Hubble Space Telescope

Cycle 12 GO Proposal

Final Reference Images for Seven Very High-Redshift Type Ia Supernovae

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Scientific Category: COSMOLOGY

Scientific Keywords: SUPERNOVAE

Instruments: ACS, NICMOS

Proprietary Period: 12

Cycle 12 primary orbits: 18

Abstract

During the spring and fall of 2002, the Supernova Cosmology Project carried out several extensive searches for very high-redshift Type Ia supernovae at the CTIO 4-m, CFHT 3.5-m, and Subaru 8-m telescopes as part of the HST program GO 9075. The program was a major success with well over 40 total supernova discoveries. Seven of these in the redshift range $0.85 < z < 1.3$ were followed by HST using ACS and NICMOS. These supernova represent the largest sample of spectroscopically confirmed Type Ia's at $z \sim 1$ followed by HST. They will allow us to place significant constraints on the cosmological parameters and test for supernova evolution when the universe was less than half its current age. Here we request ACS and NICMOS final reference images for these supernova which are necessary for proper subtraction of the underlying host galaxy light. These additional 18 orbits are needed because of a higher than anticipated rate of galaxy contamination and also because of an unexpected opportunity to obtain NICMOS data after SMOV3. The data will ensure, especially at late times when the supernova is faint, that the supernova light curves are unaffected by large systematics in the photometry.

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Number of investigators: 12

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Observing Summary:

Target	RA	DEC	V	Config/Mode/SEs	Flags	Orbits
SN 2002fc	14 00 23.29	+05 45 41.9	27.0	ACS/WFC/Imaging/F775W, F850LP	CPAR, CVZ	2
SN 2002fe	14 04 18.16	+05 19 25.6	27.0	ACS/WFC/Imaging/F775W, F850LP		2
SN 2002ff	14 03 39.82	+05 46 50.6	27.0	ACS/WFC/Imaging/F775W, F850LP		2
SN 2002fg	13 24 25.93	+27 44 33.9	27.0	ACS/WFC/Imaging/F775W, F850LP		2
SN 2002gi	13 57 12.3	+04 33 17.2	27.0	ACS/WFC/Imaging/F775W, F850LP		2
SUF02-012	02 18 51.6	-04 47 25.72	27.0	NIC2/Imaging/F110W		3
SUF02-012	02 18 51.6	-04 47 25.72	27.0	ACS/WFC/Imaging/F850LP		1
SUF02-060	02 17 34.48	-04 53 47.15	27.0	NIC2/Imaging/F110W		3
SUF02-060	02 17 34.48	-04 53 47.15	27.0	ACS/WFC/Imaging/F850LP		1
				Total orbit request:		18

Scientific Justification

Scientific Background:

Astronomers have begun to measure the fundamental parameters of cosmology through the observation of very distant Type Ia Supernovae (SNe Ia). The Supernova Cosmology Project (SCP) and the High-Z Supernovae Search Team (HZSST) have discovered approximately 150 spectroscopically confirmed high-redshift supernovae over the past six years. The supernovae are used as standardized candles to measure the history of the expansion of the universe. The results of these two studies indicate that the universe is currently accelerating and this has led to one of the "key scientific questions of our day", as identified by the NRC Committee on the Physics of the Universe (Tur02): What is the dark energy which drives this expansion? In the few years since the acceleration was first seen in the Type Ia supernova (SN Ia) Hubble diagram, the evidence has grown even stronger: complementary CMB measurements have indicated that the Universe has zero curvature (Sie03), making the SN Ia result more determinative, and – in combination with the SNe — pointing to a $[\Omega_M \approx 0.3, \Omega_\Lambda \approx 0.7]$ cosmology. This is also consistent with other astronomical mass density measurements (Perc02).

The SN Hubble diagram remains the only direct approach currently in use to study acceleration. There are ongoing studies of the details of all known relevant sources of systematic uncertainty, but none show any biases at a level that might affect the basic acceleration results. These include: any changes with z in host-galaxy extinction by ordinary dust (Rie98,Per99,Phi99,Sul03), any extinction by intergalactic gray dust (Pae03), gravitational-lensing (de)amplification of SN magnitudes (Per99), discovery selection effects (Per99,Rie98), K-correction systematics (Nug02), and population drifts in the SN environment (Sul03).

During both semesters of 2002, the SCP conducted several ground based searches using the CTIO 4-m, CHFT 3.5-m, and Subaru 8-m telescopes as part of the Cycle 10 program GO 9075. Seven spectroscopically confirmed SNe Ia were followed by HST with NICMOS and ACS. These supernovae are listed in Table 1 and their location on the Hubble diagram can be seen in Figure 1. These supernovae are the largest single sample and the finest observations to date of high-redshift SNe Ia at a $z \approx 1$. All of them have been spectroscopically confirmed and have excellently spaced, multicolor photometry. Their location on the Hubble diagram will make them an integral part of constraining the cosmological parameters, testing supernova evolution and probing the epoch of deceleration. They represent an investment of hundreds of hours of telescope time at Keck, VLT, Subaru, Gemini and CTIO and 100 orbits of HST photometry and spectroscopy with ACS and NICMOS. However, without the final reference images we propose for here, we will not be able to achieve the originally proposed goals.

There are three primary reasons that additional orbits are needed to complete this work:

(1) In the GO 9075 proposal (and previous years' proposals), we have included orbits for final images of host galaxies after the supernovae have faded. This was done for all filters in which the supernovae were imaged, but only for about half of the supernovae, since that was the rate of significant host galaxy contamination seen in the early datasets. After this GO 9075 proposal was submitted, however, subsequent supernova discoveries have exhibited an increasing rate of galaxy contamination, presumably due to the increase in redshifts. This trend has reached its culmination

with the seven supernovae discussed in this proposal, all of which require a final reference image.

(2) The ideal instrument to obtain color information for the supernovae at redshifts above $z = 1$ is NICMOS. Once NICMOS had been refurbished and tested, we requested the HST Change Board that we be allowed to use NICMOS orbits to observe the most recent SN discoveries near their peak brightness. This was a time-critical opportunity, so the Change Board agreed. However, since there is now an opportunity to go back to the TAC before the final galaxy images are obtained, we are here including these orbits in this proposal, rather than asking the Change Board.

(3) During this past year, our GO 9075 program was changed dramatically, primarily due to last-minute changes (and opportunities) caused by the Servicing Mission. Since the WFPC2 CCD's CTE was decaying, we requested to be switched to ACS imaging. We began work with this instrument within weeks of first light, and ran the program close to the original requested WFPC2 program. A few months later, we were told that it was expected that we would use a significantly smaller number of fewer orbits, since it was by then clear that ACS was more efficient than WFPC2. The project had already begun using the ACS to efficiently observe in two of the filters in the original proposal, so there is now a need to for the additional orbits necessary to complete these multiple band final galaxy images.

Justification of the Method:

The consequence of not obtaining these final references can be seen in Figure 2. All but one of these SNe Ia lie almost directly on top of their respective hosts. The underlying light can be crudely estimated by comparing the relative total fluxes at 2 different epochs and using a template SN Ia light curve at the measured redshift to extract the part which is due to the supernova. We have performed these calculations and in all cases, and in every filter, the percentage of underlying host is between 25 and 80% of the total light seen in any of the images. We can not, of course, use this method to determine the amount of host light since it requires an *a priori* knowledge of the cosmology (to determine the apparent SN Ia flux), the extinction along the line-of-sight, and the light-curve shape of the supernova.

One could propose to model the host galaxy based on the section of the host not impacted by supernova light. However, this method would fail for compact hosts (seen in several cases) or random HII regions in the arms of spiral galaxies. Even in the best case scenario of a smooth galaxy surface under the supernova one could only hope to make a correction that would be good to 10%. Thus our photometry would be limited by this systematic error, which would impact every image along the light curve. The whole purpose of GO 9075 was to obtain a high-quality light curve to correct for the light-curve shape brightness relationship and multicolor photometry near maximum light to correct for the effects of extinction along the line of sight. A 10% systematic uncertainty would propagate to an uncertainty of 0.17 magnitudes in the distance from the stretch-luminosity relationship (see Per99). The extinction correction would suffer an even worse fate as the 10% gets multiplied by a factor of 4.1 ($A_B = 4.1\ E_{(B-V)}$) and strongly degrades their impact on cosmological measurements. By acquiring reference images through this proposal and subtracting them from the individual light curve points, we eliminate all potential systematics and allow the the SNe Ia to be used as originally proposed. Finally, we note that as an additional benefit these images will allow us to extend our past studies of the impact of host galaxy morphologies of SNe Ia on the cosmological parameters (Sul03).

Table 1

SN	2002 UT	RA(2000)	Dec(2002)	i’	z
2002fc	Apr 9.4	14 00 23.29	+ 5 45 41.9	24.2	0.88
2002fe	Apr 9.5	14 04 18.16	+ 5 19 25.6	24.7	1.086
2002ff	Apr 9.6	14 03 39.82	+ 5 46 50.6	24.0	1.1
2002fg	May 7.5	13 24 25.92	+27 44 33.9	23.7	0.79
2002gi	May 7	13 57 12.3	+ 4 33 17.2	24.1	0.91
SuF02-012	Nov 3	02 18 51.60	- 4 47 25.7	25.2	1.3
SuF02-060	Nov 3	02 17 34.48	- 4 53 47.2	24.5	1.06

References

(Kno01) Knop, R. 2001, AAS, 199.1607
(Nug02) Nugent, P., A. Kim, S. Perlmutter, 2002, PASP, 114, 803.
(Pae03) Paerels, F., *et al.* 2003, ApJL, submitted.
(Perc02) Percival, W., *et al.* 2002, MNRAS, 337, 1068.
(Per99) Perlmutter, S., *et al.* 1999, ApJ, 517, 565.
(Phi99) Phillips, M., *et al.* 1999, AJ, 118, 1766.
(Rie98) Riess, A. G., *et al.* 1998, AJ, 116, 1009.
(Sie03) Sievers, J. L, *et al.* 2003, ApJ submitted. astro-ph/0205387
(Sul03) Sullivan, M., *et al.* 2003, MNRAS, in press. astro-ph/0211444
(Tur02) Turner, M.S., *et al.* 2002, Report of the Committee on the Physics of Universe, National Academies Press, 2002.

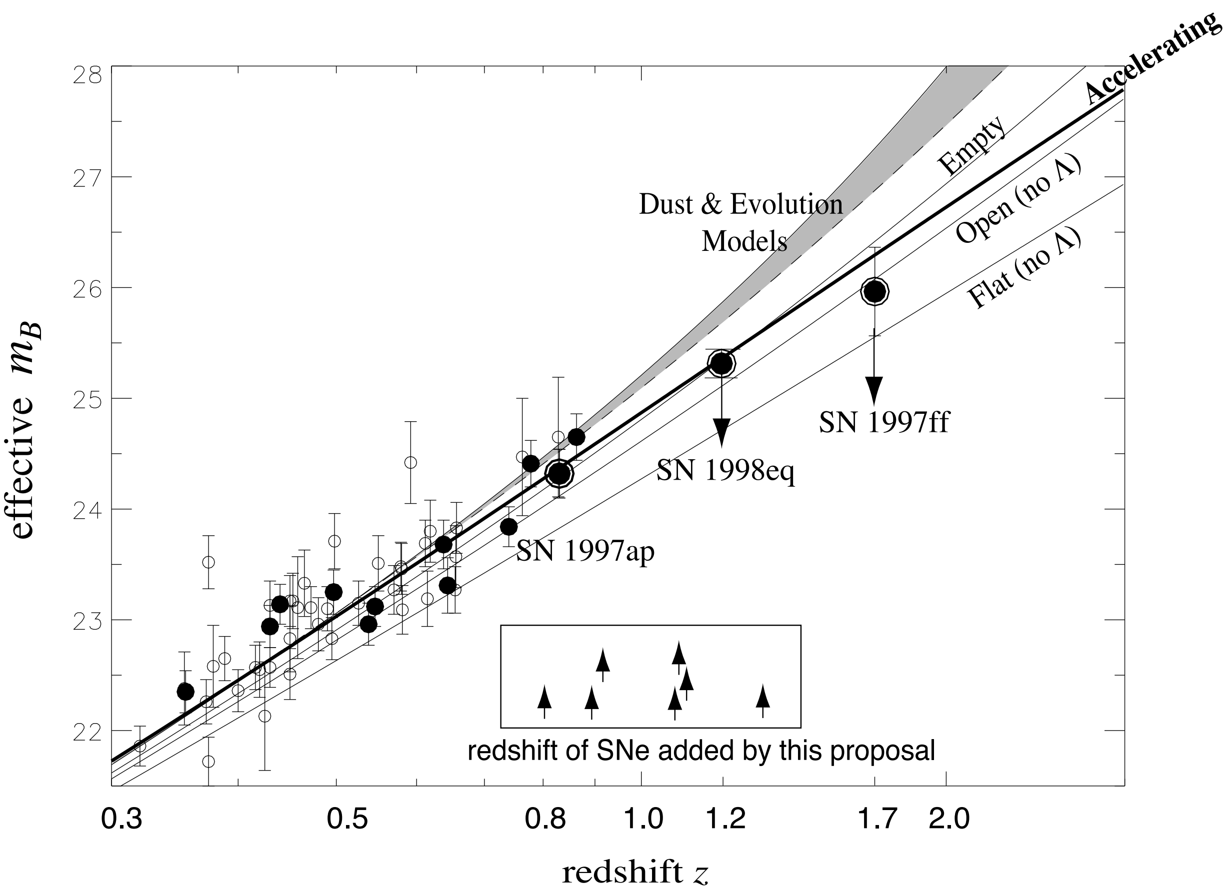

Figure 1: Open points show Hubble diagram for 42 high-z SNe (Perlmutter *et al.* 1999) including SN1997ap at z=0.83 for which HST observations were used, along with comparable non-host-extinction-corrected points (filled circles) for our HST SNe (Kno01). The Einstein-de Sitter, "Flat (no Λ)" case (Ω_M, Ω_Λ) = (1.0, 0.0) is strongly excluded by the current data. The "Open (no Λ)" case (0.28,0.00) indicates that some contribution from a cosmological constant is required for values of Ω_M favored by dynamical measurements. The magnitude difference between the best-fit "Accelerating (Λ)" world model (0.28, 0.72) and suitable ones with Ω_Λ=0 show redshift dependencies which would be very hard to mimic within the context of SNe evolution or gray dust hypotheses (the gray shaded region is an example model with uniform dust). The seven new supernovae, for which we are requesting final reference images, lie at the redshifts represented by arrows in the figure. As can be seen, we have now extended our survey beyond $z = 1$, and will be able to utilize the *shape* of the Hubble diagram to further test the evidence for a cosmological constant. The preliminary magnitude estimates of our highest redshift supernova SN 1998eq at $z = 1.2$ and the serendipitous data for SN 1997ff at $z = 1.7$ are suggestive, and the analysis that the proposed final reference images will make possible will provide far more conclusive results.

Description of the Observations

For the final few photometry points on our light curves, where the observations are background-limited, we estimate the signal-to-noise ratios for these 7 supernovae to be between 10 and 15. If we match the exposure times of the final reference images to those of the earlier images, performing the final reference subtraction will eliminate the systematics involved from *every* point on the light curve while causing only a 40% degradation in signal-to-noise. Based on our simulations, shorter exposure times result in an unacceptable $> 60\%$ reduction in signal-to-noise. On the other hand, acquisition of longer exposure times for the final reference images would not greatly improve the value of the SNe Ia, as we quickly run into the intrinsic dispersion of these objects as distance indicators (< 0.15 mags).

We were not previously able to obtain final reference images for these supernovae for a combination of reasons. Our initial Cycle 10 request was scaled back, but also in mid-cycle, we received permission from the change-request board to switch some of our orbits to NICMOS after that camera was made available. It was suggested to us at that time to propose for additional orbits in Cycle 12 to obtain final references. Thus we are requesting orbits to allow comparable length exposures to those obtained in GO 9075 for the seven SNe Ia at the last previous epoch. For each of the five observed in the spring 2002 campaign this requires a single orbit of ACS/WFC in each of 2 filters, F775W and F850LP. For each of the two supernovae observed in the fall 2002 campaign we require a single orbit of ACS/WFC in F850LP and 3 orbits of NIC2/F110W IR photometry. This leads to a total request of 18 orbits. The observations can be scheduled at any time throughout Cycle 12 while the targets are visible. Similar orientations to the original images would be preferred, but are not necessary.

Special Requirements

There are no special requirements.

Coordinated Observations

There are no coordinated observations.

Justify Duplications

These are final images of the galaxies after the SNe have faded and do not duplicate any existing data.

Previous Related HST Programs

This program is is directly related to the successful completion of GO 9075. Without these observations the program will suffer greatly.

Publications:

GO-9705: In this program, we pushed our SNe Ia studies to the highest redshifts that are feasible

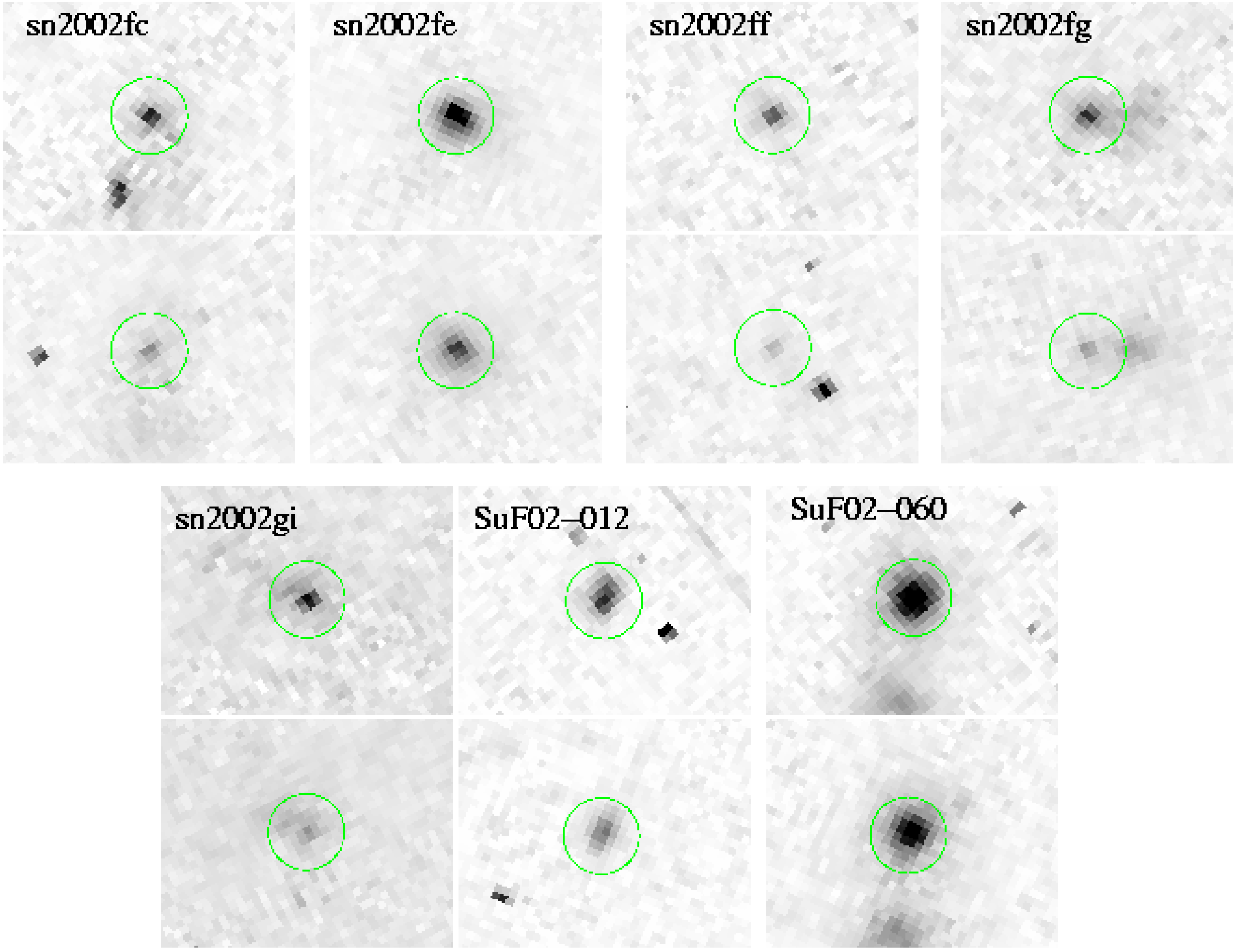

Figure 2: ACS/F850LP images of 7 high-redshift SNe Ia from our spring 2002 and fall 2002 followup campaigns. We show each object at two epochs, early in the light curve after max (top) and at late times (bottom). All but one (SN 2002fg) lie directly on top of their respective hosts, and in the case of SN 2002fg we cannot determine whether the underlying galaxy light is smooth. Therefore, final reference images are essential.

for a ground-based discovery and spectroscopic identification campaign. HST follow-up observations for this program started after servicing mission 3B in March 2002 and have been completed for the most past - final reference images are still to be taken. Coordinated with three large search campaigns using the Subaru 8 m and also with simultaneous smaller searches using the CTIO 4 m and CFHT 3.5 m, we obtained ACS/WFC and NICMOS/NIC2 photometry for multi-epoch lightcurves of seven SNe Ia at high redshift $(0.9 < z < 1.3)$. For two of the highest redshift SNe, ACS grism spectra were taken. Analysis of this ACS data is in progress. With the refurbished NICMOS, we obtained final reference images of the host of SN 1998eq, which we had previously studied in G0-8088, and these images will allow us to complete that analysis.

GO-8585: In this program we observed six SNe Ia with HST using WFPC. The supernovae were discovered in ground based searches at the CTIO 4-m, CHFT 3.5-m, and Subaru 8-m telescopes. We obtained both U- and B-band restframe photometry (using either F814W or F850LP depending on the redshift) for each supernova for a period of 2 months. Analysis of this data will be completed when the final reference images are available, scheduled for spring 2003.

GO-8313: The objective of this project, which has now been completed with a publication in press (Sul03), was to obtain snapshot unfiltered STIS images of distant galaxies of known redshift which have hosted supernovae (SNe) of Type Ia found by the SCP, 20 of which are used in the Hubble diagram of 42 type Ia SNe (Perlmutter *et al.* 1999). In Sullivan *et al.* (Sul03) we present these new results on the Hubble diagram of SNe Ia as a function of host galaxy morphology that demonstrates that host galaxy extinction is unlikely to systematically dim distant SN Ia in a manner that would produce a spurious cosmological constant. The internal extinction implied is small, even for late-type systems $(A_B < 0.3)$, and the cosmological parameters derived from those SNe Ia hosted by (presumed) dust-free early-type galaxies are consistent with our previous determination of a non-zero Λ. The brightness scatter about the Hubble line for SNe Ia in these early-type hosts is also significantly smaller than for the SNe Ia in late-type galaxies. This result was based on HST STIS "snapshot" images and Keck spectroscopy of SNe spanning the range $0.3 < z < 0.8$.

GO-8346: We had the unique opportunity of following up SN200fr, which had been discovered *14 days prior* to maximum light in its restframe. Because this supernova at z=0.54 was discovered so early we were able to obtain excellent light curves from HST in F555W, F675W and F814W spanning the period from one week prior to maximum light to 6 weeks after. Several spectra of the supernova were taken at VLT and Keck along with NIR photometry at VLT. To date, this is still the best observed high-redshift supernova and preliminary results were presented in Nobili, S. *et al.* 2001, AAS, 199,1611N.

DD-8088: WFPC2 and NICMOS (cycle 7) observations were obtained for SN1998eq at $z = 1.20$ (a record-breaking redshift for a spectroscopically confirmed Type Ia supernova; Aldering, *et al.*, 1998,IAUC,7046). The preliminary photometry is consistent with the previous results for Ω_M, Ω_Λ. With the final NICMOS image of the galaxy without the supernova recently obtained in December 2002, this analysis can now be completed.

GO-7850 and balance of **GO-7336** and **DD-7590**: WFPC2 and NICMOS observations were obtained for 11 Type Ia supernovae in the redshift range 0.36—0.86. These observations, including final references where necessary, are now complete, and the results are about to be submitted for publication in Knop, R., *et al.* 2003, (in preparation). A preliminary Hubble diagram was presented January 2002 AAS meeting. The cosmological results from these SNe are in close agreement with results from the first supernova results (Per99) that gave direct evidence for a cosmological constant. The lightcurves provided by WFPC2 for these supernovae were excellent; at the higher redshifts, these lightcurves provide a substantially better measurement of the calibrated supernova magnitude than those for comparable supernovae observed only from the ground. The color information provided by NICMOS (Burns, S., *et al.*, 2001,AAS,199.1610B), was only possible with HST. The improvement of the confidence limits on the cosmological parameters Ω_M and Ω_Λ are as good as we had previously predicted.

GO-7336 and **DD-7590**: Perlmutter *et al.*, 1998, Nature, 391, 51 reported the results of our HST and ground-based imaging and Keck spectroscopic observations of SN1997ap, which was at the time the highest redshift ($z = 0.83$) *spectroscopically confirmed* Type Ia supernova. The HST portion is based on a total of 4 orbits. HST observations of two $z = 0.83$ supernovae are included in the analysis in Per99 which reports on the results from our HST and ground-based imaging and Keck spectroscopic observations of 42 type Ia supernovae with $0.18 < z < 0.86$. The paper rules out a flat $\Omega_M = 1$ universe and presents very strong evidence for a positive cosmological constant.