depends, of course, on the telescope aperture and exposure times used for the search. Most of these seven supernovae were discovered with data that was optimal for detection of supernovae in the redshift range $z = 0.35 - 0.45$, as discussed at this meeting in more detail by Reynald Pain and Isobel Hook (Pain *et al.*,

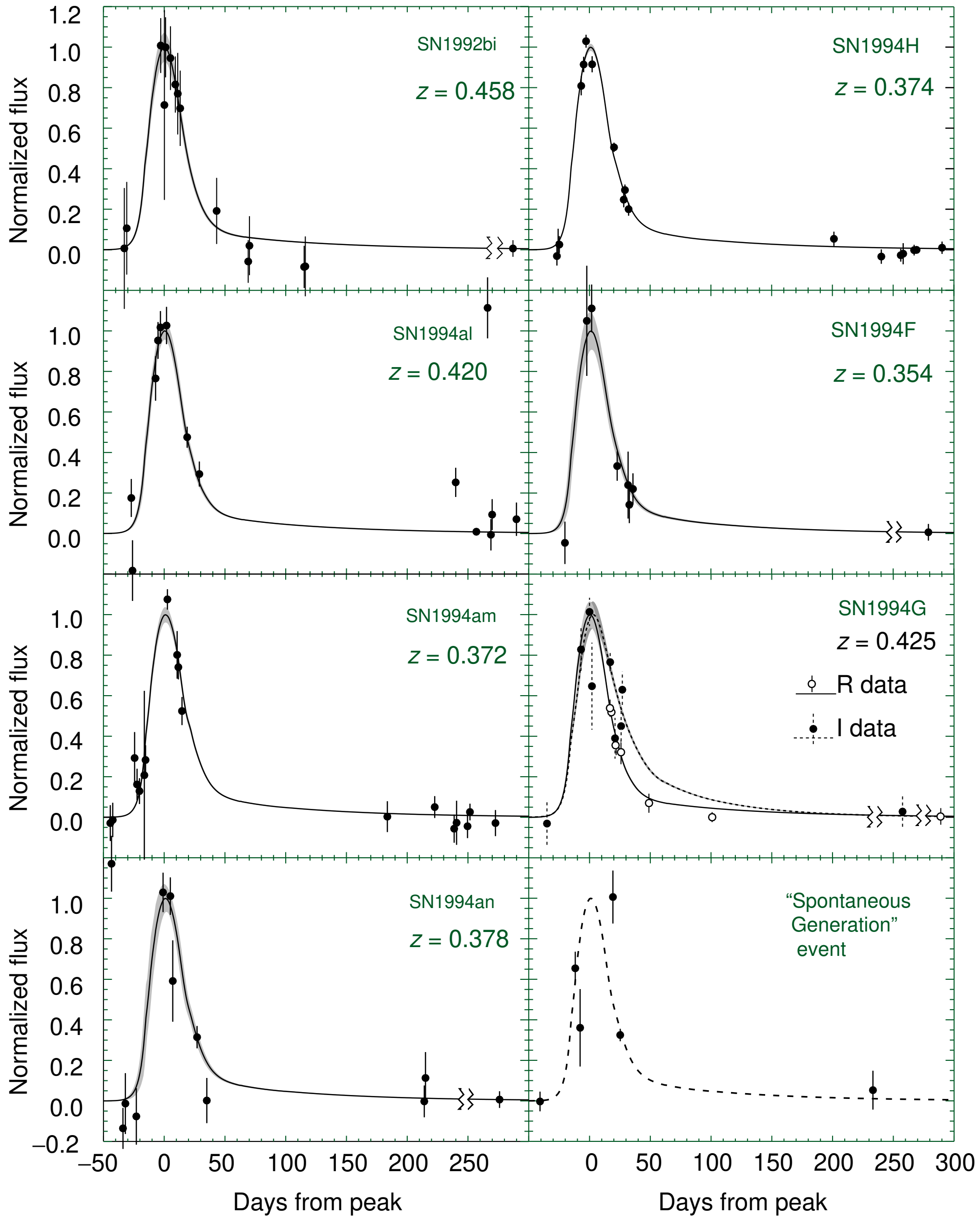

Figure 2. Preliminary R-band light curves for the first seven high-redshift supernovae. Shading behind the solid curves represent the 1-σ bounds on the best fit Leibundgut template light curve. An I-band light curve is also shown for SN 1994G; other photometry points in I and B for these supernovae are not shown on this plot. The lower right panel shows the light curve of a "spontaneous generation" event, a transient point-source of light on a region of an image where no host galaxy is visible; the follow-up photometry was not as extensive for this event.

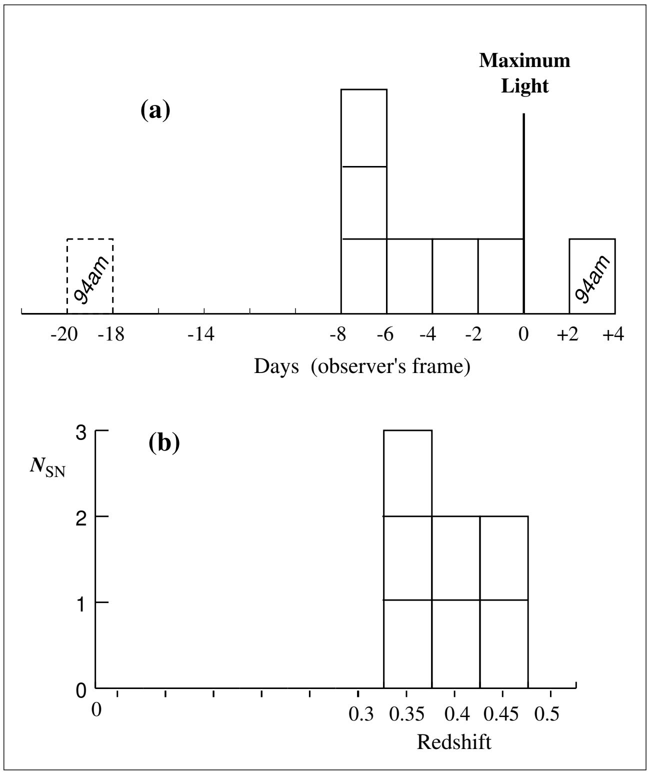

Figure 3. (a) Distribution of discovery dates, plotted as number of days before maximum light. Note that for SN 1994am the discovery was just after maximum light, but the first observations, about three weeks earlier, provide a data point well before maximum light, shown in dotted outline. (b) Distribution of redshifts.

1996). Figure 3b shows the actual redshift distribution, which matches the expected distribution quite well. Our more recent searches use observations that are over a magnitude deeper and hence favor redshifts in the range 0.4 – 0.6.

Two of the three supernova spectra observed, for SN 1994G (by Challis, Riess, and Kirshner) and SN 1994an, match well feature-for-feature to a nearby SN Ia spectrum observed on the corresponding number of days (supernova rest frame) after maximum light, after redshifting the comparison spectrum to the redshift of the distant supernova's host galaxy. The one spectrum that extends far enough into the red shows the Si II feature of an SN Ia. The third supernova spectrum, for SN 1994F, was observed during commissioning of the LRIS spectrograph (by J.B. Oke, J. Cohen, and T. Bida) on the Keck telescope and is poorly calibrated. It nevertheless shows peaks and troughs matching a redshifted SN Ia. (The three spectra will be presented in forthcoming publications.)

Although no supernova spectrum was obtained for SN 1994am, its host galaxy spectrum exhibits a large 4000-angstrom break and lacks strong emission lines, indicating an elliptical galaxy. This supernova can therefore be taken to be an SN Ia as well. Given that the lightcurve shapes are not consistent with SNe IIP, and the higher probability of finding SNe Ia given their brightness relative to the typical SNe II's, Ib's, and Ic's, it is likely that all seven of the supernovae considered here are SNe Ia (see Perlmutter *et al.* 1995a for further discussion of SN 1992bi).

4. Photometry Analysis

The data analysis involves several stages, first to reduce the observed image data to individual photometry points and then to compare these points with nearby SN Ia light curves to determine the luminosity distance and hence q_0. The supernova light in each image must be measured and the underlying host galaxy light subtracted off. At these redshifts the supernova's seeing disk usually covers a significant amount of the galaxy, so it is important to do this step correctly. Each image has different seeing, and often a different telescope's point-spread-function (PSF) varies both spatially over the field and temporally over the course of an observing night. The amount of galaxy light that must be subtracted therefore varies from image to image.

To ensure that this step does not introduce spurious fluctuations in the photometry, we have developed various analysis tests and controls to monitor the stability of the measurement. For example, we repeat the analysis used at the location of the supernova at many other locations on nearby galaxies similar to the supernova's host galaxy. These locations should show flat "light curves," since they have no supernova. If the brightness fluctuates more than expected from the sky noise, we have evidence for a mismatch of galaxy light from image to image, due for example to a poor measurement of the seeing or local PSF.

These neighboring-galaxy locations also help monitor the accuracy of the color corrections that account for slightly different filters or CCD responses between telescopes and cameras. As another check, we place "fake" supernovae on the images, and follow the analysis chain all the way through to the light curves to see that the analysis does not distort the photometry.

5. Light Curve Analysis

To compare these high-redshift supernova photometry points to nearby SN Ia light curves, it is necessary to calculate the K correction that accounts for the redshifting of the light observed in a given filter. The standard K corrections give the magnitude difference between the light emitted in a given filter band and the light observed after redshifting in that same band. Since at redshifts of order $z = 0.45$ the light received in the R band corresponds approximately to the light emitted in the B band, we calculate a generalization of the K correction, K_{RB}, that gives the magnitude difference between the rest frame B magnitude and the observed R magnitude. This is described in more detail at this meeting by Kim *et al.* (1996), and Kim, Goobar, & Perlmutter (1996).

In the past year, the case has become quite strong that SNe Ia are a family of very similar events, not all identical. Hamuy *et al.* (1995) and Riess, Press, and Kirshner (1995) present evidence indicating that this family can be described by a single parameter, essentially representing the shape or width of the light curve, and that this parameter is tightly correlated with the absolute magnitude at maximum. The broad, slow-light-curve supernovae appear somewhat brighter, while the narrow, fast-light-curve supernovae are somewhat fainter.

Hamuy *et al.* used Phillips' (1993) characterizations of this light curve width, Δm_{15}, the magnitude drop in the first 15 days past maximum, and fit their data to template light curves from supernovae representing various Δm_{15} values. Riess *et al.* added and subtracted different amounts of a "correction template" to a Leibundgut "normal" template (Leibundgut *et al.* 1991 and references therein) to represent this same light curve variation.

For our preliminary analysis, we have chosen a third alternative approach, to stretch or compress the time axis of the Leibundgut template by a "stretch factor" s. We find that this simple parameterization gives variations on the light curve that fit the variety of SNe Ia and can be translated to Phillips' Δm_{15} via the formula $\Delta m_{15} = 1.7/s - 0.6$. Calibrating nearby supernovae with this s-factor, we find the width-brightness relation can be characterized by a magnitude correction of $\Delta\text{mag} = 2.35(1 - s^{-1})$, which closely matches Hamuy *et al*'s Δm_{15} correction.

At this meeting, and since, a number of other supernova observables have been discussed as indicators of a given supernova's brightness within the SN Ia family. Branch et al. (1996) have discussed the correlation with $B - V$ and $U - B$ color, while Nugent *et al.* (1996) has pointed out indicative spectral features, suggesting that temperature may provide a single theoretical parameter that characterizes the variations within the SN Ia family. These recent developments suggest that our final reduced "data product" must include not only the K-corrected magnitude at peak, but also any available information on light-curve width, colors, and spectral features that might locate the supernova within the family of fast-and-faint to broad-and-bright SNe Ia.

6. Preliminary Scientific Results

Having gathered and reduced these data, what scientific results can we glean from them? Other talks at this meeting from the Supernova Cosmology Project group address the uses of this data to determine limits on the spatial variability of the Hubble constant (Kim *et al.* 1996), to demonstrate the time dilation of a "standard clock" at cosmological distances (Goldhaber *et al.* 1996), and to provide a first direct measurement of the SN Ia rate at $z \sim 0.4$ (Pain *et al.* 1996). We will here discuss the homogeneity and width-brightness relation of SNe Ia at $z \sim 0.4$ and implications for measuring q_0.

Note that all the results should be understood as preliminary, since we are now concluding the final stages of calibration and cross-checking the analysis.

To use high-redshift SNe Ia as distance indicators, we must first ask if the width-brightness relation holds at $z \sim 0.4$. In Figure 4, we plot the stretch factor—or equivalently Δm_{15}—versus the K-corrected and Galactic-extinction-corrected absolute magnitude (for a given q_0 and H_0), and we find a correlation that is consistent with that found for nearby supernovae (shown as a solid line). A different choice of q_0 would only change the scale on the magnitude axis (and slightly jitter the magnitude values, since the supernovae are not all at exactly the same redshift), but this would not affect the agreement between the near and distant width-brightness relation.

Using the width-brightness relation as a magnitude "correction," established using only nearby SNe Ia, tightens the dispersion of the high redshift supernova K-corrected peak magnitudes from $\sigma_{\rm raw} = 0.32$ mag to $\sigma_{\rm corrected} = 0.21$ mag. These dispersions are quite comparable to those found for nearby SNe Ia before and after correcting for the width-brightness relation.

When we turn to the other indicators of SN Ia family status, although the analysis is still incomplete, we find one good cross-check for the brightest of our high redshift supernovae, SN 1994H. For this supernova, a $B-R$ color was measured at peak, which after K-correction is an indicator of $U-B$ color in the supernova rest frame. The $B-R$ color indicates that SN 1994H is very similar to SN 1991T, which had a broad and bright light curve. SN 1991T had an s-factor of $\sim$1.08, and our preliminary value for SN 1994H is $s = 1.06 \pm 0.08$, broader and brighter than any of the other high redshift supernovae of this sample with well-measured lightcurve widths. Ideally, these cross checks will be available for all future high-redshift supernovae. This will be particularly important for cases for which the light curves are not complete enough for an accurate measurement of the lightcurve width.

For our preliminary estimate of q_0, we have used a few approaches. The first is to apply the width-brightness correction to all seven of the high-

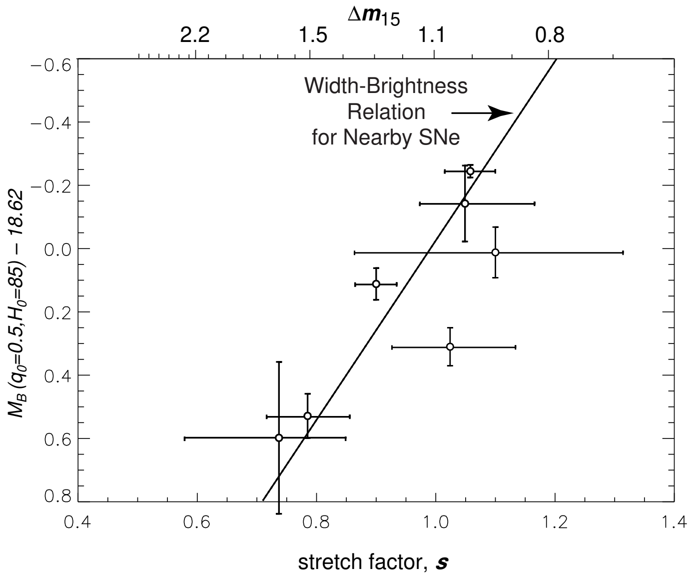

Figure 4. K-corrected absolute B magnitude (for $q_0 = 0.5$ and $H_0 = 85$ m s^{-1}Mpc^{-1}) versus stretch factor, s, representing the width of the SN Ia template light curve that best fits the high-redshift supernovae. The solid line shows the relation between M_B and s found for nearby SNe Ia.

redshift supernovae, on the assumption that they are all SNe Ia with negligible extinction and that the zero point of the width-brightness relation—the intercept of Figure 4—has not evolved in the $\sim$4 billion years back to $z \sim 0.4$. Given the range of host galaxy ages for the nearby supernovae used to derive this relation, it is unlikely that it would have a very different intercept (but the same slope) at $z \sim 0.4$.

Figure 5 shows the results of this analysis plotted on a Hubble diagram, together with the relatively nearby SNe Ia of Hamuy *et al.* (1995). Comparing the upper and lower panels, it is clear that the scatter about the Hubble line decreases for both near and high-redshift supernovae after correcting for the width-brightness relation, although the error bars increase in the cases for which the light-curve width (s-factor or Δm_{15}) is poorly constrained by the photometry data.

The three supernovae with the smallest error bars, after correction for the width-brightness relation, are all near the redshift $z = 0.37$ and their data points in Figure 5, lower panel, lie on top of each other. They favor a relatively high value for q_0. Note that before the width-brightness correction (Figure 5, upper panel) their data points spread from $q_0 \approx -0.5$ (upper dotted line) to $q_0 > 1$ (lower dotted line); generally, the correction has brightened as many points as it has dimmed.

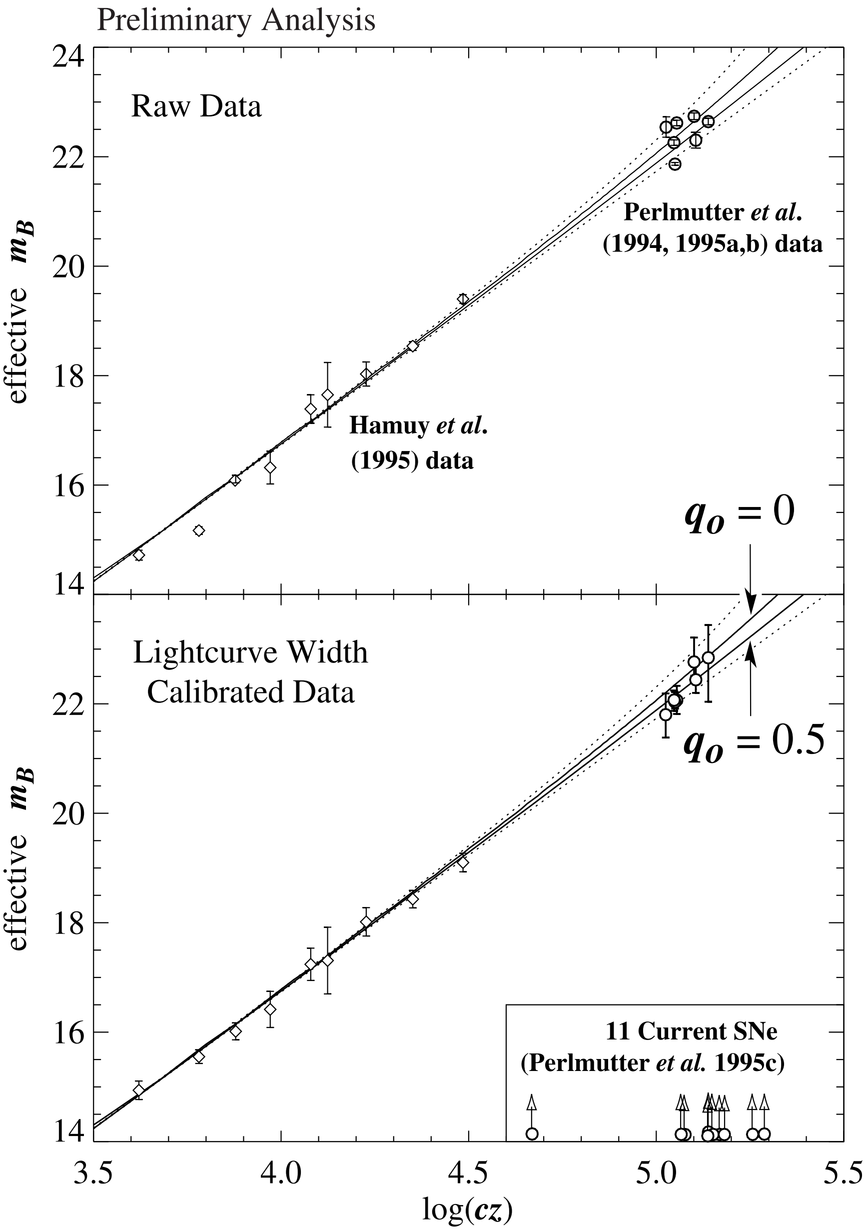

Figure 5. Hubble diagrams for first seven supernovae (preliminary analysis). Upper panel: "raw" apparent magnitude measurements, after K correction from R-band (observed) to B-band (supernova rest frame), versus redshift. The upper dotted curve is calculated for $q_0 = -0.5$, the two solid curves are for $q_0 = 0$ and $q_0 = 0.5$, and the lower dotted curve is for $q_0 = 1$. Lower panel: apparent magnitude measurements after "correction" for width-brightness relation. Note that the three points with the smallest error bars lie on top of each other, in this plot. Inset: Points represent redshifts for the most recent 11 supernova discoveries that are still being followed.

As an alternative approach to the q_0 measurement, we have also determined the value found for SN 1994G alone. In the case of this supernova we can avoid assumptions, because there is a strong spectrum for type identification, and its $B-R$ and $R-I$ colors are consistent with a "normal" SN Ia with no significant reddening. In particular, the (observed) $R-I$ color passes the (rest-frame) $B-V$ cut proposed in Vaughan *et al.* (1995) to test for normal, unreddened SNe Ia. This is also consistent with its stretch factor, which is within error consistent with an $s=1$ standard Leibundgut template. For SN 1994G, we find a preliminary value of $q_0 = 0.8 \pm 0.35 \pm 0.3$, where the second error is a preliminary bound on systematic error including a -0.1 estimate for possible Malmquist bias discussed below. This is consistent with the width-brightness-corrected result for the whole sample of seven supernovae. (We re-emphasize that these values are currently undergoing their final calibrations and cross-checks, although they are unlikely to change significantly.)

7. Discussion and Conclusion

Given the error bars, our current measurements of q_0 do not yet clearly distinguish between an empty $q_0 = 0$ and closed $q_0 > 0.5$ universe. The data do, however, indicate that a decelerating $q_0 \geq 0$ is a better fit than an accelerating $q_0 < 0$ universe. This is an important conclusion since it limits the possibility that $q_0 = \Omega_0/2 - \Omega_\Lambda$ is dominated by the cosmological constant Λ (where Ω_Λ is the normalized cosmological constant $\Lambda(3H_0)^{-2}$). In an accelerating universe, high values for the Hubble constant do not conflict with the ages of the oldest stars, because the universe was expanding more slowly in the past. However, in a "flat" universe, in which $\Omega_0 + \Omega_\Lambda = 1$, a cosmological constant $\Omega_\Lambda \geq 0.5$ would give an acceleration $q_0 \leq -0.25$, a poor fit to our data.

Note that extinction of the distant supernovae would make this evidence of deceleration even stronger, as would the possibility of inhomogeneous matter distribution in the universe as described by Kantowski, Vaughan, & Branch (1995), since both of these would lead to underestimates of q_0 if not taken into account. (Our future analyses will bound or measure extinction using multiple colors to differentiate reddening from intrinsic color differences within the SN Ia family. Riess *et al.* (1996) discussed this approach at this conference.)

It will be important to compare the q_0 value from our most distant supernovae to the value from our closest high-redshift supernovae to look for Malmquist bias. An estimate of the size of this bias using our studies of our detection efficiency as a function of magnitude suggests that a 0.2 mag intrinsic dispersion in calibrated SN Ia magnitudes would lead to an

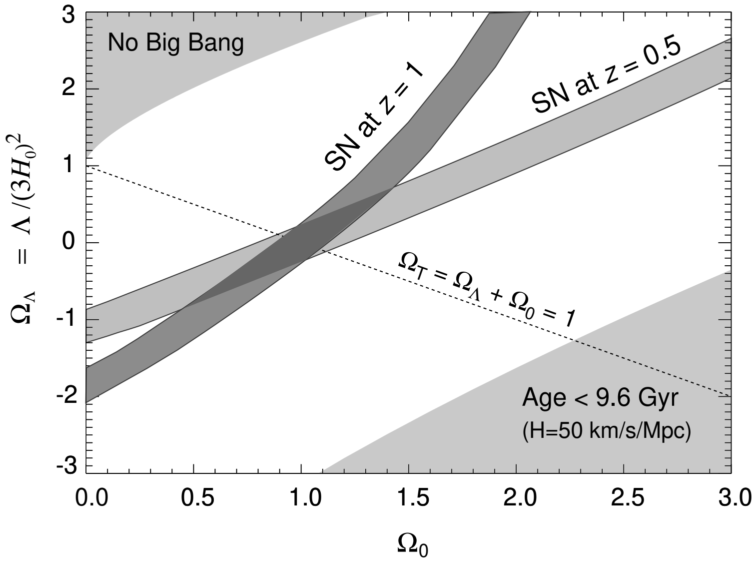

Figure 6. Theoretical bands of allowed parameter space in the Ω_Λ versus Ω_0 plane, for the hypothetical example of two SNe Ia discovered at $z = 0.5$ and at $z = 1$ in a universe with $\Omega_\Lambda = 0$ and $\Omega_0 = 1$ (from Goobar and Perlmutter 1995). The width of the bands is due to uncertainty in the apparent magnitude measurement of the supernovae. The intersection region would provide a measurement of both Λ and Ω_0. The shaded corners are ruled out by other observations, as indicated.

overestimate of 0.1 in q_0, if not accounted for (Pain *et al.* 1996, and see also Schmidt *et al.* 1996).

We will complete the observations and analyses of the next 11 supernovae soon, and be able to greatly strengthen the certainty of these conclusions. The new data set is expected to have significantly smaller error bars, particularly after calibration of the width-brightness relation, and it should be possible to distinguish the empty, $q_0 = 0$, and closed, $q_0 > 0.5$, universes. The redshift of these supernovae are plotted in the inset of Figure 5. Note that the highest redshift supernova, at $z \sim 0.65$, would be over 0.35 magnitudes brighter in a closed universe than in an empty universe.

For the future, it should be possible to measure both Ω_0 *and* Λ, even if the universe is not assumed to be flat. The apparent magnitude of a "calibrated candle" depends on both Ω_0 and Λ, but with different powers of z. The discovery of still higher redshift supernovae, at $z \sim 1$, can therefore locate our universe in the Ω_0 vs. Λ parameter plane, as shown in Figure 6. The feasibility of this measurement is discussed in Goobar and Perlmutter (1995).

We have shown here that the scheduled discovery and follow up of batches of pre-maximum high-redshift supernovae can be accomplished routinely, that the comparison with nearby supernovae can be accomplished with a generalized K-correction, and that a width-brightness calibration can be applied to standardize the magnitudes. Ideally this will now become a standard method in the field, and SNe Ia beyond $z = 0.35$ will become a well-studied distance indicator—as they already are for $z < 0.1$—useful for measuring the cosmological parameters. The prospects for this look good: already several other supernova groups have now started high-redshift searches. Schmidt *et al* (1996) and Della Valle *et al* (1996), at this meeting discussed two of these.

The many presentations at this exciting meeting have discussed recent advances in our empirical and theoretical understanding of Type Ia supernovae. The resulting supernova-based measurement of the cosmological parameters is an impressive consequence of these efforts of the entire supernova research community.

The observations described in this paper were primarily obtained as visiting/guest astronomers at the Isaac Newton and William Herschel Telescopes, operated by the Royal Greenwich Observatory at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias; the Kitt Peak National Observatory 4-meter and 2.1-meter telescopes and Cerro Tololo Interamerican Observatory 4-meter telescope, both operated by the National Optical Astronomy Observatory under contract to the National Science Foundation; the Keck Ten-meter Telescope; and the Siding Springs 2.3-meter Telescope of the Australian National University. We thank the staff of these observatories for their excellent support. Other observers contributed to this data as well; in particular, we thank Marc Postman, Tod Lauer, William Oegerle, and John Hoessel for their more extended participation in the observing. This work was supported in part by the Physics Division, E. O. Lawrence Berkeley National Laboratory of the U. S. Department of Energy under Contract No. DE-AC03-76SF000098, and by the National Science Foundation's Center for Particle Astrophysics, University of California, Berkeley under grant No. ADT-88909616.

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