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CONSTRAINTS ON COSMOLOGICAL MODELS FROM *HUBBLE SPACE TELESCOPE* OBSERVATIONS OF HIGH-*z* SUPERNOVAE

P. M. GARNAVICH,[1] R. P. KIRSHNER,[1] P. CHALLIS,[1] J. TONRY,[2] R. L. GILLILAND,[3] R. C. SMITH,[4] A. CLOCCHIATTI,[5] A. DIERCKS,[6] A. V FILIPPENKO,[7] M. HAMUY,[8] C. J. HOGAN,[6] B. LEIBUNDGUT,[9] M. M. PHILLIPS,[5] D. REISS,[6] A. G. RIESS,[7] B. P. SCHMIDT,[10] R. A. SCHOMMER,[5] J. SPYROMILIO,[9] C. STUBBS,[6] N. B. SUNTZEFF,[5] AND L. WELLS[8]

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ABSTRACT

We have coordinated *Hubble Space Telescope* (*HST*) photometry with ground-based discovery for three supernovae: Type Ia supernovae near $z \approx 0.5$ (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. We use these light curves and relations between luminosity, light-curve shape, and color calibrated from low-*z* samples to derive relative luminosity distances that are accurate to 10% at $z \approx 0.5$ and 20% at $z = 1$. When the *HST* sample is combined with the distance to SN 1995K ($z = 0.48$), analyzed by the same precepts, we find that matter alone is insufficient to produce a flat universe. Specifically, for $\Omega_m + \Omega_\Lambda = 1$, Ω_m is less than 1 with more than 95% confidence, and our best estimate of Ω_m is -0.1 ± 0.5 if $\Omega_\Lambda = 0$. Although this 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

Direct measurement of global curvature and deceleration of the universe has challenged the best efforts of observers for many decades (Humason, Mayall, & 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. 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. In addition, search strategies pioneered by Hamuy et al. (1993) and Perlmutter et al. (1997a) regularly yield a number of SNe that can be efficiently studied using prescheduled telescopes. This Letter reports results from coordinated ground-based and *Hubble Space Telescope* (*HST*) observations of distant SNe up to $z \approx 1$, which extend the luminosity-distance relation to redshifts where cosmological effects can be measured (Nørgaard-Nielsen et al. 1989; Perlmutter et al. 1997b; Schmidt 1997).

Type Ia SNe proved to be excellent distance indicators. They are not perfect standard candles, but their luminosities correlate with light-curve shape so that differences in intrinsic brightness can be assessed by observing SN light curves (Phillips 1993; Hamuy et al. 1996, hereafter H96; Riess, Press, & Kirshner 1996, hereafter RPK). The techniques of RPK and H96 produce relative distance estimates to better than 10% despite a spread of than 1 mag in intrinsic brightness. Colors of SNe Ia provide a way to correct for extinction by dust in both our Galaxy and the host. Since cosmological models predict the shape of the relation between luminosity distance and redshift, relative distances constrain curvature and deceleration independent of the Hubble constant. By using the same methods at high and low redshift, we minimize the systematic errors that could undermine an enterprise of this type. Even evolutionary effects, which have bedeviled all previous attempts to measure q_0, can be calibrated by studying contemporary samples in populations of different ages and metallicity; Schmidt et al. (1998, hereafter SSP98) demonstrate that any residual 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 $z > 0.3$ (Leibundgut et al. 1996; Riess et al. 1997). 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 SSP98. Here, we present preliminary results that combine *HST* and ground-based photometry. We analyze light curves of three SNe with redshifts between 0.4 and 1.0 using the multicolor light-curve shape (MLCS) method (RPK) and a template-fitting technique (Hamuy et al. 1995) to determine distances. We produce a consistent Hubble diagram in the range $0.01 < z < 1.0$ and use the results to constrain cosmological models. We also compare our conclusions with the results from seven high-*z* SNe studied from the ground by Perlmutter et al. (1997b).

2. OBSERVATIONS

The 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. Four fields, selected and scheduled long in advance for *HST* visibility, were imaged in broadband *V* and *I* filters, for a total search area of about 1

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[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[2] Institute for Astronomy, University of Hawaii, Manoa, HI 96822.

[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

[4] University of Michigan, Department of Astronomy, 834 Dennison, Ann Arbor, MI 48109.

[5] Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile.

[6] Department of Astronomy, University of Washington, Seattle, WA 98195.

[7] Department of Astronomy, University of California, Berkeley, CA 94720.

[8] Steward Observatory, University of Arizona, Tucson, AZ 85721.

[9] European Southern Observatory, Karl-Schwarzschild-Strasse 2, Garching, Germany.

[10] Mount Stromlo and Siding Spring Observatory, Private Bag, Weston Creek P.O., Australia.

deg^2. We compared these images with template frames of the same regions taken April 4 and 9 (UT) to detect variable objects. Seeing on the search frames was $0\farcs6$ and $0\farcs7$ (FWHM) on the template frames. A minimum of three 1200 s exposures were taken of each field and combined with a median filter. The magnitude limits were typically $I < 24.5$. 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 and inspected by eye for residual point sources.

Twelve SN candidates were identified from the search. Two 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 10 m telescope on May 4. Four of the objects were identified as SNe 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. Subsequent photometry of SN 1997ca indicated that it was in fact a SN II at low redshift.

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 3 weeks in the SN rest frame. Each epoch was allotted one *HST* orbit. For the $z \approx 0.5$ targets, the orbit was divided into an 800 s exposure in the F675W filter and a 1100 s exposure with the F814W filter. These filters approximate standard *BV* bandpasses at $z \approx 0.5$, and we have computed *K*-corrections for both the *HST* and ground-based observations according to SSP98. At $z \approx 1$, the F850LP is well matched to the rest-frame *B* band. Exposures of SN 1997ck in the F850LP filter fill the target visibility window with a minimum total exposure of 2200 s. All observations were divided into two exposures, and we combined the cosmic-ray split images using the default parameters in the STSDAS/CRREJ algorithm, which is designed to avoid confusing stellar images with cosmic rays in undersampled data. As a check, 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. Figure 1 (Plate L7) displays images of each SN made by adding all the observations.

We calibrated a sequence of stars near each SN using both *HST* and ground-based data. Magnitudes of stellar objects in the *HST* images were estimated using the prescription of Holtzman et al. (1995). Data numbers within a $0\farcs3$ radius aperture were summed, and we subtracted the background level estimated from a large region around the image. The small aperture minimized background noise. An aperture correction based on the point-spread function (PSF) of stars in the field brought the measurement to the equivalent of a $0\farcs5$ aperture, and the result converted to a magnitude in the *HST* filter system. For the F850LP filter, only a synthetic zero point (ZP) was available, which is estimated by Whitmore (1995) to be good to ≈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 *RI* 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 of the SNe ($R - I < 1.2$), the average difference between ground-based (GRD) and *HST* magnitude estimates is only $R_{\rm GRD} - R_{HST} = -0.02 \pm 0.05$ mag and $I_{\rm GRD} - I_{HST} = 0.00 \pm 0.04$ mag, verifying the Holtzmann ZPs.

From the ground, light from the host galaxy is a major source of uncertainty in measuring SN light curves. A template image

TABLE 1

SUPERNOVA PARAMETERS AND ERROR BUDGET

Parameter	1995K[a] ($z = 0.48$)	1997ce ($z = 0.44$)	1997cj ($z = 0.50$)	1997ck ($z = 0.97$)
		Error Budget		
CT correction (mag)	0.00	0.02	0.02	0.02
Zero point (mag)	0.03	0.05	0.05	0.05
Evolution[b] (mag)	0.06	0.06	0.06	0.06
Selection bias[a] (mag)	0.02	0.02	0.02	0.02
Weak lensing[c] (mag)	0.02	0.02	0.02	0.04
K-corrections[d] (mag)	0.06	0.06	0.06	0.06
Light-curve fit (RPK)[e] (mag)	0.21	0.08	0.19	0.42
Light-curve fit (H96)[e] (mag)	0.13	0.11	0.11	0.21
σ of SNe Ia[f] (mag)	0.12	0.12	0.12	0.12
		Parameters		
$m_B^{\rm max}$ (mag) (H96)	22.89	22.75	23.19	24.78
$m_V^{\rm max}$ (mag) (H96)	23.00	22.79	23.19	…
Δ (mag) (RPK)	−0.07	0.41	0.04	−0.01
Δm_{15} (mag) (H96)	1.15(09)	1.19(06)	1.16(03)	1.00(17)
A_V (mag) (RPK)	0.00	0.00	0.00	…
Galactic A_V (mag)	0.00	0.03	0.03	0.03
$m - M$ (mag) (RPK)	42.40(26)	41.83(18)	42.59(25)	44.15(45)
$m - M$ (mag) (H96)[g]	42.25(20)	42.06(19)	42.48(19)	44.06(27)

[a] From SSP98.

[b] Current observational upper limit from SSP98.

[c] From Wambsganss et al. 1997.

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

[e] Includes uncertainty in light-curve fit, extinction, and background subtraction.

[f] Dispersion in local SN Ia distances after LCS correction (RPK).

[g] Average of *B* and *V*.

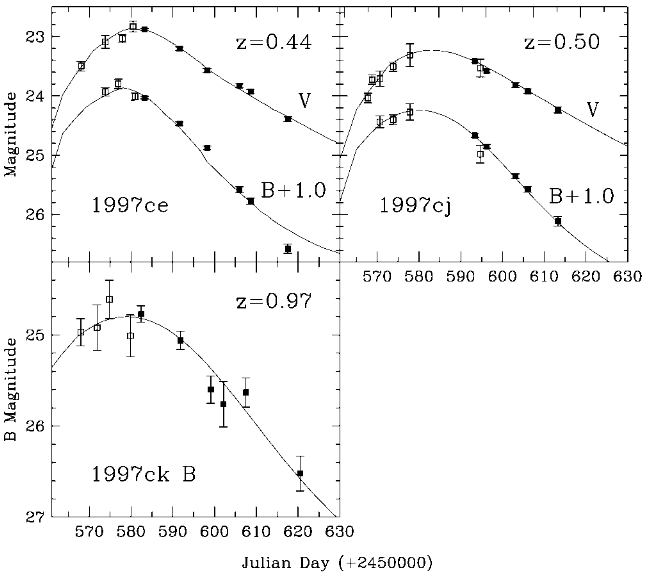

FIG. 2.—Rest frame *B* and *V* light curves of SNe 1997ce (*top left*), 1997cj (*top right*), and a *B* light curve for SN 1997ck (*bottom*). Filled points represent *HST* observations, while open points are from ground-based telescopes. The solid lines show the best-fit light curve from the MLCS method.

is often taken 1 yr after the SN maximum to subtract the host light. *HST* allows the SN and the galaxy light to be more easily separated, but the host background must still be removed. We create a template by subtracting the SN image from the *HST* data in software and assume no additional point sources exist at the position of the SN. At these large redshifts the hosts appear smooth so that this assumption is valid. For SNe 1997ce and 1997cj, an empirical 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 and 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 less than 2%) and include this error with the uncertainty in each photometric 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 SSP98. The *HST* image templates were used to subtract the host galaxy background, and the relative brightness between the SN and other stars in the field was measured 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.

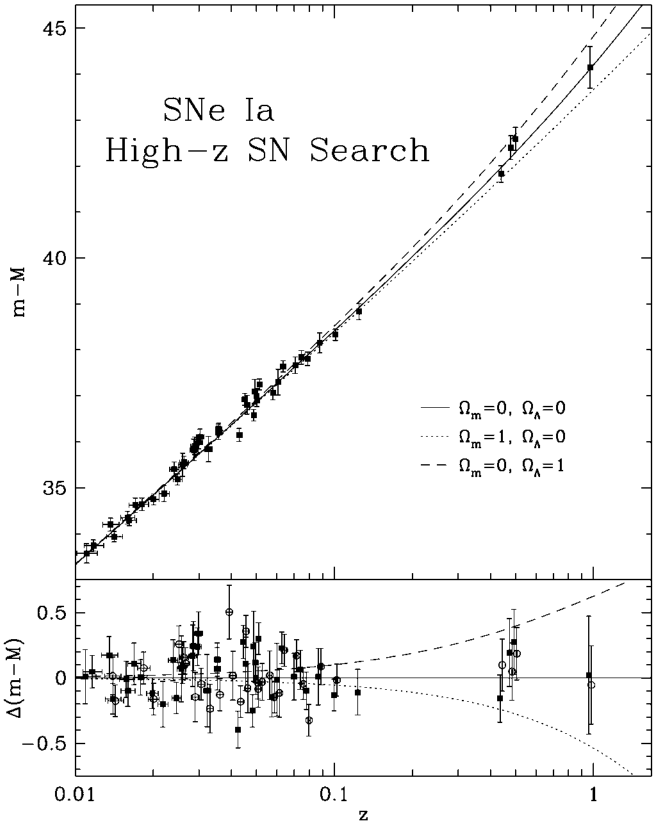

FIG. 3.—Hubble diagram for SNe Ia. The top panel shows the MLCS distance modulus vs. *z* for a large sample of low-redshift events and the four high-*z* SNe. The lower panel plots the magnitude difference between the observed SNe and the magnitude expected from a universe with $\Omega_m = \Omega_\Lambda = 0$. 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.

We list sources of statistical and possible systematic errors in Table 1. The total photometric uncertainty (including estimated error in the extinction correction) is given as an error in the light-curve fit. Selection bias (includes Malmquist bias) results from having brightness and temporal discovery limits, but the error is small owing to the tight dispersion in the corrected intrinsic luminosities of SNe Ia (SSP98). The lumpiness of the universe causes weak gravitational lensing of distant SNe, and an estimate of the systematic effect has been made by Wambsganss et al. (1997). The direct uncertainty from *K*-corrections is small (≈2%) but is magnified by a factor of 3 because of the propagation of color errors interpreted as extinction (SSP98). Even after correcting SNe luminosities using light-curve shape methods, there remains a dispersion of 0.12 mag (RPK) in the derived distances that is included in the error budget. The Holtzman calibration is expected to have a zero-point uncertainty of 3%, but recent comparisons of Holtzmann magnitudes with ground-based data suggest that ZP offsets and uncertainties of 0.05 mag are possible, and errors this large cannot be excluded with our current ground-based data. Inefficient charge transfer (CT) in WF3 causes the apparent brightness of objects to vary with pixel position. Whitmore & Heyer (1997) show 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. This made the estimated SN magnitudes brighter by between 3% and 5%, with the corrections being good to about 2%.

The total uncertainty in the derived distances is found by adding the individual errors shown in the Table 1 error budget in quadrature. The distance errors for the MLCS and template-fitting methods are very consistent except for SN1997ck, where the MLCS suffers from having only a B light curve to fit.

3. RESULTS AND DISCUSSION

The *HST* image shows that SN 1997ce occurred $0\farcs4$ south of the brighter of a pair of elongated galaxies. Keck spectra of SN 1997ce display a blue continuum with broad absorption bands that match those of a SN Ia at $z = 0.44$. The light curve shows that SN 1997ce was discovered about 8 days before maximum light in the observer's frame. The MLCS method was used to analyze the rest-frame light curves (Fig. 2) and found that SN 1997ce declined slightly faster than a normal SN Ia (MLCS parameter $\Delta = 0.41$ mag). Template fitting agreed but found a smaller correction ($\Delta m_{15} = 1.19$ mag). Differences in the derived luminosity between the two methods are not unusual for the nearby sample of SNe and underscore the benefit of increasing the sample size. 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 $0\farcs7$ 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 [O II] λ3727 provided a precise redshift of $z = 0.50$. Discovery was about 12 observer days before maximum light. Although the first planned *HST* visit was delayed due to a lack of guide stars, the light curves (Fig. 2) are still well defined by combined ground-based and *HST* data and show that SN 1997cj had a normal decline rate. MLCS fits to the B and V light curves show 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 [O II] λ3727 emission from the host galaxy 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 $\approx 2''$ 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 is small, and the extinction to SN 1997ck remains uncertain. The SN was discovered 11 days before maximum light in the observer's frame (Fig. 2). 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 overluminous 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 premaximum color is also consistent. But, as with some of the early observations of Perlmutter et al. (1997b), we do not have the data to exclude conclusively other possibilities. We treat SN 1997ck as an unreddened SN Ia when we include it in the discussion that follows.

Table 1 summarizes the error and distance estimates for this sample combined with SN 1995K from SSP98. A Hubble diagram reaching to $z = 1$ is shown in Figure 3. The data adhere closely to the expectations of relativistic cosmology as shown by the model curves. The lower panel in Figure 3 compares the data with flat and open cosmological models containing nonrelativistic matter, Ω_m, and a cosmological constant, Ω_Λ (Carroll, Press, & Turner 1992).

First, we consider only the three confirmed SNe Ia that have rest-frame B and V light curves. With the constraint of a flat universe ($\Omega_m + \Omega_\Lambda = 1$), 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, we derive $\Omega_m = -0.1 \pm 0.5$. From either method we find that $\Omega_m < 1$ with 95% confidence. Including SN 1997ck in the analysis tightens the constraints on Ω_m and Ω_Λ but does not alter the best-fit values. Our data suggest that the matter density is low. Either the universe is open or flat; if flat, then a cosmological constant makes a considerable contribution (which may 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).

Our results contrast with those of Perlmutter et al. (1997b), 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 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 $z \approx 1$ can be discovered and successfully studied with a combination of ground-based telescopes and *HST*. Refinements will be made to this data set once template images are acquired with *HST*, and additional ground-based photometric data are obtained. Our initial sample of four SNe is inconsistent with a high matter density $\Omega_m \approx 1$, 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 increase the precision of our measurement and test for sources of systematic error.

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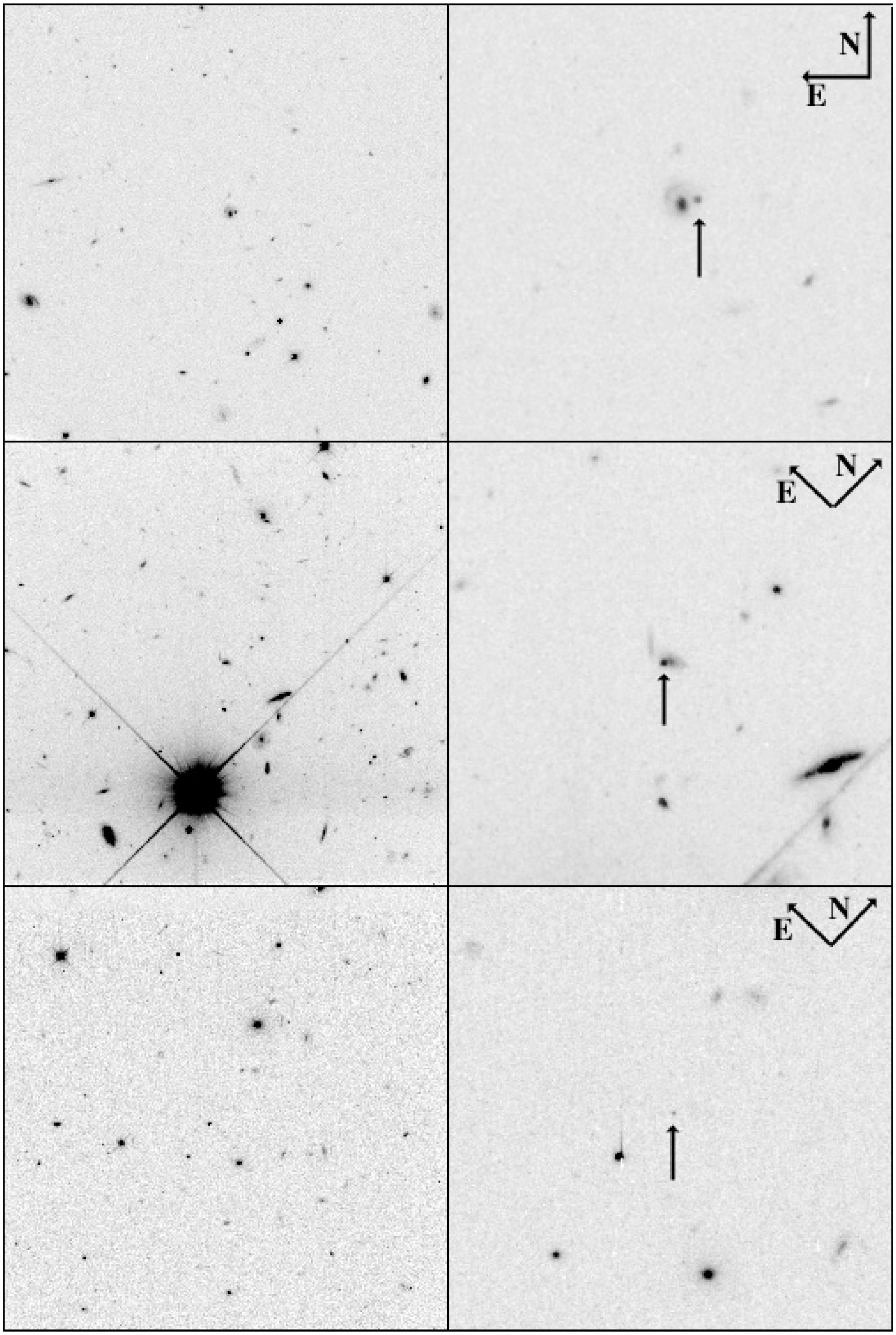

FIG. 1.—*HST* images of SNe 1997cj (*top*), 1997ce (*center*), and 1997ck (*bottom*). The full WF3 field (1.′25) is shown on the left, while the right panel shows a 3 times magnification centered on the SN.

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