Cosmological Parameters from Type Ia Supernovae at High Redshift

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Cycle 11 primary orbits: 0
Cycle 11 parallel orbits: 0

Abstract

In the remaining lifetime of the HST, we have the opportunity to obtain a Hubble diagram of Type Ia supernovae (SNe Ia) that will be of longlasting value as a record of the expansion history of the universe. This record based on SNe Ia used as calibrated standard candles directly constrains the cosmological parameters. Building on our earlier HST work that has yielded increasingly high redshifts and increasingly detailed SN Ia studies, we here propose to measure: five SN Ia at $z \sim 0.85$, and two at $z \sim 1.0$, and two beyond $z \sim 1.3$. Of these, one $z \sim 0.5$ and one $z \sim 1.0$ SN Ia will be observed spectroscopically with STIS. These data will provide powerful constraints on SN Ia evolution and abnormal dust within or between galaxies, and can reveal all but the most contrived evolutionary effects. Accurate measurement of these high redshift SNe, possible only with the HST, will dramatically shrink the major-axis of the error ellipse in the Ω_M—Λ plane, decoupling the measurements of Ω_M and Ω_Λ. This will provide the first check on the CMB measurements of a spatially flat universe, and *unambiguously* determine whether the universe contains vacuum energy. The Hubble diagram in this redshift range is the only currently feasible way to begin constraining the physics of the "dark energy" that is accelerating the universe's expansion.

From Cycle 7 NICMOS ——————————————————

HST can directly measure the cosmological parameters, Ω, Λ, and thus the curvature, Ω_k, using Type Ia supernovae (SNe Ia) as calibrated standard candles. Observations of SNe Ia spanning a large redshift range are key to decoupling Ω and Λ. For Cycles 7 & 8 we proposed a measurement of Ω and Λ with uncertainty $\sim 11\%$ by studying six SNe at $z \sim 0.5$ and six at $z \sim 0.9$ with WFPC and NICMOS; we have already embarked on this program with the Cycle 7 allocation and the results have more than met our expectations. Given the shortened lifetime of NICMOS, we are seeking orbits *now* for the remaining required NICMOS part of the project. NICMOS data are necessary because extinction correction, both at the SN host galaxy and foreground, is currently the largest part of the error budget. SN-host-galaxy extinction can be measured with rest-frame $B - V$ data; at $z \sim 0.9$ this requires NICMOS observations. The NICMOS observations bring uncertainties in the foreground extinction below the error budget for *both* $z \sim 0.9$ and $z \sim 0.5$. We therefore propose adding NICMOS observations to our Cycle 7 WFPC2 time for 3 additional SNe at $z \sim 0.9$ (completing the original goal of 6 SNe at $z \sim 0.9$) and 3 already planned SNe at $z \sim 0.5$.

End Cycle 7 NICMOS ——————————————————

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Total number of investigators: 13
Number of ESA investigators: 4 (indicated by * after name)

Observing Summary:

Target	RA	DEC	V	Configuration,mode,aperture spectral elements	Total orbits	Flags
SN02Z05-1	12 01 31	01 01 01	24	WFPC2 IMAGE F555W,F675W,F814W	18	
SN02Z08-1	12 01 32	01 02 02	24	WFPC2 IMAGE F675W,F814W,F850LP	15	
SN02Z08-2	12 01 33	01 03 03	24	WFPC2 IMAGE F675W,F814W,F850LP	15	
SN02Z08-3	12 01 31	01 01 01	24	WFPC2 IMAGE F675W,F814W,F850LP	15	
SN02Z08-4	12 01 32	01 02 02	24	WFPC2 IMAGE F675W,F814W,F850LP	15	
SN02Z08-5	12 01 33	01 03 03	24	WFPC2 IMAGE F675W,F814W,F850LP	15	
SN02Z12-1	12 01 33	01 05 05	25	WFPC2 IMAGE F814W,F850LP	22	
SN02Z12-2	12 01 34	01 06 06	25	WFPC2 IMAGE F814W,F850LP	22	
SN02Z05-1,SN02Z12-2	12 01 31	01 01 01	24	STIS/CCD IMAGE 50CCD,F28X50LP	1	
SN02Z05-1	12 01 31	01 01 01	24	STIS/CCD SPECTRA G750L	8	
SN02Z12-1	12 01 33	01 05 05	25	STIS/CCD SPECTRA G750L	12	

Observing Summary:

Target	RA	DEC	V	Configuration,mode,aperture spectral elements	Total orbits	Flags
SN981	04 00	00 00	~ 22.8	NIC2 MULTIACCUM F110W	7	
SN982	08 00	00 00	~ 22.8	NIC2 MULTIACCUM F110W	7	
SN983	09 00	00 00	~ 22.8	NIC2 MULTIACCUM F110W	7	
SN984	09 00	00 00	~ 25.3	NIC2 MULTIACCUM F110W	7	
SN985	09 30	00 00	~ 25.3	NIC2 MULTIACCUM F110W	7	
SN986	10 00	00 00	~ 25.3	NIC2 MULTIACCUM F110W	7	
				Grand total orbit request	200	

NOTE: This grand total (200) does not equal the sum of cycle 11 primary (0) and parallel (0) orbits plus cycle 12 primary (0) and parallel (0) orbits plus cycle 13 primary (0) and parallel (0) orbits on page 1

From Cycle 7 NICMOS ————————————————

above includes cycle 7 NICMOS observations.

End Cycle 7 NICMOS ————————————————

■ Scientific Justification

The Hubble diagram for Type Ia supernovae (SNe Ia), extended to redshifts well beyond $z = 0.25$ (Fig. 1), provides perhaps the most direct current measurement of the expansion history of the universe—and hence the most direct evidence for an accelerating expansion. This evidence has been increasingly strengthened, both by tests and improvements of the supernova measurements and by independent, cross-cutting cosmological measurements. In particular the recent balloon-based CMB measurements (Jaffe *et al.* 2000) have strongly indicated that the geometry of the universe is flat, reinforcing this evidence for an accelerating universe by eliminating the possibility of a low-density open universe (see Fig. 2a).

There are now two important directions to pursue with the SN Ia cosmology work, which we address in this proposal: (1) refining and further testing the SNe Ia as tools for cosmological measurements, and (2) extending and filling in the SN Ia Hubble diagram to obtain a more complete and detailed expansion history of the universe. The first of these goals seeks to take advantage of an almost unique characteristic of SNe Ia as cosmological tools: they can be studied individually by their light curves and time-varying spectra and hence calibrated individually, not simply statistically. The second goal of a more complete Hubble diagram has an additional long term aim: studying the physics of the "dark energy" that is apparently accelerating the expansion of the universe. The redshift range that we are emphasizing in this proposal completes the Hubble diagram during the epochs in which the dark energy is dominant and can be studied.

From Cycle 7 NICMOS ——————————————

NICMOS is an integral part of this program because the uncertainty in the extinction correction is currently the largest source of statistical uncertainty in using this approach to measuring the cosmological parameters. For $z \sim 0.9$ SNe NICMOS is the only source of the accurate rest-frame 5000–9000Å photometry needed to measure SN host-galaxy extinction. At NICMOS wavelengths, the SNe evade most foreground extinction, so it is necessary to obtain the NICMOS data for a subset of $z \sim 0.5$ SNe to allow uniform treatment at both redshifts. In order to complete our program it is imperative that we obtain observations of the balance of 3 SNe Ia at $z \sim 0.9$ while it is still possible with NICMOS. We will use our WFPC2 Cycle 7 and DD orbits to obtain the necessary optical data for these same SNe. We will then only have sufficient Cycle 7 WFPC time to match the comparable NICMOS measurements for 3 SNe at $z \sim 0.5$, but this will provide a foreground extinction spot check unavailable in any other way.

End Cycle 7 NICMOS ——————————————

Background: The Techniques Used and the Current State of Knowledge

The Supernova Cosmology Project developed an approach to measuring mass density Ω_M and cosmological constant Ω_Λ, using the magnitude-redshift relation for Type Ia supernovae (SNe Ia) at a range of redshifts (Perlmutter *et al.* 1997, 1998, 1999). We have demonstrated our ability to *a)* discover large numbers of high–z SNe Ia (> 20 per observing run) while they are still on the rise, *b)* obtain spectroscopic follow-up within a few days of discovery to confirm the SN type and redshift, *c)* acquire ground-based and HST lightcurve

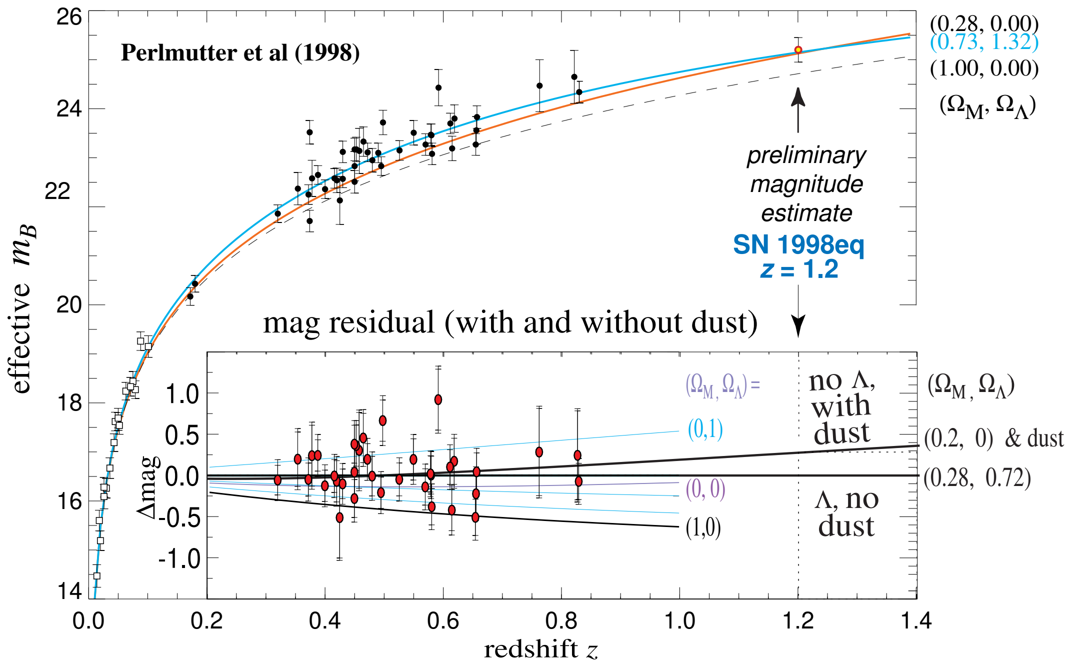


Figure 1: Hubble diagram for 42 high-z SNe (Perlmutter *et al.*1999) including SN1997ap at z=0.83 for which HST observations were used. The best-fit world model with $(\Omega_M, \Omega_\Lambda)$ = (0.73, 1.32) is drawn through the data (solid line). The Einstein-de Sitter case (1.0, 0.0) is strongly excluded by the current data (dashed line). The case $(\Omega_M, \Omega_\Lambda) = (0.28, 0.00)$ 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 world model 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 (see inset panel). By extending our survey beyond z=1, the *shape* of the Hubble diagram alone would become sufficient evidence to support a cosmological constant. The preliminary magnitude estimate of our highest redshift SN1999eq at $z = 1.2$ is suggestive, but more analysis and more SNe at this redshift (as proposed here) are necessary.

photometry, and *d)* analyze the data to obtain peak magnitudes and measure Ω_M and Ω_Λ. A Hubble diagram based on our HST and ground-based observations is shown in Fig. 1, while Fig. 3 shows HST and ground-based observations of several of our highest redshift SNe. Our results based on 42 $0.18 < z < 0.83$ SNe, including two with measurements from HST, give strong evidence that we live in an accelerating universe, dominated by a cosmological constant (or other form of "dark energy" density with sufficiently negative equation of state) (Perlmutter *et al.* 1999; see also Riess *et al.* 1998a). We find $\Omega_M = 0.28 \pm 0.08$ for a flat universe (which is a universe consistent with the recent CMB results), and constrain the combination $0.8\,\Omega_M - 0.6\,\Omega_\Lambda$ to -0.2 ± 0.1 (cf. Fig. 2a). This dramatically confirms the suggestion of Goobar & Perlmutter (1995; GP95) that a sample of SNe Ia spanning a range of high redshifts makes it possible to measure Ω_M and Ω_Λ simultaneously by constraining the confidence-region strip to a bounded ellipse. We are obtaining the final images for ~ 20 additional SNe Ia out to $z = 0.86$, including 13 for which we have obtained excellent WFPC2

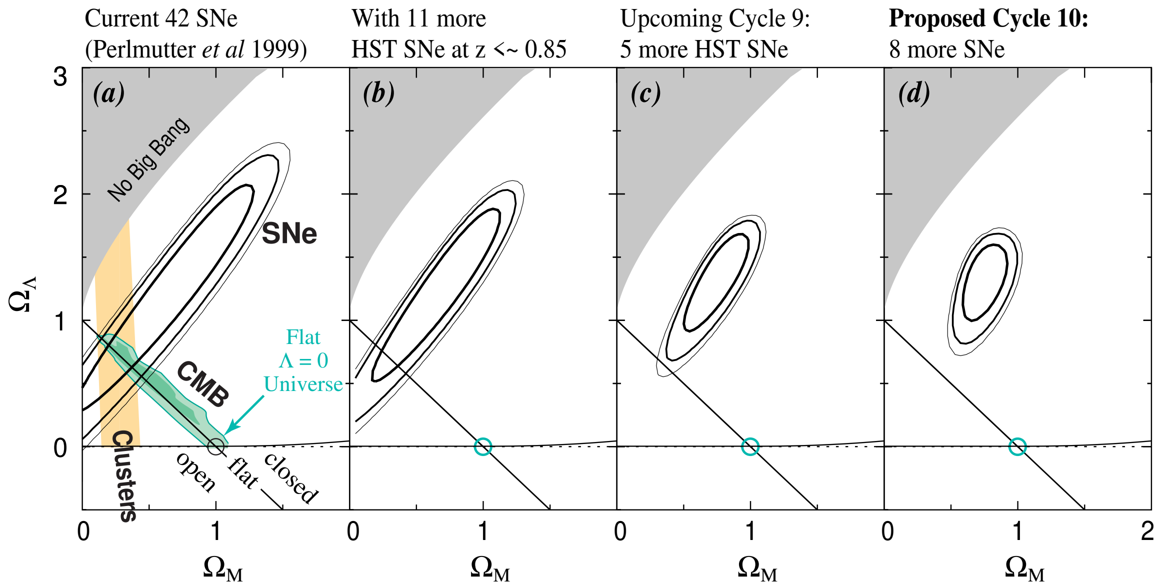


Figure 2: *(a)* 68%, 90%, and 99% confidence regions in the Ω_M—Ω_Λ plane from the 42 distant SNe Ia in Perlmutter *et al.* 1999 (including two observed with HST). These results indicate $\Omega_\Lambda > 0$, in agreement with the overlap of the recent combined CMB results (Jaffe *et al.* 2000) with the Ω_M measurements from galaxy clusters. *(b)* Expected confidence region after including our additional ~ 20 SNe Ia with $z \lesssim 0.85$, of which 11 have lightcurves from WFPC and NICMOS *(c)* Confidence region with an additional three SNe Ia at $z \sim 0.85$–1.0 and two at $z \sim 1.0$–1.3 to be observed in Cycle 9. *(d)* Now including the eight HST SNe requested in this proposal. These simulations show that our proposed program can check the curvature of the universe found by the CMB program; we dramatize the point by showing a scenario in which the universe is *not* flat, e.g., using the central Ω_m,Ω_Λ value of panel *(a)*.

and NICMOS lightcurves (cf. Fig. 2b), and the analysis of these SNe is now well underway. Our discovery and WFPC2/NICMOS follow-up of SN1998eq extends these techniques to $z = 1.2$.

(1) Refining and Testing a Cosmology Tool: SNe Ia Systematic Uncertainties

Perlmutter *et al.* (1997, 1999) provide extensive discussion of possible systematics in the measurement of Ω_M, Ω_Λ; we find that uncertainties due to K-corrections, gravitational lensing amplification, and Malmquist bias, are quite small compared to the statistical error. Remaining sources of systematic uncertainty that we showed are unlikely, but possible, are SN Ia evolution and abnormal dust within, or even between, galaxies. To proceed with the supernova cosmology studies, we have identified a series of refinements and tests that will "sharpen" this cosmological measurement tool, by addressing these two issues. We focus on three of these refinements/tests in this proposal: a spectral-feature luminosity indicator, a Hubble-diagram shape test, and a magnitude dispersion test.

Hubble diagram study of possible systematic deviations. A strong, complementary check on evolution or intergalactic grey dust will be possible with a SN Ia Hubble diagram

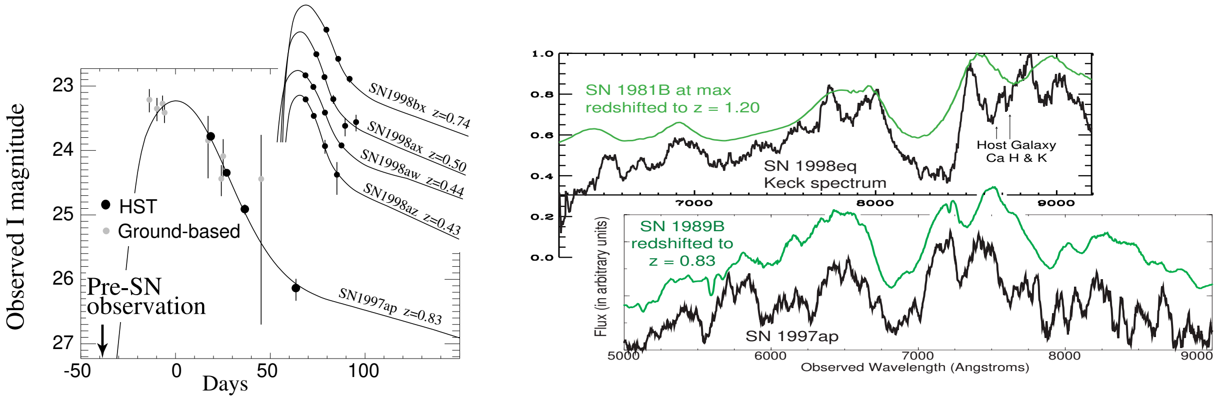
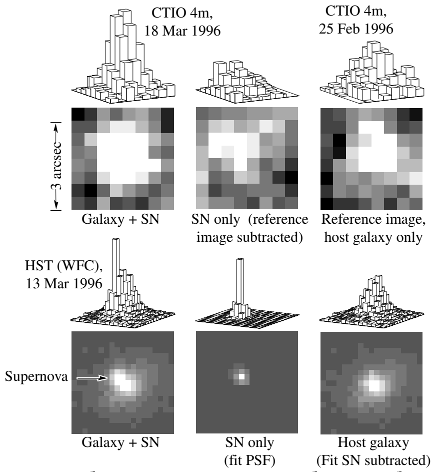


Figure 3: HST and ground-based I-band photometry for SN1997ap and Keck spectra for SN1997ap (at $z = 0.83$; Perlmutter *et al.* 1998) and SN1998eq (at $z = 1.2$, our most distant confirmed SN Ia; Aldering *et al.*, IAUC 7046). (a) Best-fit template lightcurve for SN1997ap. Unlike the ground-based photometry, in general the uncertainty in the HST photometry is less than the size of the plotted symbols. The inset shows (only) the HST photometry from a preliminary analysis of our next set of SNe. (b) The lower curves in each panel show the spectrum of the high-z SN Ia, while the upper curves show a spectrum of a nearby SN Ia for comparison. Within the noise, the low- and high-z spectra are in good agreement.

Figure 4: A comparison of ground-based and HST WF images of SN1996cl, a second $z = 0.83$ SN found by our project. This SN lies in the cluster MS1054.4-0321 which happened to be observed with HST when the SN was close to maximum light (HST image courtesy of Megan Donahue).



well-sampled over a large redshift range with an accuracy on each point approaching the 0.12 mag intrinsic dispersion of SNe Ia. Intergalactic dust or an evolutionary effect should force the SNe Ia magnitude-redshift to diverge monotonically from the magnitude-redshift relation for the *true* combination of Ω_M, Ω_Λ. Fig. 1a shows that a prediction based on our best-fit is fainter than a $\Omega_M, \Omega_\Lambda = 0, 0$ universe for $z \lesssim 0.85$, but beyond this — out at $z \sim 1.2$ where we propose to observe — our best-fit prediction becomes brighter. Thus, extension of the Hubble diagram out to $z \sim 1.2$ offers a test of dust or evolution versus $\Omega_\Lambda = 0$. Sufficient dust to explain our $z \sim 0.5$ data without Λ predicts SNe at $z \sim 0.85$ will be fainter by 0.14 mag and those at $z \sim 1.2$ will be fainter by 0.27 mag than the cosmology with Λ (Fig. 1b). *Preliminary* data for SN1998eq falls on the brighter (no dust) curve; Fig. 1a. The addition of five $z \sim 0.85$ and two $z \sim 1.2$ HST-observed SNe Ia from Cycle 10 to the similar number we expect from Cycle 9 (GO8585) will allow the dust model to be distinguished at 2.5σ at *both* redshifts. With such accuracy the trend (not just an offset) with redshift can be determined and used to constrain the physical cause of any detected systematics. If systematics are absent we should observe the transition to a *decelerating* universe over this redshift range.

Magnitude dispersion test. Most cosmological models that have ever been considered result in very smooth Hubble diagrams. It is only the non-cosmological effects, such as clumpy or abnormal dust extinction or changes/evolution in SN Ia progenitor populations, that are expected to increase the dispersion of the SNe Ia about the Hubble line. (Evolution would have to be improbably well synchronized for all SNe at each z—despite the wide range of progenitor metallicities, masses, and ages at a given z—to leave the small intrinsic dispersion unaffected.) Therefore, a good measurement of the magnitude dispersion about the Hubble line provides a strong constraint on such systematics. The sample we are proposing to study will provide sufficient statistical power (when combined with our other HST SNe Ia already observed) to detect at 3σ any process which contributes more than 0.1 mag to the dispersion. This will either detect the existence — or severely constrain the properties — of proposed mechanisms for inducing systematics errors (see, e.g. Aguirre & Haiman 2000).

From Cycle 7 NICMOS ————————————————

The most important sources of uncertainty can be alleviated by HST. They are:

Extinction. Less then 10% of nearby SNe Ia exhibit significant host-galaxy extinction, and no SNe Ia in ellipticals show evidence of extinction. Nonetheless, extinction cannot be ignored since it will cause a systematic bias in the SNe Ia Hubble diagram. Although with a large sample it may be possible to identify the least reddened SNe Ia based on crude colors or an E/S0 host morphology, this approach is wasteful of the hard-won data for high–z SNe. Structure seen on small angular scales in *IRAS* maps, and uncertainty in gas-to-dust conversion ratios, also means that Galactic foreground extinction is uncertain. Moveover, there may be extinction due to foreground galaxies, as suggested by some radio/optical studies of quasars and the discovery of quite extended dust halos in galaxies (Nelson *et al.* 1997). This would systematically increase with redshift, resulting in a systematic error in measurement of the cosmological parameters even when using "least reddened" sub-samples. NICMOS observations are therefore needed to obtain lightcurves suffering less total extinction and having sufficient wavelength lever-arm to accurately determine extinction. On page 9 we show that extinction corrections would be our dominant source of uncertainty but that with NICMOS data we should be able to keep extinction correction errors below 0.05 mag.

Host galaxy background. As Fig. 3 shows, HST images have exquisite angular resolution and a stable PSF which guarantees a reliable measurement of any small amount of host light that remains under the SN. This is a serious problem for ground-based observations because at high–z the PSF and host size are comparable, and PSF variations require the subtraction of different amounts of host light. A host subtraction error affects the SN photometry least at peak, distorting the lightcurve width and therefore the brightness calibration. HST data will largely avoid this source of error, while providing a cross-check of our host-galaxy subtraction for ground-based data on the same SNe.

End Cycle 7 NICMOS ————————————————

(2) Exploiting a Cosmology Tool: Filling a SN Ia Hubble Diagram to $z \sim 1.6$

These refinements and tests of SNe Ia as cosmological measurement tools are aimed at further improving our ability to control systematic uncertainties. However, it is important to note that currently we see no evidence for any evolution in the spectra or lightcurves between our nearby and high-z SNe (Fig 2). Indeed, there is now evidence limiting the amounts of intergalactic or abnormal host dust (Riess *et al.* 2000; Aldering 2000), and showing consistency between the lightcurves of low- and high-z SNe (Aldering *et al.* 2000). It is therefore appropriate to work to further exploit the SNe Ia as a tool for fleshing out a Hubble diagram extending to $z \sim 1.2$.

This Hubble diagram is a crucial record of the expansion history of the universe over the past ∼10 billion years, and it has the potential to become one of the lasting legacies of the Hubble Space Telescope. It is apparent that the Hubble diagram of Fig. 1 is poorly studied beyond redshift $z \sim 0.65$, and this situation will be only marginally improved with data currently being analyzed. It is only with the HST that the supernovae at these higher redshifts can be studied with sufficient S/N to provide significant constraints on the Hubble diagram.

Significant improvements are now being made in the systematic uncertainties in the supernova measurements (see, e.g., Perlmutter *et al.* 1999) due to our recent low-redshift SN campaign (Aldering 2000) and similar work. Therefore, there is now reason to improve the cosmological measurements by reducing the statistical uncertainty by almost a factor of two — that is, by studying an additional ∼100 SNe Ia. This is about the number that could reasonably be expected to be found and spectroscopically confirmed at $0.5 < z < 1.2$ with ground-based telescope resources over the remaining lifetime of the HST. The study of these SNe is therefore a key task for the HST to complete, if possible, at as rapid a rate as is manageable. As discussed in the observation details below, 8 such SNe can be reliably discovered and confirmed with current ground-based facilities during Cycle 10.

This redshift range that we propose to populate in this HST Cycle is aimed at addressing several of the more important scientific questions of our day. First, it fills the redshift range out to $z \sim 1$ that is most important for the study of the "dark energy" that can accelerate the universe. (At higher redshifts matter dominates.) The simplest measurement to characterize this dark energy is the effective equation-of-state ratio, $w \equiv p/\rho$. The current constraints on w are consistent with a very wide range of dark energy theories, including Einstein's Cosmological Constant (for which $w = -1$) (Perlmutter *et al.* 1999, Garnavich *et al.* 1998); the proposed data set, together with data now being analyzed can tighten these constraints by 50%, potentially ruling out several contending theories if the current w value holds.

A single number, the effective w for all redshifts, is not the most complete dark energy characterization possible, however. Recent work by Weller and Albrecht (2000) has shown that dark energy theories can be differentiated on the Hubble diagram at $0.3 \lesssim z \lesssim 1$ by their behavior over the range of z. In particular, several extant theories that could not be differentiated if the Hubble diagram was only observed at one redshift, *could* be differentiated if the full range of redshifts was sampled. While there are always theories that can be proposed to avoid differentiation by any dataset, the Hubble diagram that the HST obtains in this redshift range will be the only constraint of this type on the fundamental question of the nature of the dark energy.

Populating the Hubble diagram beyond $z \sim 1$ addresses an additional fundamental question, the curvature of the universe. While additional SNe Ia over the $z \lesssim 0.85$ range of the current datasets will improve the current statistical uncertainty by $\sqrt{N}$, additional SNe Ia beyond $z \sim 0.85$ can dramatically shorten the major-axis of the current Ω_M—Ω_Λ error ellipse (cf. GP95 and Fig. 2). Figs. 2c & 2d are simulated results showing how our upcoming and proposed HST observations of SNe Ia spanning $0.85 < z < 1.2$ would constrain the allowed values in the Ω_M–Ω_Λ plane, compared with the existing 42 SNe (Fig. 2a), and with the addition of SNe now being analyzed (Fig. 2b). In the example of Fig. 2d our proposed HST observations, which would double the number of extinction-corrected confirmed type Ia SNe beyond $z \sim 0.8$, would rule out $\Omega_\Lambda = 0$ at well over 3σ. For a flat universe, Ω_M and Ω_Λ could be constrained to $\sim 6\%$. The resulting estimate of Ω_M, for *any* Ω_Λ, is still accurate to ± 0.15 in this simulation.

As Fig. 2d shows these data would be a first check on the CMB acoustic-peak measurements that indicate a flat geometry. Moreover, unlike CMB-based experiments, no assumption for the initial power spectrum (e.g., CDM) is needed. Even the most advanced experiments being planned (e.g. Planck), while tightly constraining $\Omega_M + \Omega_\Lambda$, will not constrain the complementary value, $\Omega_M - \Omega_\Lambda$, as well as our experiment can. The observations proposed here are a big step towards the important goal of obtaining an accurate measurement of Ω_M,Ω_Λ which is completely independent of the CMB results.

Conclusion

In the remaining lifetime of the HST, we have the opportunity to obtain a Hubble diagram that will be of longlasting value as a record of the expansion history of the universe over the last 10 billion years. This record is one of the only known ways to constrain the physics of the dark energy that apparently is accelerating the universe's expansion. Only HST observations can provide the photometric accuracy of ~ 0.11 mag and lightcurve coverage needed to fully exploit high-redshift SNe Ia for determining the cosmological parameters and realize the full potential of Fig 2d. Combined with STIS spectroscopic observations, these accurate measurements of SNe Ia in the redshift range $z \sim 0.5$–1.2, in conjunction with those we have already obtained at $z \lesssim 0.8$, can reveal all but the most contrived evolutionary effects. These proposed supernova measurements will thus serve double-duty, both refining and exploiting a cosmology measurement tool.

From Cycle 7 NICMOS ——————————————

Only HST observations can provide the photometric accuracy, lightcurve phase coverage, and optical-NIR wavelength coverage needed to fully exploit SNe Ia as calibrated standard candles for determining the cosmological parameters. This may be the last chance to obtain these NIR measurements for a long time.

End Cycle 7 NICMOS ——————————————

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Description of the Observations

The Need for HST: The most important sources of uncertainty in measuring high-redshift SN can be alleviated by HST. They are:

Terrestrial sky background. From the ground the overwhelming source of noise is the sky background. Since SNe Ia are point sources, they take full advantage of background reduction possible with the exquisite angular resolution of HST, and lower diffuse background in space. For spectroscopy the noise is strongly structured and dominated by systematic errors due to very strong emission from OH sky lines. When these lines overlap with key SNe spectral features, measurement of such features is exceedingly difficult (see Fig. 4) or impossible.

Host galaxy background. As Fig. 5 shows, HST images have exquisite angular resolution and a stable PSF which guarantees a reliable measurement of any small amount of host light that remains under the SN. This is a serious problem for ground-based observations because at high–z the PSF and host size are comparable, and PSF variations require the subtraction of different amounts of host light. A host subtraction error affects the SN photometry least at peak, distorting the lightcurve width and therefore the brightness calibration. Likewise for spectroscopy, galaxy features can easily overwhelm key SNe spectral features, severely compromising the use of spectral luminosity indicators (see Fig. 4). HST data largely avoids this source of error for both photometry and spectroscopy.

Lightcurve Phase Coverage. A well-sampled lightcurve in at least one band is crucial to determine peak date and width, needed to determine the calibrated peak brightness. HST restframe U lightcurves are especially critical for $z \sim 1.2$ SNe; at best their photometry can be obtained near peak from the ground and restframe B can only be obtained with WFPC2 at peak. Interpretation of spectral features relies on knowledge of lightcurve phase, while lightcurve width is the point of comparison for spectral luminosity indicators. Only space-based observations can guarantee this regular time coverage. Ground-based observations of transient events are notoriously plagued by instrument block scheduling, weather, etc..

Optimal Redshift Distribution: Our HST program has the dual aim of testing for the presence of hypothesized systematics while further constraining the amount and nature of the "dark energy" in the likely event that systematics are small. Our discovery of SN1998eq (Aldering, *et al.*, IAUC 7046) demonstrated that wide-area detectors on large telescopes at excellent sites now enable the discovery of SNe Ia out to $z \sim 1.2$. For a search out to this redshift, ~ 20 good SNe Ia can be harvested during Cycle 10 (with no more than ~ 5 at $z \sim 1.2$). Thus, we have optimized the redshift distribution of these proposed HST SNe Ia with an upper envelope set by the number of SNe Ia which can be discovered and spectroscopically confirmed as a function of redshift, but decreased to account for Poisson fluctuations, uncertainties in the SNe Ia rate, ground-based weather, and using $z = 1.2$ as an upper limit. We have further emphasized redshifts where cross-filter K-corrections are small. Given these constraints, our calculations, (see Fig. 3d) show that two $z \sim 1.2$ SNe Ia along with five $z \sim 0.85$ SNe Ia make the greatest improvement over our current results (Figs. 3a & 3b). Photometry of these SNe Ia, along with spectroscopy of a $z \sim 0.5$ and a $z \sim 1$ SN Ia, also allow questions of SN Ia evolution and abnormal dust to be directly addressed.

Optimal Sampling of the Lightcurves: As with our previous HST SNe, we plan to observe these 8 SNe at five epochs spaced every 7 restframe days, starting soon after discovery. After the SNe have faded, observations will be made of their host galaxies to obtain a baseline point. Monte Carlo tests of this sampling strategy on sample light curves (randomized with respect to discovery date) show this timing to be close to optimal for determining the lightcurve peak and width in a given amount of observing time.

From Cycle 7 NICMOS ————————————————

We plan to observe the 6 SNe with NICMOS at five epochs soon after discovery. For the $z \sim 0.5$ SNe the observations will each be separated from the next by $7{\pm}1$ days, and for the $z \sim 0.9$ SNe we will increase the separation to $9{\pm}1$ days to account for the increased time-dilation of the light-curve at these redshifts. After the SNe have faded, observations will be made of their host galaxies. We have run extensive Monte Carlo tests of this sampling strategy on sample light curves (randomized with respect to discovery date) and found this timing to be close to optimal for a given amount of observing time. In particular if follow-up commences within seven days of discovery, observations evenly distributed over the ~ 35 day period ($\sim$20 days in the SN rest frame) are optimal to parameterize the light curve. Four photometry points sampled over the peak of the light curve are the bare minimum needed to use the SNe for cosmological measurements, because three data points determine the peak and four data points determine the width of the light curve. For this definitive measurement of SN light curves at the HST, it would be optimal to use five data points over the light curve peak, since this sampling improves the measurement for the slightly earlier or later discoveries (with respect to maximum light).

End Cycle 7 NICMOS ————————————————

Host Galaxy Extinction Corrections: Extinction correction significantly decrease the intrinsic dispersion (from ~ 0.17 to ~ 0.12 mag), giving each SN $2\times$ greater statistical weight. This improved precision is the key to our planned photometric checks for any systematic bias in the *shape* of — or increased dispersion around — the SNe Ia Hubble diagram due to abnormal dust, or SN evolution. Since total-to-selective extinction is 4.1 for B-V, accurate colors are essential for producing final extinction corrected measurements having small uncertainties. WFPC2 can provide accurate B-V for all but the highest redshift ($z > 1$) SNe Ia. For those, WFPC2 can provide the restframe B peak brightness; this can be combined with a restframe V peak brightness obtained from ground-based NIR photometry. (Here an HST lightcurve width from restframe U is crucial since we could not follow the lightcurve sufficiently past peak from the ground.)

Photometry Filters: Our filters are chosen to cover the restframe UBV spectral region — where SNe Ia are brightest and for which there is extensive comparison data from nearby SNe Ia. For SNe Ia at $z \sim 0.55$, F555W, F675W and F814W are nice matches to restframe UBV. At $z \sim 0.85$, restframe U and B map to F675W and F814W; at this redshift F850LP is a moderately good match to restframe V. At $z \sim 1.2$, F814W is a good match to restframe U, while F850LP is a moderately good match to restframe B.

From Cycle 7 NICMOS ————————————————

Our choice of filter is set by the need to obtain a large wavelength lever-arm so that extinction can be accurately determined, while confining ourselves to the rest-frame VRI spectral region for which there is extensive comparison data from nearby SNe Ia. The latter point is doubly important because it allows us to supplement the B and V templates, which are the current standard, with R and I lightcurve templates to capitalize on the smaller *total* extinction in the rest-frame VRI. The limited amount of rest-frame NIR lightcurve data precludes working at even longer wavelengths. A further constraint on our filter choice is that our sources are faint and therefore the use of broad filters is desirable. These needs can be satisfied quite well using filters F140W or F110W for $z \sim 0.5$ SNe and filter F110W for $z \sim 0.9$. The choice of the F140W filter is not independent of the choice of camera, and we discuss the influence of camera choice in the next section.

End Cycle 7 NICMOS ————————————————

Photometry Exposure Times: In Perlmutter *et al.* 1999 we find $I \sim 23.5$ at peak for SNe Ia at $z \sim 0.85$, and for SN1998eq at $z = 1.20$ we find $I \sim 24.4$. To achieve the requisite 0.11 mag accuracy after width-brightness and extinction corrections requires 3% photometry at five epochs over the -7 to $+25$ restframe day portion of the lightcurve. (Extinction correction comprises most of the final uncertainty, and only uncertainties uncorrelated between the restframe B and V enter into this error component). Our current HST data show that total integration of one orbit for the first four epochs and two orbits for the remaining epoch for SNe Ia in F814W at $z \sim 0.85$, along with one orbit with F675W and three orbits with F850LP, both at maximum, will achieve the required wavelength coverage and photometric accuracy. Like SN1998eq, the $z \sim 1.2$ SNe Ia observed in F814W will require two orbits for the first three epochs, three orbits for the fourth, and four orbits for the fifth epoch. F850LP observations of these SNe Ia at peak will require five orbits. Finally, for the $z \sim 0.55$ SN Ia to be observed with STIS spectroscopy, one orbit per epoch per filter is required. For integration times of 1/2 orbit per image SN photon noise dominates the statistical error budget in all cases. At maximum the exposures are slightly longer than needed to obtain the desired photon S/N, but this has the important benefit of reducing systematic uncertainties from CTE at all epochs by raising the background. (We will further mitigate CTE effects by locating the SNe Ia closer to the readout amplifier. These measures will keep the CTE corrections below 5% one year from now according to the WFPC2 CTE calculator.) All SNe Ia will require at least one orbit for final reference images in each band. These observations are not time-critical, so initial final reference images will require one orbit each and if there is indication of possible host contamination up to two additional orbits per filter will be used.

From Cycle 7 NICMOS ——————————————

At peak we expect $J \sim 22.2$ (~ 2 μJy) for SNe Ia with $z \sim 0.5$ and $J \sim 23.1$ (~ 1 μJy) for SNe Ia with $z \sim 0.9$. Based on results obtained to date by other NICMOS observers, we have assumed a high limiting readnoise of 20 electrons in estimating exposure times. Given the reported cosmetic problems on the NICMOS array, we will break each orbit into at least three dithered exposures. With these parameters, readnoise is comparable to, or larger than, the typical SN photon noise in a 0.15 arcsecond aperture. Our targets are point sources, so NICMOS Camera 2 offers the best trade-off between resolution and readnoise-limited sensitivity. SNe Ia fade much less rapidly in rest-frame V than at B or U up until 40 days after peak, so a single orbit observation using NIC2+F110W will give good photometric accuracy (3–5%) over the critical portion of the lightcurve spanning -10 to $+30$ days around peak brightness for all of our target SNe. Note that the NICMOS exposure-time calculator gives more optimistic values since it reports a lower effective readnoise, so our estimates may seem more conservative than expected. If the readnoise performance of NICMOS improves over that seen in the most recent observations, we would then prefer to use Camera 1. Camera 1 properly samples point sources in the J-band, whereas Camera 2 is undersampled. Moreover, filter F140W is available on Camera 1; this filter provides a somewhat better wavelength lever-arm for determining extinction and it has the same rest-frame spectral coverage at $z \sim 0.9$ as does F110W at $z \sim 0.5$ making differential color measures between our sets of intermediate- and high–z more robust.

The rest-frame B-band extinction is about 1.8× the observed WFPC2+F814W minus NIC2+F110W color excess. With 3–5% photometry, the error in the color at peak brightness with ~ 6 datapoints should be less than 3%, giving an error in the extinction correction of roughly 0.05 mag for rest-frame B – well below the intrinsic dispersion in de-reddened SNe Ia peak magnitudes. By using rest-frame V, R, or I templates, the uncertainty in the extinction corrections will be further reduced since the total extinction is smaller. Galactic foreground extinction at J is 65% of that at I and 47% that at R. Thus, NICMOS observations will guarantee that the uncertainty in Galactic extinction corrections will be below other sources of uncertainty. Note that since the SN lightcurve is fit to a template for each bandpass, NICMOS observations do not need to be coordinated with WFPC observations to yield accurate colors (although such coordination is important for minimizing HST acquisition overhead and maximizing HST scheduling efficiency).

End Cycle 7 NICMOS ——————————————

Synopsis: We request 18 WFPC2 orbits and 8 STIS orbits for one $z \sim 0.55$ SN Ia, 15 orbits each for restframe UBV observations of five $z \sim 0.85$ SNe Ia, and 22 orbits each for restframe UB observations of two even higher redshift (z$\sim$ 1.2) SNe Ia. For one of the $z \sim 1$ SNe Ia, STIS spectroscopy totaling 13 orbits is also requested. This totals 158 orbits, including lightcurve, peak colors, and half of the maximum possible number of reference images for all SNe Ia, and spectroscopy for two SNe Ia. Only HST can provide the deep imaging and spectroscopy at high spatial resolution with a stable PSF, and phase coverage, needed to accurately measure the intrinsic luminosities, colors, and spectral indices for high–z SNe needed to determine the cosmological parameters while testing for systematics.

From Cycle 7 NICMOS ————————————————

In summary, 7 orbits each are requested for NICMOS Camera 2 observations of three high–z ($z \sim 0.9$) and three intermediate-z (z$\sim$ 0.5) SNe Ia in the F110W or F140W filters. This results in a total request of 42 orbits. Only NICMOS can provide the deep NIR imaging at high spatial resolution with a stable PSF needed to accurately measure intrinsic luminosities for high–z SNe and determine the cosmological parameters.

End Cycle 7 NICMOS ————————————————

Special Requirements

None. Our search strategy guarantees the date of discovery, lightcurve phase, redshift range, and possible sets of coordinates. We discover sufficient numbers of SNe to screen for those with preferred redshifts and positions with respect to HST guide stars. Thus, we specify our observing plan well before the actual discovery of the new SNe.

Coordinated Observations

The SN searches use the CFHT12K mosaic and CTIO 4m MOSAIC. Search observations of a several hours each night embedded in week-long observing runs are robust against inclement weather. Optical spectroscopic follow-up is obtained at Keck and VLT. NIR observations (restframe B and V) are obtained at Keck, VLT, and Gemini.

Justify Duplications

None.

Previous HST Programs

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, then the *highest redshift* ($z = 0.83$) *spectroscopically confirmed* Type Ia supernova. The HST portion is based on a total of 4 orbits.

Perlmutter *et al.*, ApJ, 1999 reports on the results from our HST and ground-based imaging and Keck spectroscopic observations of 42 type Ia supernovae with $0.18 < z < 0.86$. HST observations of two $z = 0.83$ are included in the analysis. The paper rules out a flat $\Omega_M = 1$ universe and presents very strong evidence for a positive cosmological constant.

GO-7850 and balance of **GO-7336** and **DD-7590**:

WFPC2 and NICMOS observations were obtained for an additional 11 type Ia supernova with redshifts between 0.36 and 0.86. The final reference images needed to complete the lightcurve analysis are now being obtained. Based on preliminary analysis (see Fig. 2a) we anticipate that excellent distances will result for these SNe. It is on the basis of the demonstrated success of these observations (and those of SN1998eq described just below) that we feel confident that the program proposed herein also will be successful.

DD-8088:

WFPC2 and NICMOS observations were obtained for SN1998eq at $z = 1.20$ (another record-breaking redshift for a spectroscopically confirmed Type Ia supernova; Aldering, *et al.*, 1998, IAUC 7046). The preliminary photometry (shown in Fig. 1) is consistent with the previous results for Ω_M, Ω_Λ—at this stage, this is suggestive but not conclusive.

GO-8346:

We had the unique opportunity of following up Beethoven during this cycle. Beethoven, at z=0.54, was discovered *14 days prior* to maximum light in the restframe of the supernova. Because this supernova was discovered so early we were able to obtain magnificent light curves from HST in F555W, F675W and F814W 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. This is *by far* the best observed high-redshift supernova to date.

GO-8313:

This Snapshot proposal has begun obtaining STIS imaging of the host galaxies of our high-redshift supernovae. We will use the morphology information to study the variation of SNe luminosity as a function of host galaxy environment, as a further test for SN Ia evolution.

GO-8585:

These observations have yet to occur. Three supernovae with $0.5 < z < 0.85$ and two with $z > 1.2$ will be followed with HST in the Spring semester.

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Items to check: