Constraints on Cosmological Models from Hubble Space Telescope Observations of High-z Supernovae

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ABSTRACT

We have coordinated *Hubble Space Telescope* photometry with ground-based discovery for three supernovae: two SN Ia near $z \sim 0.5$ (SN 1997ce, SN 1997cj) and a third event at $z = 0.97$ (SN 1997ck). The superb spatial resolution of *HST* separates each supernova from its host galaxy and leads to good precision in the light curves. The *HST* data combined with ground-based photometry provide good temporal coverage. We use these light curves and relations between luminosity, light curve shape, and color calibrated from low-z samples to derive relative luminosity distances which are accurate to 10% at $z \sim 0.5$ and 20% at $z = 1$. The redshift-distance relation is used to place constraints on the global mean matter density, Ω_m, and the normalized cosmological constant, Ω_Λ. When the *HST* sample is combined with the distance to SN 1995K ($z = 0.48$), analyzed by the same

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precepts, it suggests that matter alone is insufficient to produce a flat Universe. Specifically, for $\Omega_m + \Omega_\Lambda = 1$, Ω_m is less than 1 with $> 95\%$ confidence, and our best estimate of Ω_m is -0.1 ± 0.5 if $\Omega_\Lambda = 0$. Although the present result is based on a very small sample whose systematics remain to be explored, it demonstrates the power of *HST* measurements for high redshift supernovae.

Subject headings: –cosmology:observations– galaxies:distances and redshifts– supernovae:general supernovae: individual (SN 1995K, SN 1997ce, SN 1997cj, SN 1997ck)

1. Introduction

The direct measurement of global curvature and deceleration of the Universe has challenged the best efforts of observers for many decades (Humason, Mayall and Sandage 1956, Baum 1957, Sandage 1988). Progress has been stymied by a lack of reliable standard candles and yardsticks, and the difficulty of making precise measurements on faint objects at high redshift. Two recent advances now offer the hope of solving this classical problem: the empirical calibration of Type Ia supernovae (SNe Ia) as precise distance indicators, and new technology that allows the measurement of supernova (SN) properties at large distances. This *Letter* reports the results from coordinated ground-based and *Hubble Space Telescope* (*HST*) observations of distant SNe up to $z \sim 1$ in an effort to extend the luminosity-distance relation to regions where the cosmological effects of deceleration and curvature can be measured (Nørgaard-Nielsen et al. 1989; Perlmutter et al. 1997; Schmidt 1997).

Type Ia SNe are proven to be excellent distance indicators. They are not perfect standard candles, but their luminosities correlate with light curve shape so differences in intrinsic brightness can be taken into account by observing the SN light curve (Phillips 1993; Hamuy *et al.* 1996 [H96]; Riess, Press, & Kirshner 1996 [RPK]). Using the techniques of RPK and H96, relative distance estimates to individual events are accurate to better than 10% despite a range of more than a magnitude in intrinsic brightness. Colors of SNe Ia provide a way to correct for extinction by dust in both our Galaxy and the host. Cosmological models predict the shape of the relation between luminosity distance and redshift, thus relative distances constrain curvature and deceleration independent of the Hubble constant. By using the same methods at high and low redshift, based on our extensive study of SN Ia, we expect to minimize the systematic errors that can undermine any enterprise of this type. Even evolutionary effects, which have bedevilled all previous attempts to measure q_0, can to some extent be calibrated by studying contemporary samples in populations of different ages and metallicity; Schmidt et al. (1997a, [SSP97]) demonstrate that any current population-dependent bias in luminosity is less than $m - M = 0.06$ mag.

Our team has undertaken a program to discover and study SNe Ia at $z > 0.3$ (Schmidt *et al.* 1995, 1997b; Kirshner *et al.* 1995; Suntzeff *et al.* 1996; Garnavich *et al.* 1996, 1997a, 1997b; Leibundgut *et al.* 1996; Riess *et al.* 1997; Tonry *et al.* 1997). We have discovered more than 70 candidates which include nearly 30 confirmed SN Ia. Results from our first discovery (SN 1995K at $z = 0.48$), a detailed description of our techniques, and a discussion of possible systematic errors are given by SSP97. Here, we present preliminary results from our ground-based search combined with *HST* and ground-based photometry. *HST*'s exquisite imaging reduces the contribution from host galaxy light and *HST*'s indifference to lunar phase provides continuous coverage over the period needed to define the shape of the light curve. In §2 we discuss the discovery and photometry of two SNe Ia at $z \sim 0.5$ and an object at $z \sim 1$ which is very probably a type Ia event. In §3 we analyze the light curves using the Multicolor Light Curve Shape (MLCS) method (RPK) and a template fitting technique (Hamuy *et al.* 1995) to determine distances. In §4, we produce a consistent Hubble diagram in the range $0.01 < z < 1.0$ and use the results to constrain cosmological models.

2. Observations

2.1. The Search

The *HST*-coordinated search for distant SNe was conducted at the Canada-France-Hawaii Telescope (CFHT) on 1997 April 29 and 30 (UT) using the UH8K CCD mosaic. The camera has eight 4096x2048 pixel arrays and a field of view of nearly 0.5 degrees with a scale of 0.21 arcsec/pixel. Four fields, selected and scheduled long in advance for *HST* visibility, were imaged in broad-band I and V filters, for a total search area of about one square degree. We compared the images with template frames of the same regions taken April 4 and 9 (UT) to detect variable objects. The seeing on the search frames was between $0.5''$ and $0.6''$ and approximately $0.7''$ (FWHM) on the template frames. A minimum of three 1200 second exposures were taken of each field and combined with a median filter. This process eliminates cosmic ray events, CCD flaws and asteroids. The magnitude limit of each field varied with exposure times and seeing, but typical isolated stellar images could be detected to $I < 24.5$. In software, the two sets of images were aligned, convolved to match point-spread functions, scaled, and subtracted. The subtracted images were then searched in software for residual point sources and inspected by eye.

Twelve SN candidates were identified from the search. Two of the objects had blue

$V - I$ colors unlike any high-redshift SN Ia. Spectra of eight of the remaining candidates were obtained with the Multiple-Mirror Telescope on May 1 and 2, and with the Keck 10m telescope on May 4. One of the candidates had a spectrum characteristic of an active galactic nucleus, two could not be classified, one was a SN II at $z = 0.28$, and four of the objects were identified as SN Ia (Tonry et al., 1997). We selected SNe 1997ca, 1997ce, 1997cj and 1997ck for *HST* observations based on the *HST* scheduling requirement to have exactly one target in each of the four fields and the likelihood that the target was a SN Ia before maximum from the spectrum and the photometry in hand on May 5. Subsequent photometry of SN 1997ca indicated that it probably is not a SN Ia. A reanalysis of the spectrum shows that it is consistent with a SN II at $z \sim 0.4$.

2.2. *HST* and Ground-based Imaging

Following discovery, photometry of the SNe was obtained with a variety of ground-based telescopes and eventually with *HST*. Even for a well-coordinated program, the interval between discovery and the first *HST* observation can be more than two weeks so earth-based data are important to define the light curve before maximum light.

Our first WFPC2 images were obtained on 1997 May 12, just a week after the Keck spectra. We observed each SN in the WF3 chip on six visits spanning approximately three weeks in the SN rest frame. Each epoch was allotted one *HST* orbit. For the $z \sim 0.5$ targets, the orbit was divided into a 800 second exposure in the F675W filter and a 1100 second exposure with the F814W filter. These filters approximate the standard B and V bandpasses at $z \sim 0.5$ and we have computed K-corrections for both the *HST* and ground-based observations according to SSP97. At $z \sim 1$, the F850LP is well matched to the rest frame B band while the V band is shifted beyond the limits of WFPC2 sensitivity. The exposures of SN 1997ck in the F850LP filter were set to fill the target visibility window with a minimum total exposure of 2200 seconds. All observations were divided into two exposures, and we combined the cosmic-ray split images using the default parameters in the STSDAS/HST_CAL/WFPC/CRREJ algorithm which is designed to avoid confusing stellar images with cosmic rays in undersampled data. As a test, we performed aperture photometry on bright, unsaturated stars observed at each epoch and found a scatter of less than 0.01 mag, consistent with the predicted statistical error. Plate 1 displays images of each SN made by adding all the observations.

We calibrated a sequence of stars near each supernovae using both *HST* and ground-based data. The magnitudes of stellar objects in the *HST* images were estimated using the prescription of Holtzman *et al.* (1995). The data numbers within $0.3''$ radius aperture were summed and we subtracted the background level estimated from a large region around the image. The small aperture was selected to minimize background noise, so an aperture correction based on the PSF created from stars in the field was applied to bring the measurement to the equivalent of a $0.5''$ aperture and the result converted to a magnitude in the *HST* filter system. For the F850LP filter, only a synthetic zeropoint (ZP) was available but it is estimated by Whitmore (1995) to be good to $\sim 3\%$.

Observations of standard stars and three of the *HST* fields were obtained in the R and I bands under photometric conditions on three nights with the Hawaii 88-inch telescope in 1997 May. The F675W and F814W magnitudes for 15 stars in common with the Hawaii data were converted to R and I magnitudes using ZPs and second order color terms provided by Holtzman *et al.* (1995). There is a significant color residual between the two calibrations, but for the seven stars with colors similar to those expected for the SNe ($R - I < 1.2$), the average difference between the ground-based (GRD) and *HST* magnitude estimates is only $R_{GRD} - R_{HST} = -0.02 \pm 0.05$ mag and $I_{GRD} - I_{HST} = 0.00 \pm 0.04$ mag, verifying the Holtzmann ZPs.

From the ground, light from the host galaxy is a major source of uncertainty in measuring SN light curves. *HST* allows the SN and the galaxy light to be more easily separated, but the host background must still be removed. For SNe 1997ce and 1997cj, an empirical point-spread-function (PSF) derived from nearby stars in the field was scaled to the peak brightness of the SN and subtracted from each observation. The four pixels at the SN position were smoothed, then all the epochs combined to produce one high signal-to-noise ratio image. This template was subtracted from each *HST* epoch leaving only the SN and other stars in the image to be measured with aperture photometry. The PSF subtraction is not perfect, and we have estimated, through simulations, the uncertainty in the background (always $< 2\%$), and included this error with the estimated statistical error of each measurement. The host galaxy for SN 1997ck was insignificant in the F850LP filter, so no correction was necessary.

Reduction of the ground-based data followed the procedures outlined by SSP97. The *HST* image templates, described above, were used to subtract the host galaxy background, and the relative brightness between the SN and other stars in the field were estimated for each frame using PSF fitting routines in DoPHOT (Schechter, Mateo, & Saha 1993). Artificial stars were added and measured to estimate the uncertainty of each measurement, with these errors added in quadrature to those resulting from the imperfect template.

In both cases, the ZP (and color term for the ground-based data) were determined using the F675W and F814W magnitudes of the field stars on the *HST* frame. K-corrections were applied to both the *HST* and ground-based data to bring the F675W and F814W magnitude estimates to rest-frame B and V respectively.

In addition to the statistical errors (shot-noise) in the SN magnitudes, there are sources of possible systematic error which contribute to the SN distance estimates and we list them in Table 1. The Holtzman calibration is expected to have a zeropoint uncertainty of 3%, but recent comparisons of Holtzmann magnitudes with ground-based data suggests that ZP offsets and uncertainties of 0.05 mag are possible, and errors of this magnitude cannot be excluded with our current ground-based data. Inefficient charge transfer (CT) in the WF3 causes the apparent brightness of objects to vary with pixel position. A recent characterization of the CT problem for WFPC2 by Whitmore & Heyer (1997) shows that the loss of charge along columns can be as large as 7% and depends on object brightness and background level as well as pixel position. We applied their corrections to all the magnitude estimates after interpolating to a $0.3''$ aperture and this lowered the estimated SN magnitudes by between 3% and 5%, with the corrections being good to about 2%. Tests by Hill *et al.* (1997) found differences in the WFPC2 ZP between long and short exposures amounting to 5%. However, these offsets are symptomatic of the CT problem and are corrected in our data with the new algorithm.

3. Results

The *HST* image shows that SN 1997ce occurred $0.4''$ south of the brighter of a pair of elongated galaxies. Keck spectra of SN 1997ce displayed a blue continuum with broad absorption bands which matched those of a SN Ia at $z = 0.44$. The light curve showed that SN 1997ce was discovered about 8 days before maximum light in the observer's frame (roughly 6 days in the rest frame). The MLCS method was used to analyze the rest-frame light curves (Figure 1) and found that SN 1997ce declined slightly faster than a normal SN Ia. Template fitting agreed, but found a smaller correction. The MLCS fit found no reddening of this SN, consistent with the color at maximum of $B - V \approx 0$.

The host galaxy of SN 1997cj is a spiral with the SN offset by $0.7''$ to the west. The MMT spectrum of SN 1997cj showed features consistent with a SN Ia at a redshift of 0.5 and a narrow emission line of [OII] $\lambda3727$ provided a precise redshift of $z = 0.50$. Discovery was about 12 observer days before maximum light. Although the first planned *HST* visit could not be made due to a lack of guide stars, the light curves (Figure 1) are still well defined by combined ground-based and *HST* data and show SN 1997cj to have a normal decline rate. MLCS fits to the B and V light curves argue that the object is not reddened.

The Keck spectrum of SN 1997ck was too weak to show the broad features of the SN, but strong emission from the host galaxy corresponding to [OII] $\lambda3727$ indicated a redshift of $z = 0.97$. The $V - I$ color was consistent with a SN Ia before maximum. The host is not easily seen in the F850LP *HST* images, but in the R and I ground-based frames it appears as a very elongated, low surface-brightness patch extending $\sim 2''$ to the northwest. The blue color of the host may indicate a population of young stars and there is a corresponding possibility of dust extinction. Because of the high redshift, only a rest-frame B light curve could be constructed. The color derived from the difference between the I and the F850LP filters is consistent with no reddening. However, the wavelength baseline in the rest frame is small, and the extinction to SN 1997ck remains a major uncertainty. The SN was discovered 11 days before maximum light in the observer's frame (Figure 1). The MLCS method, working with only one bandpass, finds that SN 1997ck has a normal decline rate. Template fitting suggests that this is a slightly over-luminous SN. Although the evidence that this is truly a SN Ia is less certain for SN 1997ck than for the other objects, the light curve looks exactly like a SN Ia light curve at z = 0.97 and the pre-maximum color points in the same direction. But, as with some of the early observations of Perlmutter *et al.* (1997), we do not have data to exclude conclusively other possibilities. We treat SN 1997ck as an unreddened SN Ia when we include it in the discussion that follows.

4. Discussion

Table 1 summarizes the error and distance estimates for this sample combined with SN 1995K from SSP97. A Hubble diagram reaching to $z = 1$ is shown in Figure 2. The data adhere closely to the expectations of relativistic cosmology as shown by the model curves. The lower panel in Figure 2 shows a detailed comparison with the predictions of flat and open cosmological models containing two components, nonrelativistic mater, Ω_m, and a cosmological constant, Ω_Λ (Caroll, Press and Turner 1994).

First, we will only consider the three confirmed SN Ia which have rest frame B and V lightcurves. With the constraint of a flat Universe ($\Omega_m + \Omega_\Lambda = 1$), and minimizing χ^2 for the combined set of low-z and high-z SNe, we find $\Omega_m = 0.4^{+0.3}_{-0.3}$ for the MLCS technique and $\Omega_m = 0.3^{+0.3}_{-0.3}$ using the template fitting method. Alternatively, with Ω_Λ set to zero, our allowed range for normal matter is $\Omega_m = -0.1 \pm 0.5$. We find that $\Omega_m < 1$ with 95% confidence with both methods. Including SN 1997ck in the analysis tightens the constraints on Ω_M and Ω_Λ, but does not significantly alter the above best fit values. The indication from our data is that the matter density is low; as shown in Figure 3, either the Universe is open, or if flat, then a cosmological constant makes a considerable contribution (which may be in conflict with limits from gravitational lensing statistics (Kochanek 1996)). These conclusions agree with those from dynamical estimates of the density of clustered matter (Lin *et al.* 1996, Carlberg *et al.* 1996) and from the comparison of the Hubble time with estimates of the nuclear burning ages of globular clusters (Reid 1997).

Table 1. Supernova Parameters and Error Budget

	1995K[1]	1997ce	1997cj	1997ck
Error Budget				
CT Correction (mag)	0.00	0.02	0.02	0.02
ZP (mag)	0.03	0.05	0.05	0.05
Evolution[2](mag)	0.06	0.06	0.06	0.06
Selection Bias[1](mag)	0.02	0.02	0.02	0.02
Weak Lensing[3](mag)	0.02	0.02	0.02	0.04
K-corrections[4](mag)	0.06	0.06	0.06	0.06
Light Curve Fit RPK[5](mag)	0.21	0.08	0.19	0.42
Light Curve Fit H96[5](mag)	0.13	0.11	0.11	0.21
σ of SNe Ia (mag)	0.12	0.12	0.12	0.12
Parameters				
z	0.48	0.44	0.50	0.97
m_B^{max} (mag)	22.89	22.75	23.19	24.78
m_V^{max} (mag)	23.00	22.79	23.19	...
Δ (mag)	-0.07	0.41	0.04	-0.01
Δm_{15} (mag)	1.17(09)	1.19(06)	1.16(03)	1.00(17)
A_V MLCS (mag)	0.00	0.00	0.00	...
Galactic $(E(B-V))$ (mag)	0.00	0.01	0.01	0.01
$m-M$ RPK (mag)	42.40(26)	41.83(18)	42.59(25)	44.15(45)
$m-M$ H96[6](mag)	42.29(20)	42.06(19)	42.48(19)	44.06(27)

[1]From SSP97

[2]Current observational upper limit from SSP97

[3]From Wambsganss *et al.* 1997

[4]Includes propagated effect on extinction, $3.1\sigma E(B-V)$

[5]Includes uncertainty in light curve fit, extinction and background subtraction

[6]Average of B and V

These results contrast with those of Perlmutter *et al.* (1997), which preferred a high matter density even in flat models. Although there are cosmological models acceptable to both data sets at the 68% level, the probability that the two samples have the same parent distribution is less than 10%. More SNe at $z > 0.4$, colors and spectra for all the new objects, and a detailed comparison of the two approaches should resolve this apparent disagreement.

We have shown that SNe with redshifts as large as $z \sim 1$ can be discovered and successfully studied with a combination of ground-based telescopes and *HST*. Further refinements will be made to this data set once template images are acquired with HST, and additional ground based photometric data is obtained to determine a more precise photometric zero point for the fields. Our initial sample of four SNe rules out models with a high matter density $\Omega_m \sim 1$, although the strength of these conclusions should be tempered by the less-than-perfect data set for SN 1997ck and the small size of our present sample. Additional objects will allow us to significantly increase the precision of our measurement, and test for sources of systematic error such as evolution. Extending the multicolor approach to $z \sim 1$ with high precision will be possible with NICMOS or future orbiting near-infrared instruments.

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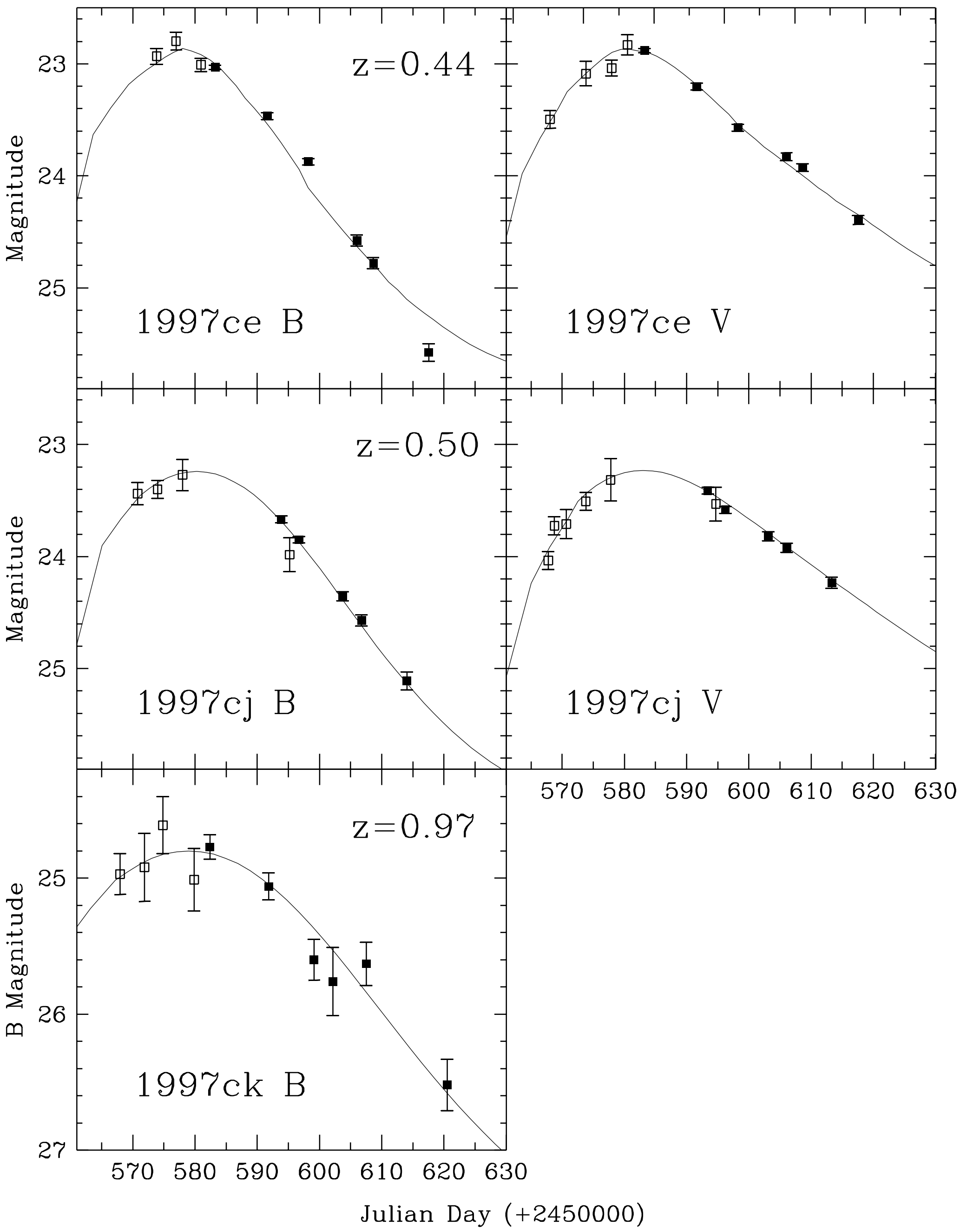

Fig. 1.— Rest frame B and V light curves of SNe 1997ce (top) and 1997cj (middle) amd a B light curve for SN 1997ck (bottom). The filled points represent *HST* observations while the open points are from ground-based telescopes. The solid lines show the best fit light curve from the MLCS method.

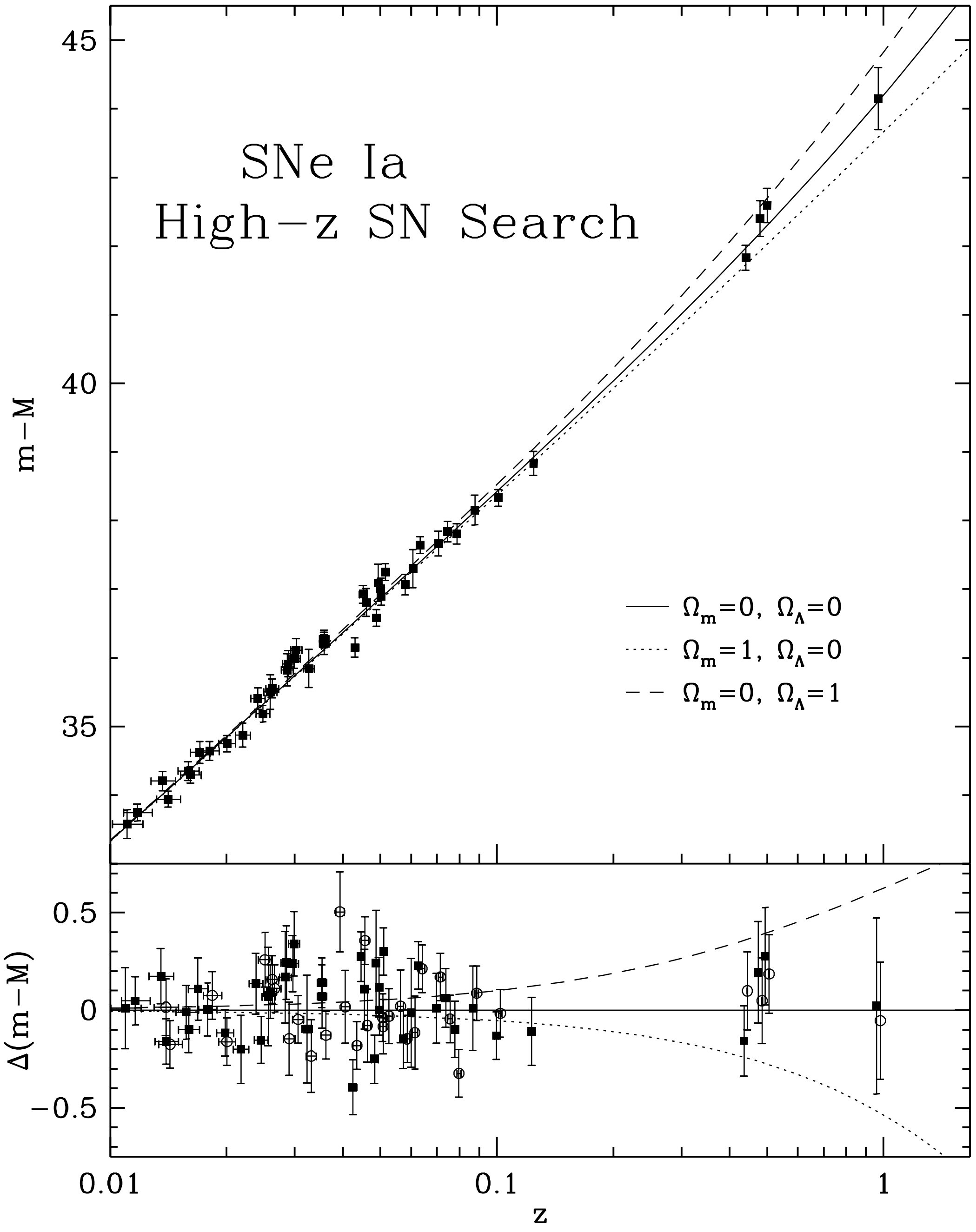

Fig. 2.— The Hubble diagram for SNe Ia. The top panel shows the MLCS distance modulus versus z for a large sample of low redshift events and the four high-z SNe. The lower panel plots the magnitude difference between the observed SNe and the magnitude expected from a Universe with $\Omega_m = \Omega_\Lambda = 0$. The open circles show the SNe distances estimated using the techniques and scale from H96. The redshift for SNe where both techniques have been applied has been slightly shifted for clarity.

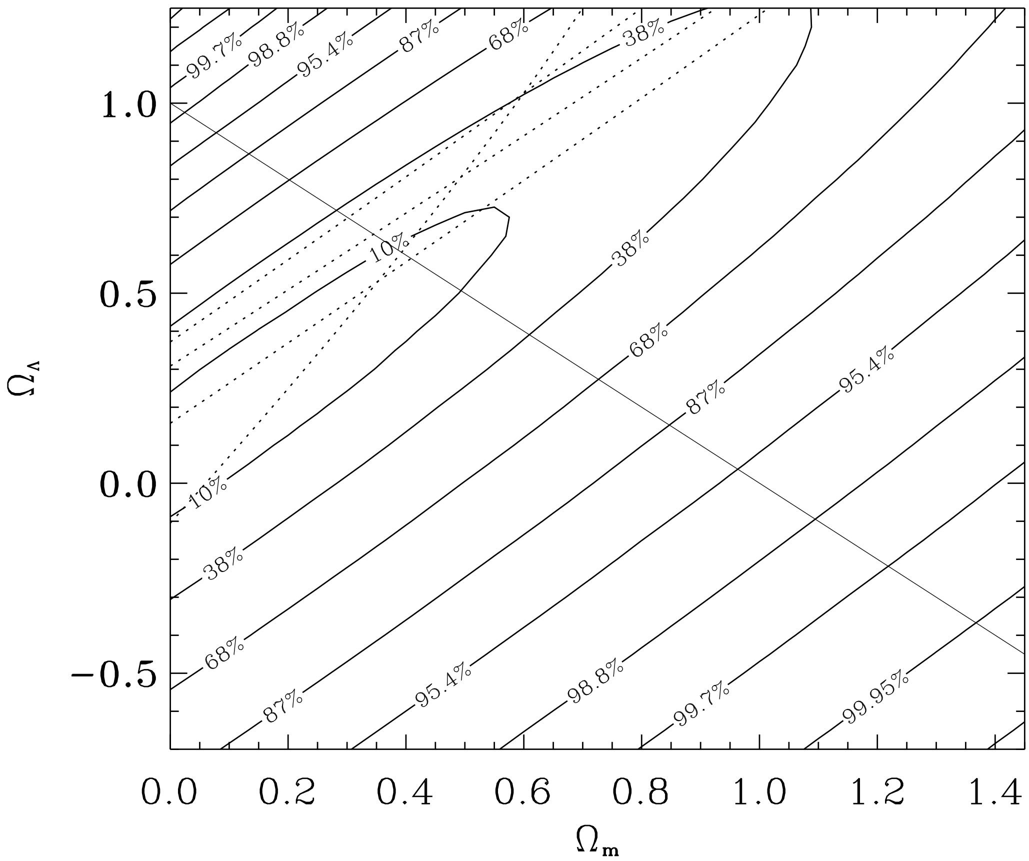

Fig. 3.— Confidence contours in the Ω_m, Ω_Λ plane for the high-z SNe listed in Table 1 using the MLCS distances. The solid diagonal line represents the locus for a flat Universe. The broken lines are the locus for individual SNe using distances estimated from the template fitting method.

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Table 2. High-z Supernova Photometry

Julian Day[1]	Telescope	Filter[2]	B^3	V^3
SN 1997ce				
545.1	CFHT	I	...	>25.5
568.1	CFHT	I	...	23.50 (08)
573.9	MDM	B45,V45	22.92 (07)	23.09 (11)
577.0	WIYN	R	22.80 (08)	...
578.0	WIYN	I	...	23.04 (07)
580.5	H88	R,I	23.01 (06)	22.83 (09)
583.3	HST	675W, 814W	23.03 (02)	22.88 (02)
591.7	HST	675W, 814W	23.47 (03)	23.20 (03)
598.2	HST	675W, 814W	23.87 (03)	23.57 (03)
606.0	HST	675W, 814W	24.58 (05)	23.83 (03)
608.7	HST	675W, 814W	24.78 (05)	23.93 (03)
617.6	HST	675W, 814W	25.58 (08)	24.39 (04)
SN 1997cj				
542.8	CFHT	I	...	>25.6
567.8	CFHT	I	...	24.03 (08)
568.8	CFHT	I	...	23.73 (08)
570.7	MDM	B45,V45	23.44 (10)	23.71 (13)
573.8	MDM	B45,V45	23.40 (08)	23.51 (08)
577.8	KP2.1	B45,V45	23.27 (14)	23.31 (19)
593.4	HST	675W, 814W	23.67 (03)	23.41 (03)
594.7	WIYN	R,I	23.98 (15)	23.53 (15)
596.2	HST	675W, 814W	23.85 (03)	23.58 (03)
603.1	HST	675W, 814W	24.36 (04)	23.82 (04)
606.1	HST	675W, 814W	24.57 (05)	23.92 (04)
613.3	HST	675W, 814W	25.11 (08)	24.23 (05)

Table 2—Continued

Julian Day[1]	Telescope	Filter[2]	B^3	V^3
SN 1997ck				
543.1	CFHT	I	>25.9	...
568.0	CFHT	I	24.97 (15)	...
571.9	MDM	V45	24.92 (25)	...
574.8	MDM	Gunn-z	24.61 (21)	...
579.9	H88	I	25.01 (23)	...
582.4	HST	850LP	24.77 (09)	...
591.8	HST	850LP	25.06 (10)	...
599.1	HST	850LP	25.60 (15)	...
602.1	HST	850LP	25.76 (25)	...
607.5	HST	850LP	25.63 (16)	...
620.5	HST	850LP	26.52 (19)	...

[1] −2450000

[2] B45 and V45 are defined in SSP97

[3] Errors given in parentheses are from photon noise only