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S. Perlmutter, S. Deustua, S. Gabi, G. Goldhaber, D. Groom, I. Hook, A. Kim, M. Kim, J. Lee, R. Pain, C. Pennypacker, I. Small A. Goobar, R. Ellis, R. McMahon, B. Boyle, P. Bunclark, D. Carter, K. Glazebrook, M. Irwin, H. Newberg, A.V. Filippenko, T. Matheson, M. Dopita, J. Mould, W. Couch

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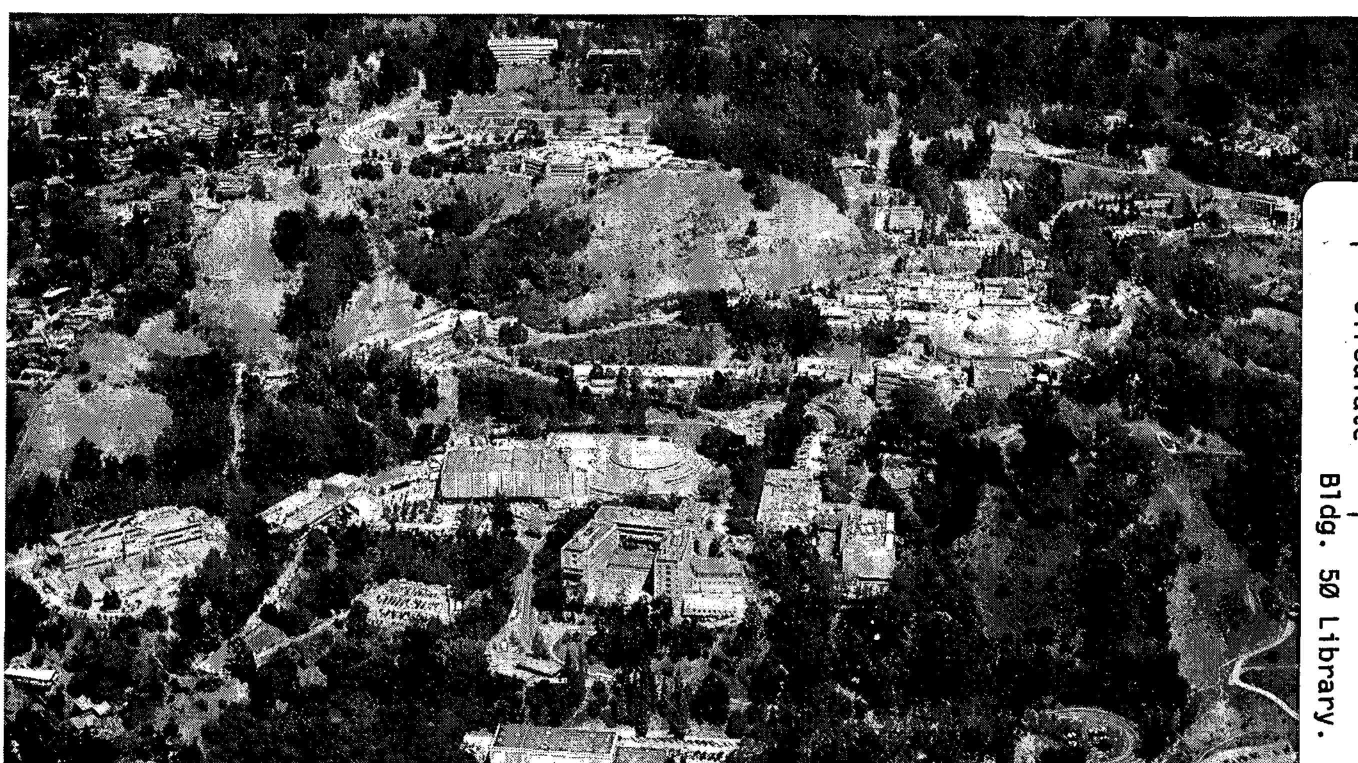

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FOUR PAPERS BY THE "SUPERNOVA COSMOLOGY PROJECT"*

I. Scheduled Discoveries of 7+ High-Redshift Supernovae: First Cosmology Results and Bounds on q_0, S. Perlmutter, *et al.*

II. K Corrections for Type Ia Supernovae and a Test for Spatial Variation of the Hubble Constant, A. Kim, *et al.*

III. Observation of Cosmological Time Dilation Using Type Ia Supernovae as Clocks, G. Goldhaber, *et al.*

IV. The Type Ia Supernova Rate at $z \sim 0.4$, R. Pain, I.M. Hook, *et al.*

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

The Supernova Cosmology Project: I

S. PERLMUTTER[1], S. DEUSTUA, S. GABI, G. GOLDHABER, D. GROOM, I. HOOK, A. KIM, M. KIM, J. LEE, R. PAIN[2], C. PENNYPACKER AND I. SMALL

E. O. Lawrence Berkeley National Laboratory & Center for Particle Astrophysics, University of California, Berkeley

A. GOOBAR

University of Stockholm

R. ELLIS AND R. MCMAHON

Institute of Astronomy, Cambridge University

B. BOYLE, P. BUNCLARK, D. CARTER, K. GLAZEBROOK[3] AND M. IRWIN

Royal Greenwich Observatory

H. NEWBERG

Fermi National Accelerator Laboratory

A. V. FILIPPENKO AND T. MATHESON

University of California, Berkeley

M. DOPITA AND J. MOULD

MSSSO, Australian National University

AND

W. COUCH

University of New South Wales

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

[1]Presented by S. Perlmutter, e-mail address: *saul@LBL.gov*

[2]Current address: CNRS-IN2P3, University of Paris

[3]Current address: Anglo-Australian Observatory

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

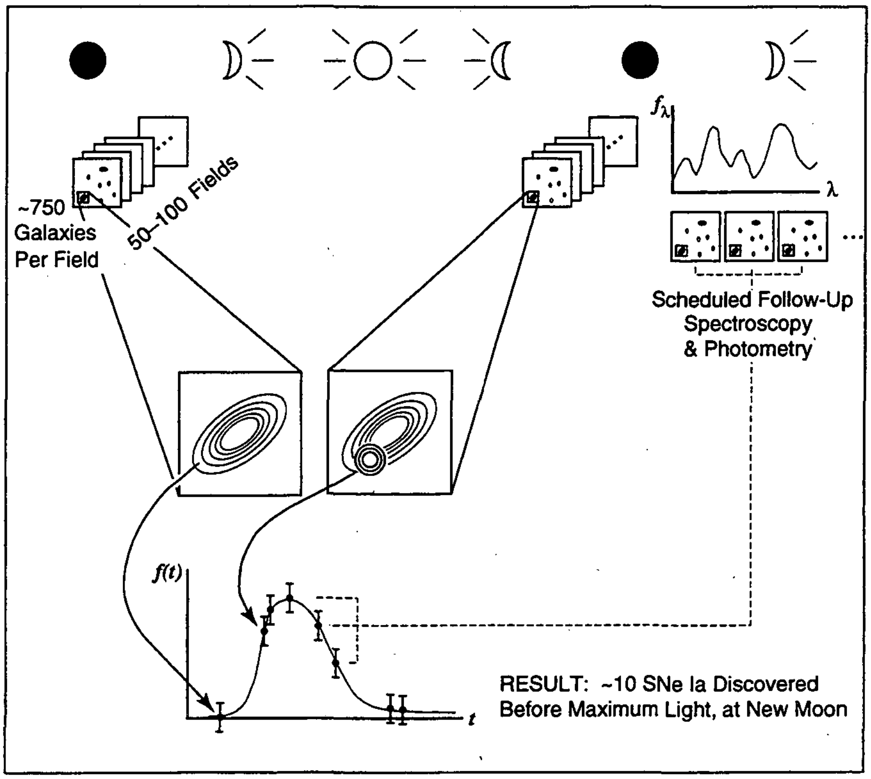

Figure 1. Search strategy designed to discover batches of ~10 high-redshift supernovae on demand, just before new moon, and while the supernovae are still brightening, i.e. before "maximum light." The follow-up spectroscopy and photometry can therefore be scheduled, and can follow the supernovae over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

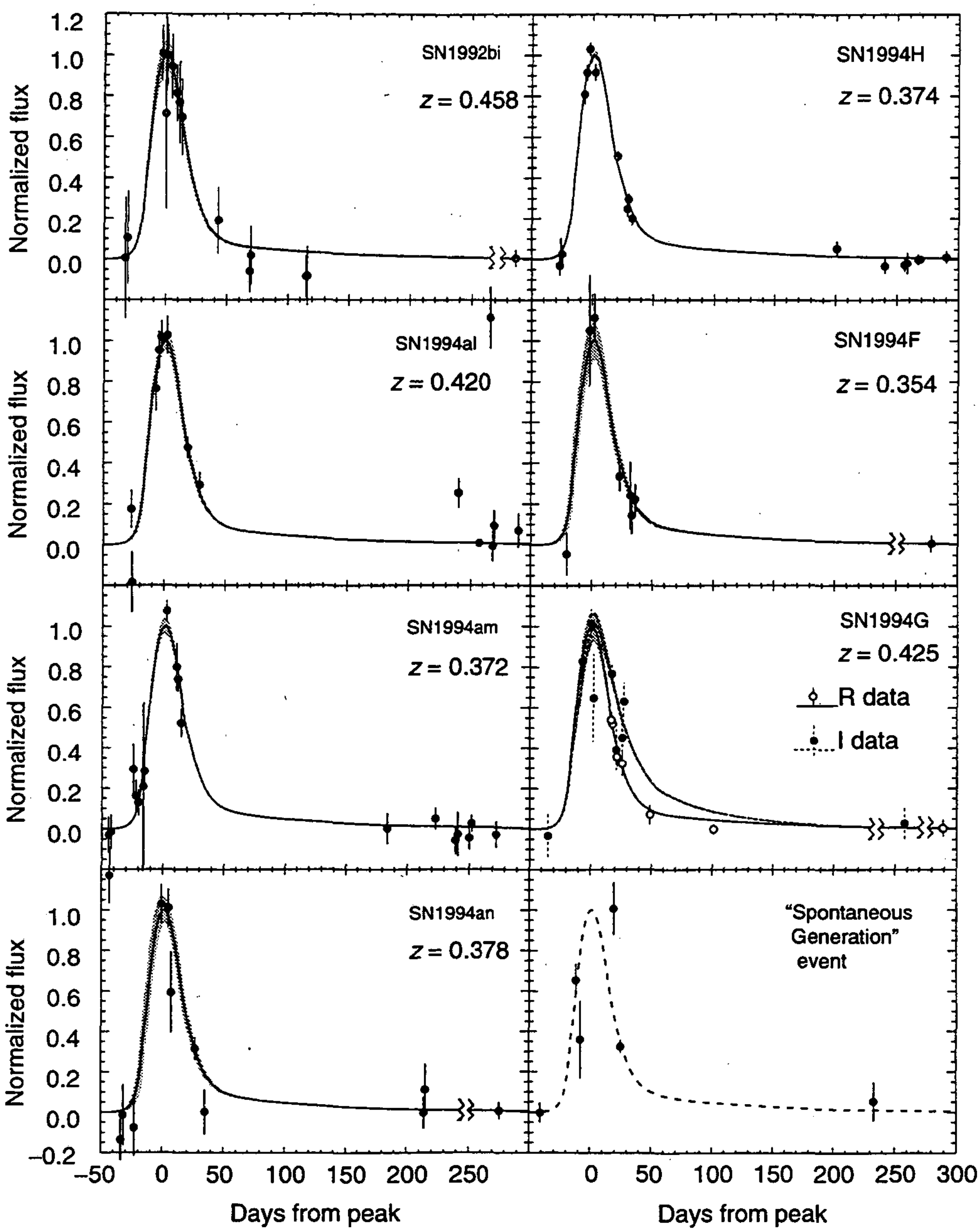

Figure 2. Preliminary R-band light curves for the first seven high-redshift supernovae. Shading behind the solid curves represent the 1-σ bounds on the best fit Leibundgut template light curve. An I-band light curve is also shown for SN 1994G; other photometry points in I and B for these supernovae are 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.

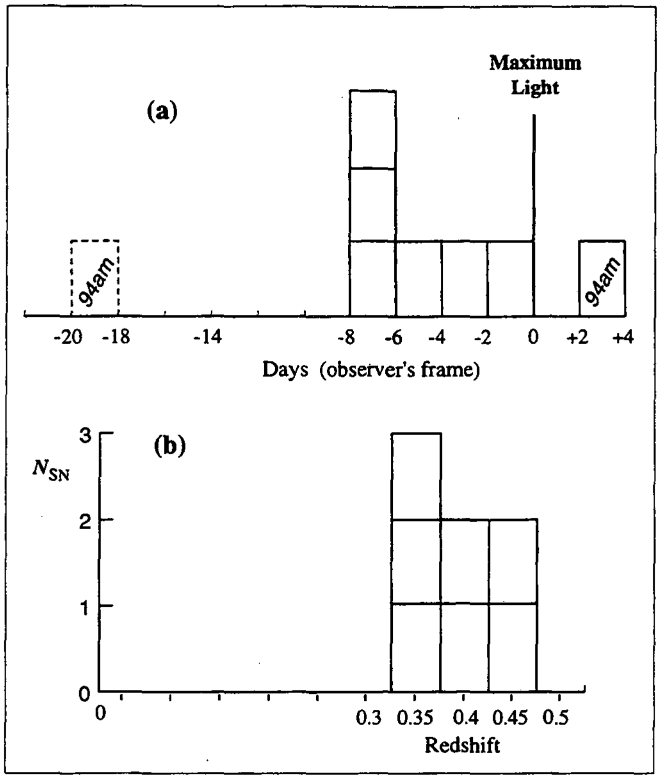

Figure 3. (a) Distribution of discovery dates, plotted as number of days before maximum light. Note that for SN 1994am the discovery was just after maximum light, but the first observations, about three weeks earlier, provide a data point well before maximum light, shown in dotted outline. (b) Distribution 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 $\sigma_{\text{raw}} = 0.32$ mag to $\sigma_{\text{corrected}} = 0.21$ 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-

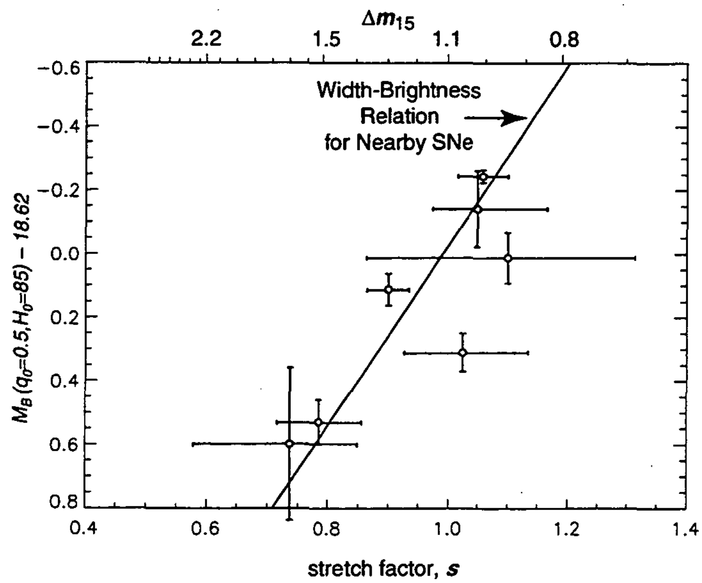

Figure 4. K-corrected absolute B magnitude (for $q_0 = 0.5$ and $H_0 = 85$ m s^{-1}Mpc^{-1}) versus stretch factor, s, representing the width of the SN Ia template light curve that best fits the high-redshift supernovae. The solid line shows the relation between M_B and s found for nearby SNe Ia.

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 ~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.

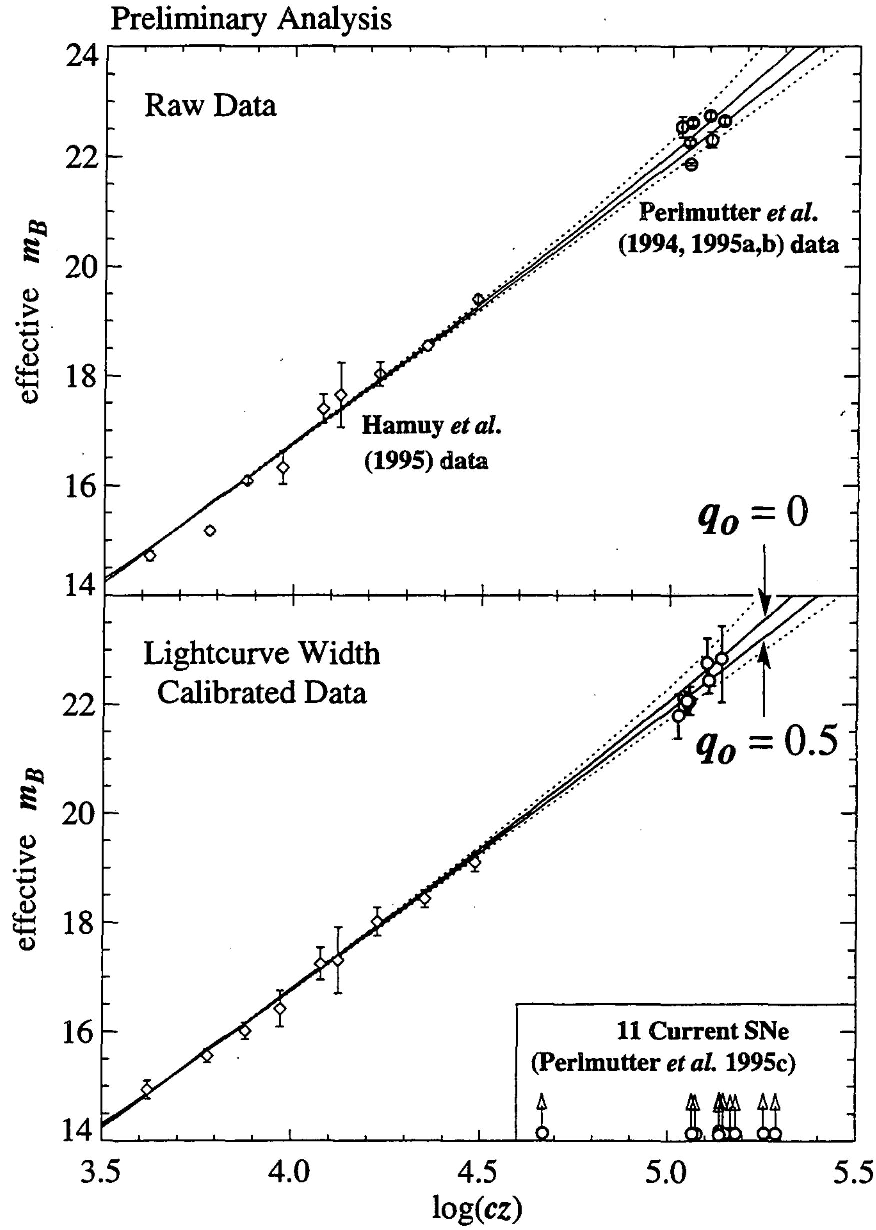

Figure 5. Hubble diagrams for first seven supernovae (preliminary analysis). Upper panel: "raw" apparent magnitude measurements, after K correction from R-band (observed) to B-band (supernova rest frame), versus redshift. The upper dotted curve is calculated for $q_0 = -0.5$, the two solid curves are 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

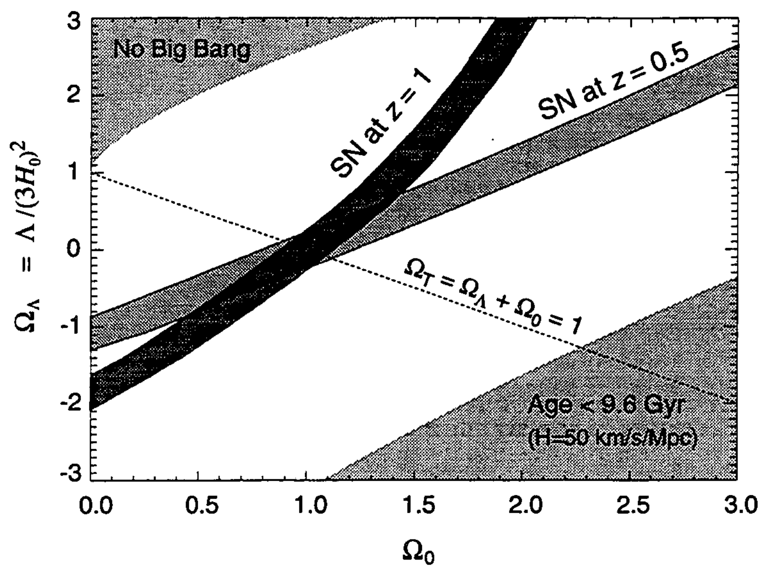

Figure 6. Theoretical bands of allowed parameter space in the Ω_Λ versus Ω_0 plane, for the hypothetical example of two SNe Ia discovered at $z = 0.5$ and at $z = 1$ in a universe with $\Omega_\Lambda = 0$ and $\Omega_0 = 1$ (from Goobar and Perlmutter 1995). The width of the bands is due to uncertainty 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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K CORRECTIONS FOR TYPE IA SUPERNOVAE AND A TEST FOR SPATIAL VARIATION OF THE HUBBLE CONSTANT

The Supernova Cosmology Project: II

A. KIM[1], S. DEUSTUA, S. GABI, G. GOLDHABER, D. GROOM,
I. HOOK, M. KIM, J. LEE, R. PAIN[2], C. PENNYPACKER, S. PERLMUTTER AND
I. SMALL
E. O. Lawrence Berkeley National Laboratory & Center for Particle Astrophysics, University of California, Berkeley

A. GOOBAR
University of Stockholm

R. ELLIS, K. GLAZEBROOK[3] AND R. MCMAHON
Institute of Astronomy, Cambridge University

B. BOYLE, P. BUNCLARK, D. CARTER AND M. IRWIN
Royal Greenwich Observatory

H. NEWBERG
Fermi National Accelerator Laboratory

A. V. FILIPPENKO AND T. MATHESON
University of California, Berkeley

M. DOPITA AND J. MOULD
MSSSO, Australian National University

AND

W. COUCH
University of New South Wales

Abstract.

Cross-filter K corrections for a sample of "normal" Type Ia supernovae (SNe) have been calculated for a range of epochs. With appropriate filter choices, the combined statistical and systematic K correction dispersion of the full sample lies within 0.05 mag for redshifts $z < 0.7$. This narrow dispersion of the calculated K correction allows the Type Ia to be used as a cosmological probe. We use the K corrections with observations of seven

[1]Presented by A. Kim, e-mail address: *agkim@LBL.gov*
[2]Current address: CNRS-IN2P3, Paris
[3]Current address: Anglo-Australian Observatory

SNe at redshifts $0.3 < z < 0.5$ to bound the possible difference between the locally measured Hubble constant (H_L) and the true cosmological Hubble constant (H_0).

1. Introduction

The homogeneity and brightness of Type Ia SN peak magnitudes have long made it a popular standard candle (Branch and Tammann 1992). Recent observations, as discussed in this meeting, now indicate that Type Ia's appear to form a family, rather than a set of identical objects. However, magnitude corrections based on independent observables can make the Type Ia a calibrated candle. Correlations between peak magnitude and light curve shape (Hamuy et al. 1995; Riess, Press, & Kirshner 1995) or spectral features (Nugent et al. 1995), have made it possible to use the Type Ia as a calibrated candle with B magnitude dispersions of ~ 0.2 mag. Alternatively, the use of Type Ia sub-samples can provide an improved standard candle. Supernovae with high quality data that pass certain color cuts show a low dispersion in B magnitudes of < 0.28 mag (Vaughan et al. 1995).

In order to use SNe as a tool for cosmology, we use K corrections (Oke & Sandage 1968) to account for the redshifting of spectra and its effect on nearby and distant flux measurements in different passbands. The sparseness of spectroscopic observations of any individual high-redshift SN requires us to use a statistical approach to K corrections. K corrections must therefore show a small magnitude dispersion to maintain the usefulness of the SN as a standard or calibrated candle.

As of June 1995, the Supernova Cosmology Project had discovered seven SNe lying in the range $0.3 < z < 0.5$ (Perlmutter et al. 1995; Perlmutter et al. 1996) . In a standard Friedmann cosmology, their apparent magnitudes depend on Ω and Λ through the luminosity distance. Perturbations on a homogeneous and isotropic universe can cause the locally measured Hubble constant (H_L) to differ from the global Hubble constant (H_0), as demonstrated by Turner, Cen, and Ostriker (1992). In this case if the SN calibrators lie within the local peculiar flow, then the high-z SN apparent magnitudes will additionally depend on H_L/H_0. A scenario in which $H_L/H_0 > 1$ has been suggested by Bartlett et al. (1994) and others to reconcile theoretical arguments for a low Hubble constant with the recent observational evidence for a large Hubble constant. We use our seven supernovae, with K corrections, to place bounds on H_L/H_0.

2. The K Correction

The generalization of the K correction of Oke & Sandage relating y band observations of redshifted objects with x band observations taken in the supernova rest frame is given by

$$
\begin{aligned}
K_{xy} &= -2.5\log\left(\frac{\int \mathcal{Z}(\lambda)S_x(\lambda)d\lambda}{\int \mathcal{Z}(\lambda)S_y(\lambda)d\lambda}\right) + 2.5\log(1+z) \\
&\quad + 2.5\log\left(\frac{\int F(\lambda)S_x(\lambda)d\lambda}{\int F(\lambda/(1+z))S_y(\lambda))d\lambda}\right) \\
&= -2.5\log\left(\frac{\int \mathcal{Z}(\lambda)S_x(\lambda)d\lambda}{\int \mathcal{Z}(\lambda)S_y(\lambda)d\lambda}\right) \\
&\quad + 2.5\log\left(\frac{\int F(\lambda)S_x(\lambda)d\lambda}{\int F(\lambda')S_y(\lambda'(1+z))d\lambda'}\right) \qquad (1)
\end{aligned}
$$

where $F(\lambda)$ is the spectral energy distribution at the supernova, $S_x(\lambda)$ is the x'th filter transmission, and $\mathcal{Z}(\lambda)$ is an idealized stellar spectral energy distribution at $z = 0$ for which $U = B = V = R = I = 0$ in the photometric system being used. K_{xy} is thus defined so that $m_y = M_x + \mu + K_{xy}$. If $S_x = S_y$, the first term drops out and this reduces to the K correction of Oke & Sandage. If $S_x(\lambda)$ is proportional to $S_y(\lambda(1+z))$, then statistical and systematic errors from the SN spectra, through the second term, are reduced.

We calculate generalized K corrections using Equation 1 with Bessell's (1990) color zeropoints and realizations of the Johnson-Cousins UBVRI filter system. (Note that Hamuy et al. (1995) had previously calculated single-filter standard K corrections.) We use a sample of SN data that includes 29 spectra from epochs $-14 \leq t^B_{max} \leq 76$ days (in the supernova rest frame) after blue maximum for SN 1981B, SN 1990N, and SN 1992A. The SN 1981B data are from Branch et al. (1983), SN 1990N data are described in Leibundgut et al. (1991), and SN 1992A data are described in Suntzeff et al. (1995) and Kirshner et al. (1993).

Figures 1 and 2 plot K_{BR} and K_{VR} for $z = 0.5$ as a function of SN rest frame epoch. The scatter in the data points reflects both statistical errors in the spectra, as well as SN to SN differences in K corrections. They also demonstrate the reduction of errors when filter pairs are chosen to match at the appropriate redshift, i.e. $S_x(\lambda)$ proportional to $S_y(\lambda(1+z))$. Based on analysis of different filter combinations at a range of redshifts, we find that with proper filter choice, these errors can be constrained within < 0.05 mag for redshifts $0 < z < 0.7$ and to within even smaller errors at epochs prior to 20 days after maximum light.

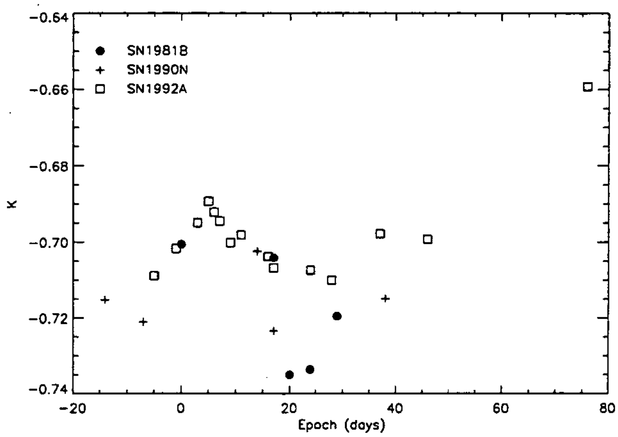

Figure 1. $K_{BR}(z = 0.5)$ as a function of epoch for SN 1981B, SN 1990N, and SN 1992A.

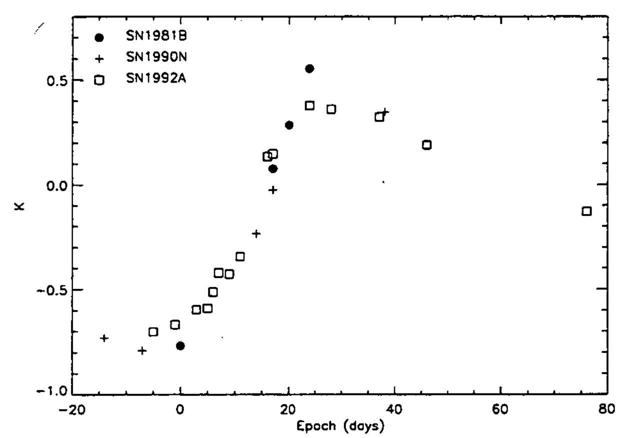

Figure 2. $K_{VR}(z = 0.5)$ as a function of epoch for SN 1981B, SN 1990N, and SN 1992A.

For more detailed discussion of the generalized K correction, see Kim, Goobar, & Perlmutter (1996).

3. Hubble Constant Constant?

We consider objects at a distance of $z > 0.3$ to be within the cosmological flow of standard Friedmann cosmology. Thus, the expected peak apparent magnitude of a Type Ia supernova beyond $z = 0.3$ can be calculated as a function of the mass density of the universe Ω_M ($\Lambda = 0$):

$$m_R = M_B + 5\log(3 \times 10^3 R_L(z; \Omega_M)) + K_{BR} + 25 - 5\log(h_0), \quad (2)$$

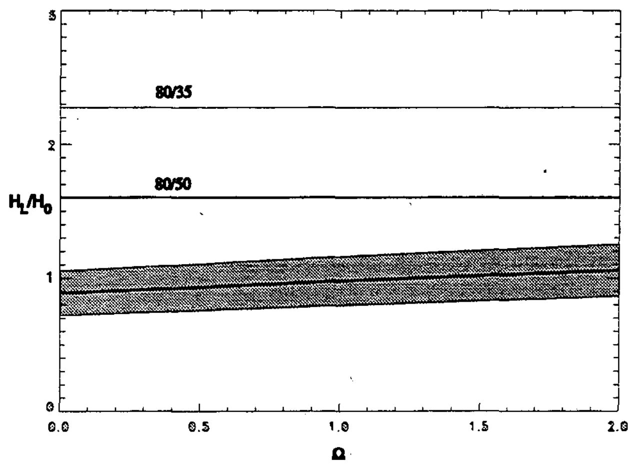

Figure 3. H_L/H_0 as determined from seven supernovae, as a function of Ω ($\Lambda = 0$).

where K_{BR} is the K correction and

$$R_L(z;\Omega_M) = \frac{4}{\Omega_M^2}\left[1 + \Omega_M(z-1)/2 + (\Omega_M/2 - 1)\sqrt{\Omega_M z + 1}\right] \quad (3)$$

If we use $M_B = -18.52 + 5\log(h_L/0.85) \pm 0.06$ from Vaughan, Branch, & Perlmutter 1995, we find

$$5\log\left(\frac{H_L}{H_0}\right) = m_R - 5\log(R_L) - K_{BR} - 24.22 \pm 0.06. \quad (4)$$

We have used preliminary analysis of seven high redshift supernovae (described by Perlmutter et al. in this volume), to calculate values for H_L/H_0 for a range of Ω_M, varying from 0 to 2 (see Figure 3). The shaded region represent a one sigma error bar on the value of H_L/H_0. A value of $H_L/H_0 = 80/35 = 2.29$ is strongly excluded, making peculiar velocities an unlikely cause for the disparity between Freedman et al.'s (1994) recent H_0 measurements for Virgo Cepheids and theoretical arguments (e.g. Bartlett et al.) for a low Hubble constant. We reach the same conclusion when using the magnitude corrections based on the width-brightness relation described in Perlmutter et al. 1996.

With the current data, it is impossible to simultaneously measure q_0 and H_L/H_0. In the future, with SNe well sampled in a broad range of redshifts, it should be possible to look for significant spatial (or temporal) deviations from the predicted Friedmann expansion.

4. Conclusions

We conclude that filter-matching K corrections give small enough errors to make SNe useful as cosmological probes. In the future, we will calculate K corrections using more SN spectra and we will search for a relation between light curve shapes and K corrections. Although we do not see such a correlation for the SNe that we have examined so far, which have only moderate departures from the Leibundgut template lightcurve, such a relation is likely to exist at some level since SN colors appear to be correlated with light curve shape, as discussed at this meeting by Riess et al.(1996) and Suntzeff et al.(1996).

We find that we can rule out significant spatial variation of the Hubble constant for $0 \leq \Omega_M \leq 2$. We plan to calculate H_L/H_0 for cosmologies with a cosmological constant, although positive values of Λ will only strengthen our limit.

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OBSERVATION OF COSMOLOGICAL TIME DILATION USING TYPE IA SUPERNOVAE AS CLOCKS

The Supernova Cosmology Project : III

G.GOLDHABER[1], S. DEUSTUA, S. GABI, D. GROOM, I. HOOK,
A. KIM, M. KIM, J. LEE, R. PAIN[2], C. PENNYPACKER, S. PERLMUTTER AND
I. SMALL
E. O. Lawrence Berkeley National Laboratory & Center for Particle Astrophysics, University of California, Berkeley

A. GOOBAR
University of Stockholm

R. ELLIS AND R. MCMAHON
Institute of Astronomy, Cambridge University

B. BOYLE, P. BUNCLARK, D. CARTER, K. GLAZEBROOK[3] AND
M. IRWIN
Royal Greenwich Observatory

H. NEWBERG
Fermi National Accelerator Laboratory

A. V. FILIPPENKO AND T. MATHESON
University of California, Berkeley

M. DOPITA AND J. MOULD
MSSSO, Australian National University

AND

W. COUCH
University of New South Wales

Abstract. This work is based on the first results from a systematic search for high redshift Type Ia supernovae. Using filters in the R-band we discovered seven such SNe, with redshift $z = 0.3 - 0.5$, before or at maximum light. Type Ia SNe are known to be a homogeneous group of SNe, to first order, with very similar light curves, spectra and peak luminosities. In this

[1]Presented by G. Goldhaber, e-mail address:*gerson@LBL.gov*
[2]Current address: CNRS-IN2P3, University of Paris
[3]Current address: Anglo-Australian Observatory

talk we report that the light curves we observe are all broadened (time dilated) as expected from the expanding universe hypothesis. Small variations from the expected $1 + z$ broadening of the light curve widths can be attributed to a width-brightness correlation that has been observed for nearby SNe ($z < 0.1$). We show in this talk the first clear observation of the cosmological time dilation for macroscopic objects.

1. Introduction

In an ongoing systematic search, we have recently discovered and studied seven supernovae (SNe) at redshifts between $z = 0.35$ and 0.46 as discussed in Perlmutter's talk at this conference. For details on search technique, light curves, and spectra, see Perlmutter et al. 1996.

2. Supernova Homogeneity

As discussed in several talks at this conference, Type Ia supernovae are, as a class, highly homogeneous. They are explosion events that are apparently triggered under very similar physical conditions. Their "light curves" scatter by less then $\sim 25\%$ RMS in brightness (Vaughan et al 1995a, 1995b), and less than 15% RMS in full-width-at-half-maximum (Perlmutter 1996), in a sample of "normal" Type Ia supernovae, after rejecting the abnormal $\sim$15% with red colors (see Vaughan et al 1995a). Their spectral signatures also follow a well-defined evolution in time. A paper giving all the photometric and spectroscopic measurements for our SNe,as well as a detailed discussion of the evaluation of q_0, is in preparation.

Most of our SNe have been followed for about a year. For three of our SNe we have obtained spectra at an early enough time to observe both the characteristic SN spectrum as well as the host galaxy spectrum. These three supernova spectra, in their rest system, all have spectral features matching nearby Type Ia's at the same epoch in great detail. In the other cases, we could not obtain the spectra early enough, due to inclement weather, so that by the time the spectra were taken the SN light could not be separated from the galaxy spectrum. Redshifts z were obtained from the host galaxy spectra. All these details on the spectra will be presented in our forthcoming paper (Perlmutter et al. 1996).

In the present paper we will make use of the "standard" nature of the Type Ia SNe light curves. This feature allows us to consider the Type Ia supernovae as "clocks" at cosmological distances.

3. The Observed SNe

Due to the large redshifts we are aiming for, we have carried out our search using R-band filters, while most of the data on nearby SNe was taken in B-band or V-band filters. To compare our data with nearby measurements in B-band magnitudes, we use a template compiled by B.Leibundgut. To this template curve we have to apply a K correction which compares the SN spectrum as observed "nearby" in a blue filter with the red shifted spectrum as observed at high z values in a red filter (as discussed by A. Kim at this meeting and Kim, Goobar, & Perlmutter 1996). The resulting new templates—one for each redshift—are then in the R-band in which our data was taken.

The recent work of Phillips (1993), Hamuy et al (1995), and Riess et al.(1995) has emphasized the *inhomogeneity* of Type Ia light curve shapes, particularly for the "non-normal" redder Type Ia's. Perlmutter (1996) provides a single-parameter characterization of these light curve differences, which is simply a time-axis stretch factor, s, which stretches (or compresses) the Leibundgut template light curve. From this study based on *nearby* SNe it was shown that this stretch factor s extends over a range of 0.65 to 1.1. To observe the effect of cosmological time dilation experimentally the expected dilation factor $1 + z$ is modified by the stretch factor s. The observable effect is then $d = s(1 + z)$. Since s is asymmetric around 1, for low values of s which occur for the most extreme 15% of non-normal Type Ia supernovae with red colors, the $1 + z$ effect can be essentially cancelled by s, giving an observed dilation of $d \approx 1$.

4. Fit to the data.

We fit each of our observed seven SNe to the R-band template light curve using the fitting program MINUIT (James and Roos 1994). Each SN is fit to this template, expressed now in normalized counts, (rather than in magnitudes). We fit three variables: the height of the light curve, the day of peak light and a time dilation, d, of the width of the light curve.

As an illustration of the cosmological time dilation effect, we show in Fig 1 one of our seven SNe R-band light curve data points, SN 1994H, plotted against the observed time axis. The dashed curve is the best fit Leibundgut template with K corrections, with no time dilation, i.e. d fixed at $d = 1$. This gives a $\chi^2/DoF = 3.1$. The solid curve is the best fit with d fixed at $d = 1 + z$ for a $\chi^2/DoF = 1.3$. This corresponds to the slowing down of our "clock", with the cosmological time dilation expected for a redshift of $z = 0.374$.

Given the asymmetric spread of light curve widths discussed above, we can predict what the distribution should look like at high redshifts for a

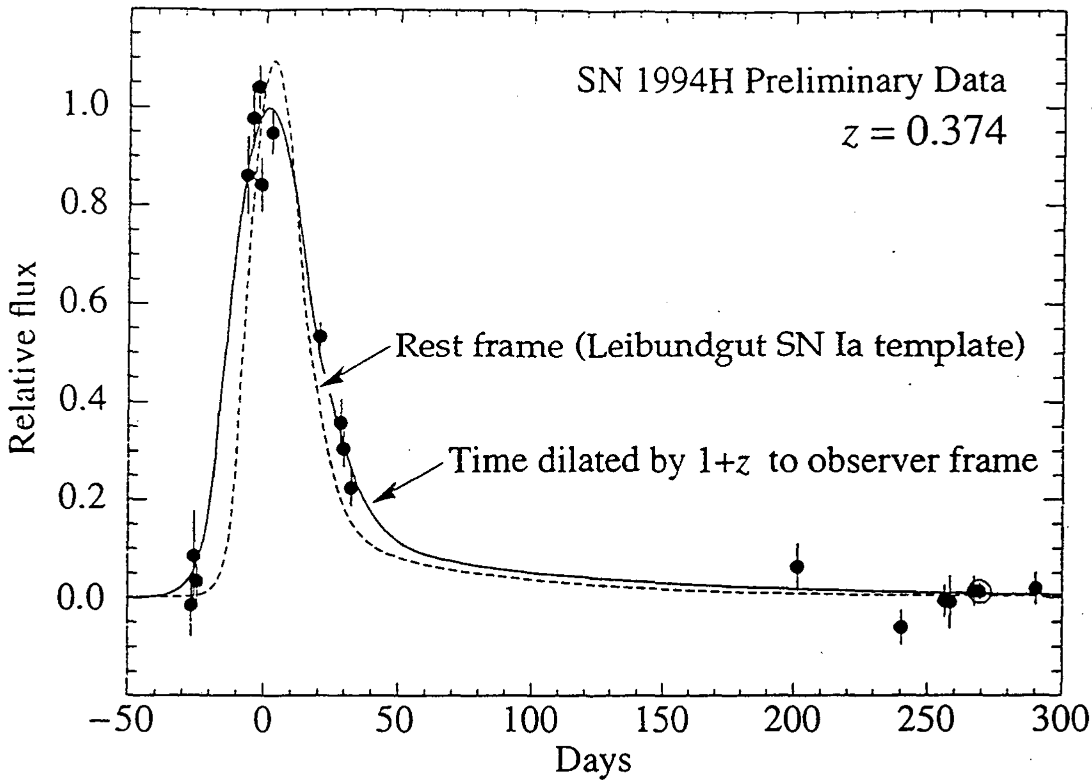

Figure 1. The best fit light curves for $SN94H$, under the hypothesis $d = 1$ dashed curve, and $d = 1 + z$, solid curve, where $z = 0.374$. The open circle corresponds to the reference image used.

universe with and without time dilation. These predictions are indicated by the shaded bands of Figure 2. Note that at redshifts between $0.1 < z < 0.5$, any examples of Type Ia supernovae with an observed width greater than $s(1 + z) = 1.1$ provide evidence for the time-dilation model; the narrower supernovae neither help nor hurt in distinguishing the models since the two ranges both are consistent with supernovae with observed width smaller than 1.1. At redshifts higher than $z = 0.5$, all supernovae become useful for separating the two models, since there is no overlap. Fig 2 also shows the actual data for the best-measured five of our seven SNe, plotted on top of these predicted ranges for the two models.

We can make this test even more powerful, even at redshifts $0.1 < z < 0.5$, by using another *independent* observable to indicate the intrinsic width of the supernova. Vaughan et al (1995) and Branch et al (1996) have shown that supernova color can indicate the width (and brightness) of a given supernova. $B - V$ color can distinguish among the narrow $s < 1$

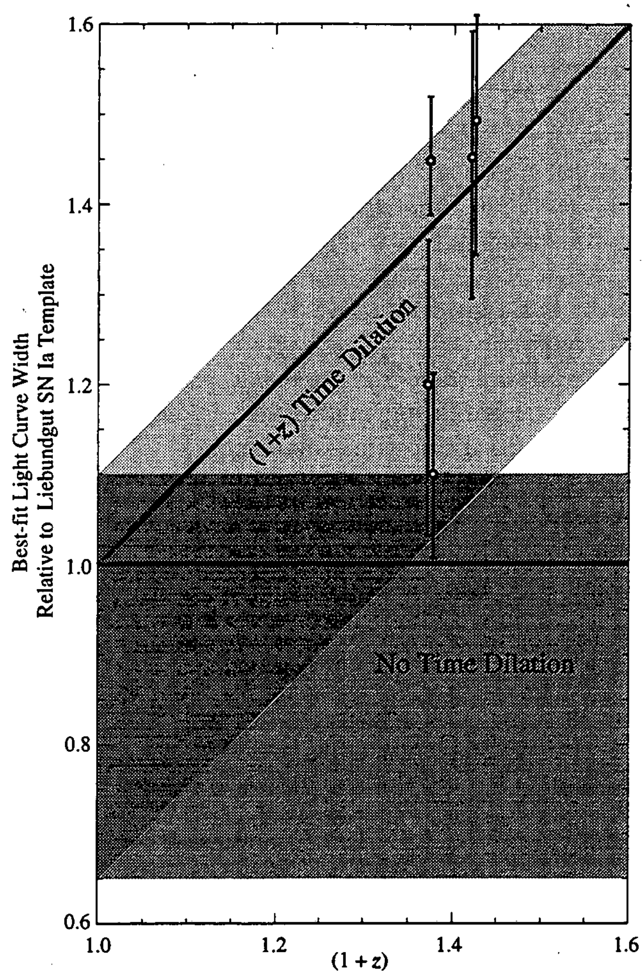

Figure 2. The observed fitted time dilation d plotted against $1+z$ The diagonal band corresponds to the time-dilation hypothesis taking into account the region of width-stretch,s, observed for nearby SNe. The band along the x-axis corresponds to the no-time-dilation case. The observed deviations from the time dilation case can be attributed to the known distribution in width caused by the width-peak-magnitude correlation folded into the experimental error.

supernovae, while $U - B$ color appears to identify the width and brightness of a supernova within the entire range from $0.6 < s < 1.1$. (It is possible to confuse intrinsic color differences with reddening, if sufficient photometry points are not available, however this is not a problem for the brighter, slower supernova light curves that appear *bluer*, and thus are not confused with reddened supernovae.)

So far we have completed color analysis of points on the light curve for two of the supernovae, SN94H and SN94G. SN94H has an observed $B-R$ color near peak consistent with a rest-frame $U-B$ color of ~-0.6, indicating that this supernova is like the nearby SN 1991T, which has a stretch factor of $s = 1.08 \pm 0.05$. SN94G has an $R-I$ color lightcurve that is consistent with a supernova with $s = 1.0 \pm 0.1$, and not consistent with narrower light curve supernovae. (Note that neither of these light curves is consistent with significant reddening.) In Figure 3, we plot these two supernovae after dividing out the intrinsic width, s, deduced from their color, and adding in quadrature the extra error bar's uncertainty. On this plot the two models now appear as lines, not ranges.

It is clear from Figures 2 and 3, that the time dilation model is the much better fit to the data. The $\chi^2/DoF = 0.13$ for the time dilation hypothesis, the diagonal line on Figure 3, while $\chi^2/DoF = 12.6$ for the no-time-dilation hypothesis, the line along the x-axis. Thus for the majority of our distant SNe the values for d are dominated by the cosmological time dilation. We are obtaining color information on all the more recent supernovae to make it possible to plot future observations on Figure 3, after identifying the intrinsic width from the color.

5. Historical note.

A measurement such as we have performed was first proposed by O. C. Wilson, in 1939, as a simple test of the conjecture that astronomical redshifts are explained by an expanding universe model, rather than, e.g., "the gradual dissipation of photonic energy," later called the "tired light" model. The expanding universe has by now won almost universal acceptance, this classical test, while attempted by Rust (1974) has however never been demonstrated until now, due to the lack of sufficiently distant "standard clocks." In an expanding universe, the time dilation, d , should match the redshift of spectral features, $d = 1 + z$, while a tired light model implies no time dilation, $d = 1$, at any redshift. (Even in an expanding universe, some "tiring" of light could occur, and this test could also be turned around to bound the extent to which photons lose energy traveling through intergalactic space.) While some of the errors in our fit of the lightcurve dilation-factor are large, it is clear that we have observed the time dilation of macroscopic clocks at cosmological distances.

6. Discussion

There is one source of concern that must still be addressed: how certain are the Type Ia identifications? We expect to find primarily Type Ia since these are the brightest SNe by typically 2 magnitudes. For three of our SNe we have spectral identification and their light curves are consistent with the

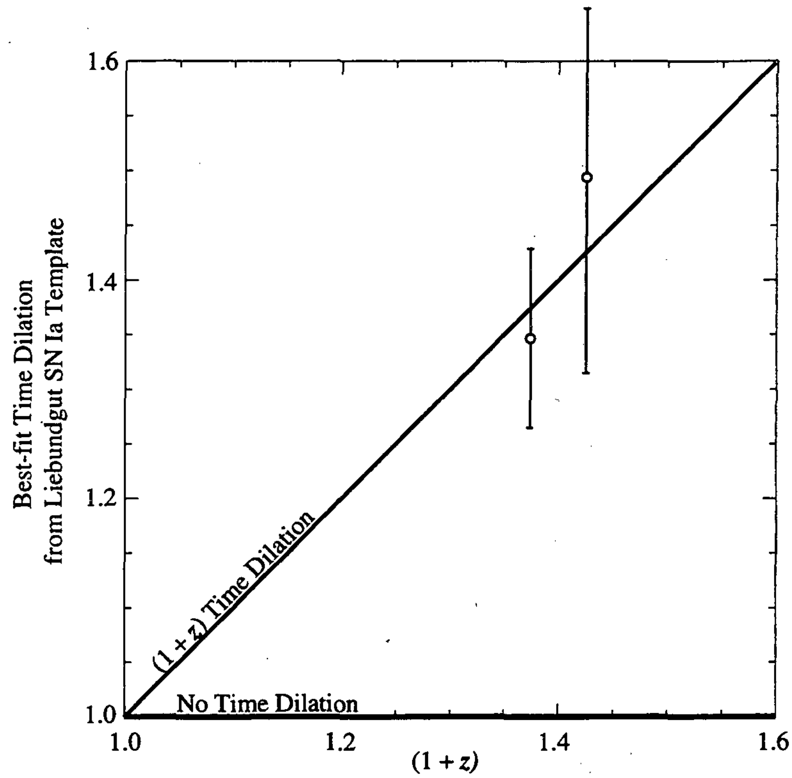

Figure 3. A plot of d/s for two of our SNe, SN94H and SN94G for which the stretch, s, was deduced from the SNe colors.

other four. One of the remaining four SNe was discovered in an eliptical galaxy, and therefore is highly likely to be a Type Ia. In sum, the current set of data are very likely to all be SNe Ia.

Acknowledgements

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THE TYPE IA SUPERNOVA RATE AT $z \sim 0.4$

The Supernova Cosmology Project: IV

R. PAIN, [1,2], I. M. HOOK[1], S. PERLMUTTER, S. DEUSTUA, S. GABI, G. GOLDHABER, D. GROOM, A. G. KIM, M. Y. KIM, J. C. LEE, C. R. PENNYPACKER AND I. A. SMALL
E. O. Lawrence Berkeley National Laboratory & Center for Particle Astrophysics, University of California, Berkeley

A. GOOBAR
University of Stockholm

R. ELLIS, R. MCMAHON AND K. GLAZEBROOK[3]
Institute of Astronomy, Cambridge University

AND

B. BOYLE, P. BUNCLARK, D. CARTER AND M. IRWIN
Royal Greenwich Observatory

Abstract. We present the first measurement of the rate of Type Ia supernovae at high redshift. The result is derived using a large subset of data from the Supernova Cosmology Project as described in more detail at this meeting by Perlmutter et al. (1996). We present our methods for estimating the numbers of galaxies and the number of solar luminosities to which the survey is sensitive, the supernova detection efficiency and hence the control time. We derive a rest-frame Type Ia supernova rate at $z \sim 0.4$ of $0.82\ ^{+0.54}_{-0.37}\ ^{+0.42}_{-0.32}\ h^2$ SNu where the first uncertainty is statistical and the second includes systematic effects.

1. Introduction

Beginning with the discovery of SN 1992bi (Perlmutter et al 1995), we have developed search techniques and rapid analysis methods that allow systematic discovery and follow up of "batches" of high-redshift supernovae.

[1]Presented by I. Hook (*imh@mh1.lbl.gov*) and R. Pain (*rpain@lpnax1.in2p3.fr*)
[2]Current address: CNRS-IN2P3, University of Paris
[3]Current address: Anglo-Australian Observatory

The observing strategy developed compares large numbers of galaxies in each of ~50 fields observed twice with a separation of ~3 weeks. This search schedule makes it possible to precisely calculate the "control time," the effective time during which the survey is sensitive to a Type Ia event.

For this analysis, we have studied a set of 52 similar search fields observed in December 1993 and January 1994. The data were obtained using the "thick" 1242×1152 EEV5 camera at the 2.5m Isaac Newton Telescope, La Palma. The projected pixel size is $0.56''$, giving an image area of approximately $11' \times 11'$. Exposure times were 600s in the R_{Mould} filter, and the images typically reach a 3σ limit of $R = 23$mag. Seeing was typically around $1.4''$. Many of the fields were selected due to the presence of a high-redshift cluster ($z \sim 0.4$). Suitable clusters and their redshifts were taken from Gunn, Hoessel & Oke (1986) and from the ROSAT catalog. The total useful area covered in this study is 1.73 sq deg.

The analysis procedure and method for finding SNe can be summarized as follows. For most fields, two first-look "reference" images were obtained and for all fields two second look "search" images were obtained $2-3$ weeks after the reference images. The images were flat-fielded and zero-points for the images were estimated by comparison with E (red) magnitudes of stars in the APM (Automated plate measuring facility, Cambridge, UK) POSSI catalog (McMahon & Irwin 1992). The search images were combined (after convolution to match the seeing of the worst of the four images) and the combined reference images were subtracted from this after scaling in intensity. The resulting difference image for each field was searched for SN candidates.

In this subset of the search data three SNe were found with redshifts 0.354, 0.375 and 0.420 determined from spectra of the host galaxies. For the purposes of this analysis, we assume these are all Type Ia SNe (see Perlmutter et al. 1996). The method used to calculate the rate can be divided into two main parts: (i) estimation of the number of galaxies and the total stellar luminosity (measured in $10^{10}\,L_{B\odot}$) to which the survey is sensitive and (ii) estimation of the SN detection efficiency and hence the control time.

2. Galaxy counts

In order to compare the distant SN rate with local equivalents, we need to know the redshifts of the galaxies we have surveyed. In this work we use the galaxy counts derived from the analysis of Lilly et al (1995) to estimate the number of galaxies sampled as a function of redshift. R band counts as a function of redshift were calculated by Lilly based on the analysis of magnitude–redshift data obtained in the Canada-France Redshift Survey

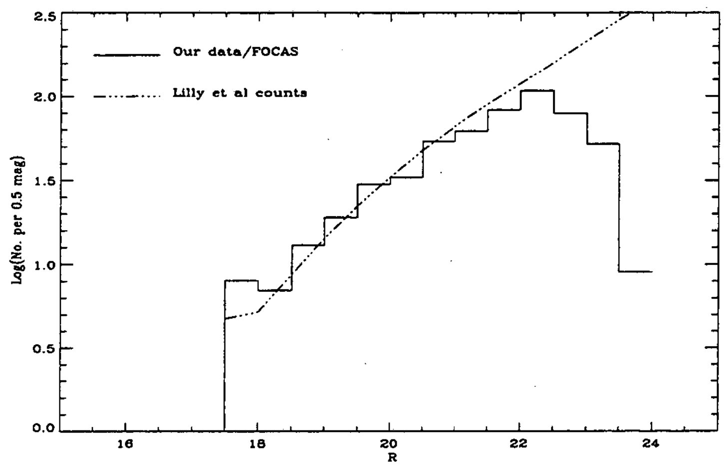

Figure 1. **Number of galaxies as a function of magnitude determined from one of our non-cluster images using FOCAS. The dashed-dot line shows the counts derived from the analysis of Lilly et al (1995), integrated over the redshift range $0 < z < 2$, and normalized to the image area of 0.03 sq deg.**

(Lilly et al, 1995 and references therein). To check that the assumed distribution of galaxies with R magnitude and redshift, $N(z, R)$, give reasonable galaxy counts compared to our data, we have plotted the number of field galaxies classified by the FOCAS software package, as a function of apparent magnitude, on one of the search images that was *not* targeted at a galaxy cluster. The R-band galaxy counts given by the analysis of Lilly et al (1995) integrated over the redshift range $0 < z < 2$ (dash-dotted line) are shown on the same scale, assuming an effective area for this image of 0.03 sq deg (Figure 1).

Many of our search fields were chosen specifically to target high-redshift clusters. For each of these fields, we estimate the number of cluster galaxies by counting galaxies as a function of R magnitude in a box of size 500×500 pixels centered approximately on the center of the cluster as estimated by eye from the images. The counts in a similar box in a region of the image away from the cluster were subtracted from the cluster counts to give the cluster excess counts as a function of R mag. Typically a cluster contributes 10% of the galaxy counts on an image. We assign these galaxies to the cluster redshift, and add the cluster contribution to the $N(z, R)$ for that image given by the models.

Values of reddening due to the Galaxy were supplied by D. Burstein (derived from Burstein & Heiles, 1982) for each field and applied to the data assuming $R_V = 3.1$ and $A_R/A_V = 0.751$ (Cardelli et al, 1989).

3. Control times and detection efficiencies

To calculate the control times we assumed that SN magnitude as a function of time follows the average of the best-fit, time-dilated and K-corrected Leibundgut (1988) Type Ia template light curves (the generalized K correction described by Kim et al. (1996) and Kim, Goobar & Perlmutter (1995), was used here). The control time is then given by the weighted sum of days during which the SN can be detected, where the weighting is by the detection efficiency, ϵ.

This detection efficiency is a function of the magnitude difference Δm (zero if Δm is negative), which is itself a function of time t relative to maximum, and δt, the time separation of the search and reference images. It depends on the quality of the subtracted images (seeing, transmission) together with the detailed technique (convolution, selection criteria) used to extract the signal (SNe candidates) from the background (cosmic rays, asteroids, bad subtractions, etc). In addition, there is a slight dependence on the host galaxy magnitude. The detection efficiency was calculated using a Monte-Carlo method. A synthetic image was created for every field by adding simulated supernovae to the search images using point-spread-functions drawn from each search image. The reference images were subtracted from the synthetic search images using exactly the same software as used for the supernova search and the number of simulated SNe that satisfy the selection criteria was determined. This technique allows us to measure detection efficiencies as a function of supernovae magnitude individually for every field, thus taking into account the other parameters mentioned above.

Figure 2(a)-(c) shows the fractional number of simulated SN recovered, as a function of SN magnitude (at detection) for the three fields in which SNe were found. Figure 2(d) shows the efficiency as a function of relative surface brightnesses of the SN and host galaxy. This last parameter gives an indication of the effect of SN location with respect to the host galaxy. Although this is a small effect, it was taken into account. For a typical field the detection efficiency is over 85% for any added fake stellar object brighter than $R = 22.0$ magnitude (Note that the more recent searches of this project have worked with significantly deeper images).

4. SN Ia Rates

4.1. SURVEY RATE

Before calculating the luminosity-weighted SN rate, we first determine a "survey rate" of SN discoveries that a search for Ia SNe can expect to obtain, per square degree. We give the rate in a range of 1 mag in R,

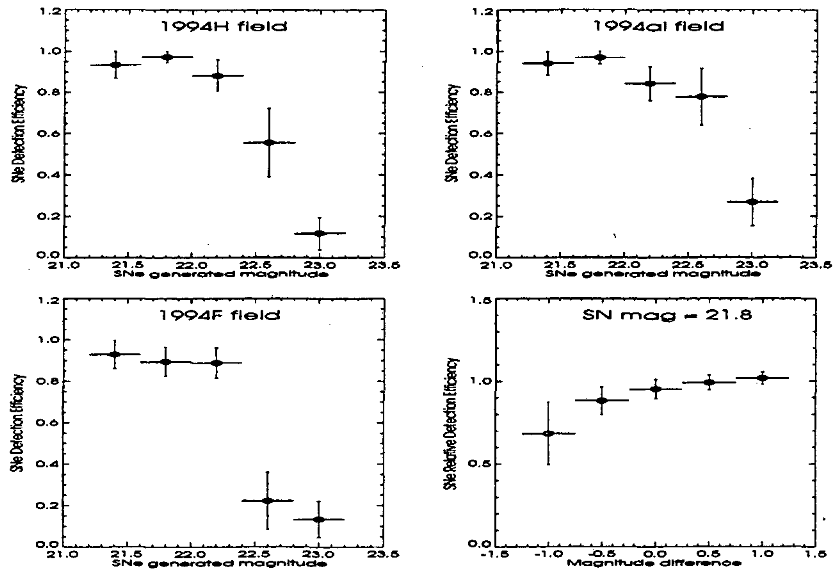

Figure 2. (a)-(c) Detection efficiency as a function of relative SN to host surface brightness. (d) Detection efficiency as a function of magnitude for the three difference images in which SNe were found. The vertical error bars show the 1σ statistical uncertainty, and the horizontal bars show the bin ranges.

centered on the mean peak R magnitude of the 3 SNe found in this search, $R = 21.8$. The survey rate is given by

$$survey\ rate\ (21.3 < R < 22.3) = \frac{N_{SN}}{\sum_i area_i \times \Delta T_i}.$$

where $N_{SN} = 3$ is the number of SNe we found in the 1 magnitude range, and ΔT_i is the control time for field i, computed for a SN with magnitude $R = 21.8$ at maximum. For example a value of $\Delta T_i = 21$ days was found for the field containing SN1994H observed on 1993 December 19 and 1994 January 12, 24 days apart. We measure a survey rate for $21.3 < R < 22.3$ of $34.4\ ^{+23.9}_{-16.2}$ SNe $year^{-1} deg^{-2}$ (the error quoted is statistical only). In practice this translates to 1.73 SNe per square degree discovered with a 3 week baseline, in data with limiting magnitude $R \sim 23$ ($S/N \sim 3$ for R=23).

4.2. RATE IN SNU

To calculate the rate in SNu, we compute the expected redshift distribution of SNe, $N_{exp}(z)$, which is proportional to the observed SN rate, $r_{SN}(1+z)^{-1}$,

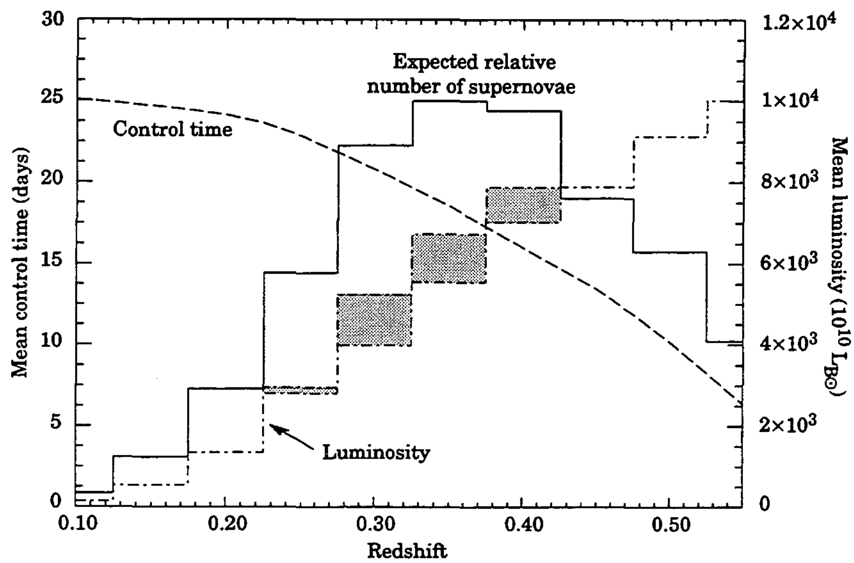

Figure 3. The expected number of supernovae as a function of z (solid histogram) together with the overall control time (dashed curve) and the luminosity-weighted number of galaxies (dash-dot histogram). The contribution to the luminosity from clusters is shown by the shaded area. The December 1993-January 1994 search data was most likely to find SNe with redshifts between $z = 0.3$ and $z = 0.4$. Between $z = 0.3$ and $z = 0.55$, the search was more than 50% efficient. Note that our more recent searches go deeper than this data.

where r_{SN} is the rate in the rest-frame of the supernovae. It is given by

$$N_{exp}(z) = \frac{r_{SN}}{1+z} \sum_R \sum_i N_{gal}(z,R)_i \times L_B(z,R) \times \Delta T_i(z,R)$$

where i runs over all fields, R is the galaxy apparent R magnitude and L_B is the galaxy rest-frame B band luminosity in units of $10^{10}\,\mathrm{L_{B\odot}}$. The control times ΔT, in units of centuries, have been calculated for each field in bins of z and R (the size of the bins is 0.5 mag in R, 0.05 in z).

To compute the rest-frame B band galaxy luminosities from apparent R magnitudes, we used $B-R$ colors and B-band K corrections supplied by Gronwall & Koo. Note that the combined color, K and evolution correction is small in the redshift range of interest $(0.3-0.5)$ since the observed R band is close to the rest-frame B-band. In this calculation $\mathrm{M_{B\odot}} = 5.48$ and $q_0 = 0.5$ were assumed. The rest frame supernovae rate r_{SN} at $z \sim 0.4$ was obtained by fitting the redshift distribution of observed SNe to the expected distribution, $N_{exp}(z)$ using a maximum-likelihood fit using Poisson statistics. The mean redshift corresponding to this rate is $< z >=$

TABLE 1. Systematic Uncertainties. Uncertainties in the rate are in h^2 SNu.

Source	uncertainty
Luminosity estimate	0.09
Cluster contribution	0.02
Galaxy extinction	0.01
APM calibration	0.10
Detection efficiency	0.08
non-standard SNe	0.29
Scanning efficiency	$-0.00 + 0.27$
Total syst. uncertainty	$-0.32 + 0.42$

0.38. We derive a value for the SN rate of

$$r_{SN}(z = 0.38) = 0.82 \,^{+0.54}_{-0.37}\, h^2 \text{ SNu}.$$

where the error is statistical only.

4.3. SYSTEMATIC UNCERTAINTIES

We have studied various sources of systematic uncertainty. Table 1 summarizes their contributions. For given assumed galaxy counts, the main contribution comes from the fact that Type Ia SNe are not perfect standard candles.

We also tested the sensitivity of our result to the assumed form of galaxy evolution, $N(z, R)$, by recalculating the rate using the model of Gronwall & Koo (1995) and that used by Glazebrook et al (1995). These give values for the rate of $1.61^{+1.05}_{-0.73}h^2$ SNu and $1.27^{+0.83}_{-0.57}h^2$ SNu respectively. Although there is a large difference in the results derived using the counts of Lilly et al compared with the other models, we choose not to include this in the systematic uncertainty. For the purposes of this analysis we use the Lilly et al counts, since these are based on data that are well-matched to our survey in magnitude and redshift range, and only small amount of extrapolation was required in converting from the I to R band.

Host galaxy inclination and extinction effects could not be estimated following the analysis used for nearby searches because of the different detection techniques involved. A correct estimation would require modeling of galaxy opacities, which is beyond the scope of this paper. We therefore compare our uncorrected value with uncorrected values for nearby searches, Altogether, we estimate the total systematic error to be $^{+0.32}_{-0.42}$ and we assume the Lilly et al counts for $N(z, R)$.

5. Discussion and Conclusion

This measurement is the first direct measurement of the Type Ia rate at high redshift. In their pioneering work searching for high redshift supernovae, Hansen et al. (1989) discovered a probable Type II event at $z = 0.28$ and a Type Ia event at $z = 0.31$ (Nørgaard-Nielsen et al., 1989), however no estimates of SN Ia rates were published based on this discovery.

Nearby Supernovae rates have been carefully reanalyzed recently (Cappellaro et al. 1993a & 1993b, Turatto et al., 1994, Van den Bergh and McClure, 1994, Muller et al. 1992) using more precise methods for calculating the control times and correcting for inclination and over-exposure of the nuclear regions of galaxies in photographic searches. The rate obtained for Type Ia SNe are now consistent among these groups and vary between 0.2 h^2 SNu and 0.7 h^2 SNu depending on the galaxy types (E, Sa etc., higher rates are found in later type galaxies). Taking into account the facts that at $z \sim 0.4$ the ratios of galaxy type are different and using the Type Ia rates reported in Cappellaro et al (1993b), we calculate a local rate of 0.53 ± 0.25 h^2 SNu for the mix of galaxies expected at $z \sim 0.4$. Our measured value of $0.82^{+0.68}_{-0.49}h^2$ SNu (where statistical and systematic uncertainties have been combined), although slightly higher, agrees with this value within the uncertainty and indicates that Type Ia rates do not change dramatically out to $z \sim 0.4$. Note, however that correcting for host galaxy extinction and inclination may change this conclusion.

Theoretical estimates of Type Ia SNe rates have been derived from stellar and galaxy evolution models. Calculations were done mostly for elliptical galaxy type. Recent calculations, based on evolutionary models of elliptical galaxies, predict rates of $\sim 0.1h^2$ SNu (Ferrini & Poggianti 1993). Assuming a factor of ~ 2 higher rate in non-elliptical galaxies compared to ellipticals (Capellaro et al. 1993b) and a mix of galaxy types as above, we convert this to an overall rate of Type Ia SNe at $z \sim 0.4$ in all galaxy types, and derive a value of $\sim 0.37h^2$ SNu. Our total uncertainty of $^{+0.68}_{-0.49}$ in the measurement presented in this paper does not allow any firm conclusion but our observed rate seems to lie above this theoretical prediction. There may be an increase of Type Ia rate with redshift. Ruiz-Lapuente, Burkert & Canal (1995) predict significant increase in rate for redshifts between 0.4 and 0.8 depending on the specific model they consider. In the near future, our ongoing high-z SN search and others should provide enough data to constrain the theoretical calculations.

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Ernest Orlando Lawrence Berkeley National Laboratory
Technical and Electronic Information Department
University of California | Berkeley, California 94720