Cosmological Parameters from Type Ia Supernovae at High Redshift

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Cycle 10 primary orbits: 158
Cycle 10 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: one SN Ia at $z \sim 0.5$, five at $z \sim 0.85$, and two beyond $z \sim 1.0$. 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.

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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
				Grand total orbit request	158	

■ 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.

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 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 and NICMOS lightcurves (cf. Fig. 2b), and the analysis of these SNe is now well underway.

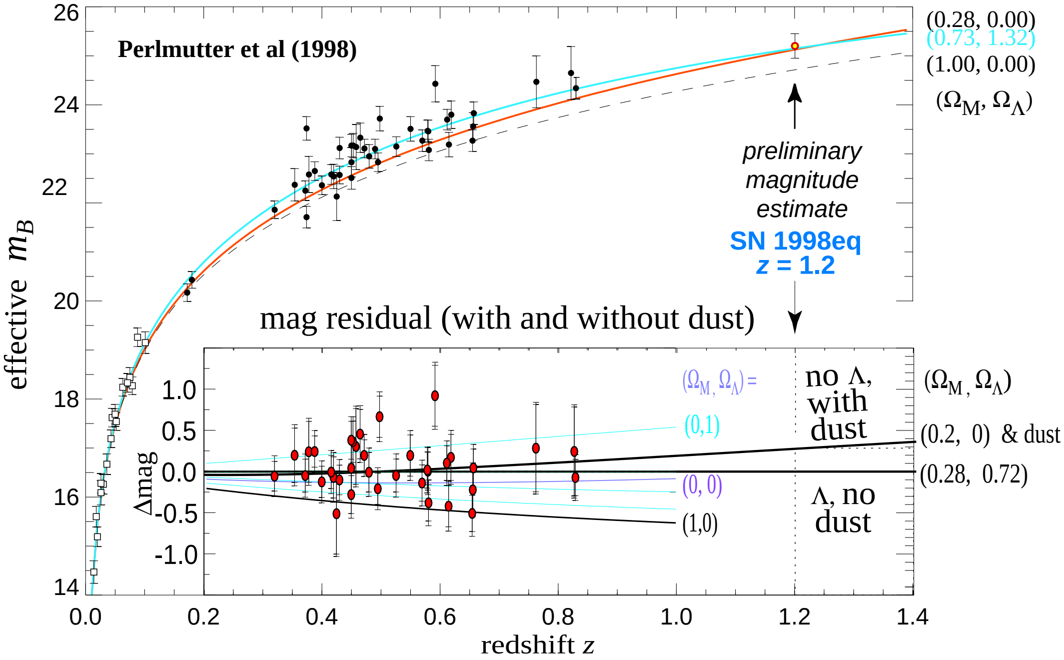

Figure 1: Hubble diagram for 42 high-z SNe (Perlmutter *et al.*1999) including SN1997ap at z=0.83 for which HST observations were used. The best-fit world model with $(\Omega_M, \Omega_\Lambda)$ = (0.73, 1.32) is drawn through the data (solid line). The Einstein-de Sitter case (1.0, 0.0) is strongly 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.

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

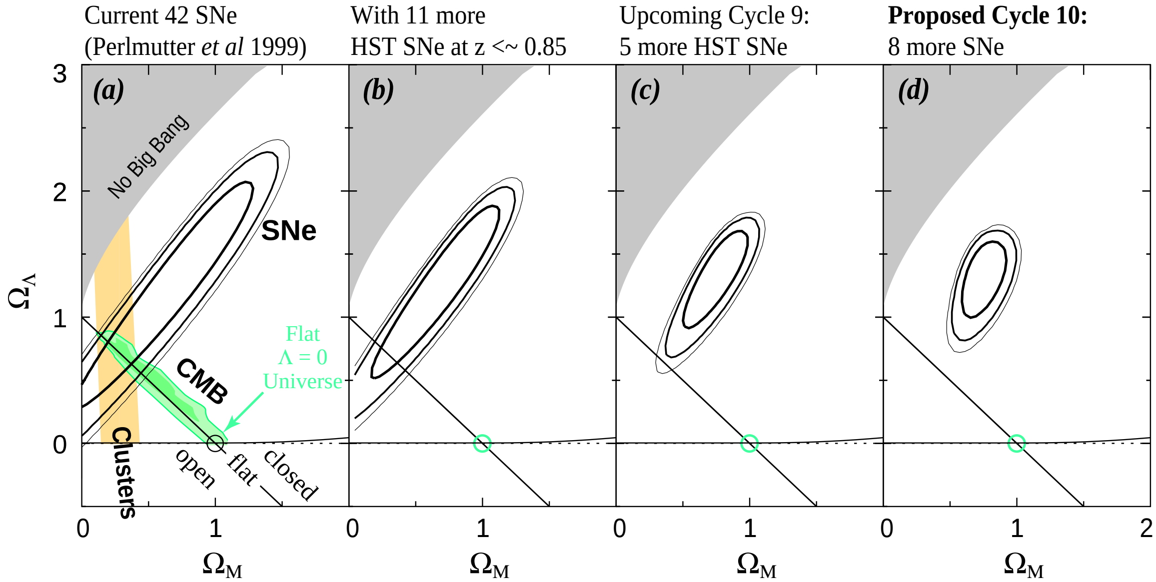

Figure 2: *(a)* 68%, 90%, and 99% confidence regions in the Ω_M—Ω_Λ plane from the 42 distant SNe Ia in Perlmutter *et al.* 1999 (including two observed with HST). These results indicate $\Omega_\Lambda > 0$, in agreement with the overlap of the recent combined CMB results (Jaffe *et al.* 2000) with the Ω_M measurements from galaxy clusters. *(b)* Expected confidence region after including our additional $\sim$ 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)*.

Hubble-diagram shape test, and a magnitude dispersion test.

A spectral-feature luminosity indicator. In all recent SN Ia studies, the timescale (or shape) of the lightcurves have been used as a luminosity indicator to reduce the intrinsic dispersion in peak luminosity from $\sim$ 0.35 mag to $\sim$ 0.17 mag (Hamuy *et al.* 1995, 1996; Riess *et al.* 1995; Perlmutter *et al.* 1997, 1999), or even as low as $\sim$ 0.12 mag, if multi-band measurements are used (Riess *et al.* 1996 (R96)). This low dispersion is found using a dataset of low-redshift supernovae that span a wide range of host galaxy environments, providing a strong indication that any evolution of the properties of SN Ia progenitors is likely to be accounted for by the lightcurve timescale-luminosity relation (R96). Since this is a key issue for the use of SNe Ia as cosmological tools, we propose to study an alternative luminosity indicator at high redshift first suggested by Nugent *et al.* (1995; (N95)), the spectral feature ratios of Ca II and Si II shown in Figs. 4a,c.

Fig. 4e shows the tight relationship between the lightcurve timescale parameter (here we use s, the timescale stretch relative to a standard SN Ia template; Perlmutter *et al.* 1997) and the Si II spectral ratio measured for low-redshift supernovae (see N95 for Ca II plot). These spectral ratios have not yet been exploited at high redshift, where they are

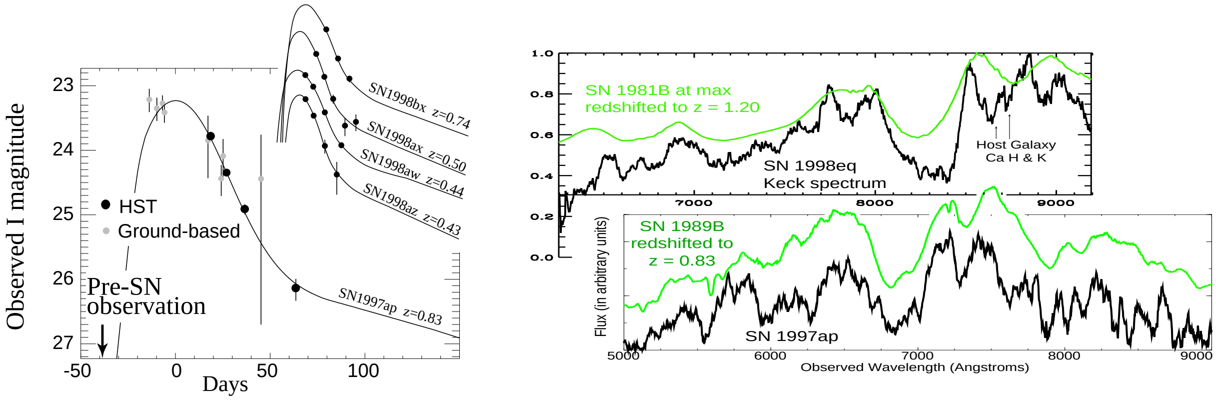

Figure 3: HST and ground-based I-band photometry for SN1997ap and Keck spectra for SN1997ap (at $z = 0.83$; Perlmutter *et al.* 1998) and SN1998eq (at $z = 1.2$, our most distant confirmed SN Ia; Aldering *et al.*, IAUC 7046). (a) Best-fit template lightcurve for SN1997ap. Unlike the ground-based photometry, 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.

very difficult to obtain with ground-based data due to host galaxy and sky contamination, as shown in Fig. 4b,d. We propose to use STIS to make the first such measurements at two redshifts in the range of our HST SN Ia sample, $z \sim 0.5$ and $z \sim 1$. If successful, this technique could become a standard calibration/evolution check for future high-z SN Ia work.

For a $z \sim 0.5$ SN Ia STIS can provide a good quality spectrum near maximum light, which will provide two cross-checks for evolution. We will be able to compare the WFPC2 lightcurve timescale stretch parameter, s, to the spectral ratios $\mathcal{R}$(Ca II) and $\mathcal{R}$(Si II) to look for deviations from the relation seen for low-z SNe Ia (Nugent *et al.* 1995, Riess *et al.* 1998b). A potential sign of evolution—or perhaps an extra calibration parameter—could be discovered if the spectroscopic and photometric measurements disagree. The intrinsic dispersion in this relation is $\sigma_s \sim 0.12$. Monte Carlo simulations indicate that measuring $\mathcal{R}$(Ca II) to 7% and $\mathcal{R}$(Si II) to 16% degrades σ_s by less than 20%. Thus measurement of both these features for a SN Ia at $z \sim 0.5$ will allow a better than 3σ detection of evolutionary effects which could sufficiently alter the SN brightness to make the current datasets consistent with a flat, $\Omega_M = 1$ universe. For a $z \sim 1.0$ SN Ia, $\mathcal{R}$(Ca II) can be measured sufficiently well to also detect evolution-induced changes with respect to a flat, $\Omega_M = 1$ universe at better than 3σ. Combined with an accurate determination of the lightcurve phase from WFPC2, we will be able to look for differences between the STIS $z \sim 0.5$ spectrum and those of similar SNe Ia at lower redshift. For instance the kinetic energy of the explosion and the ^{56}Ni mass can be constrained using the velocities of several Fe II (^{56}Ni decay product) lines.

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 well-sampled over a large redshift range with an accuracy on each point approaching the

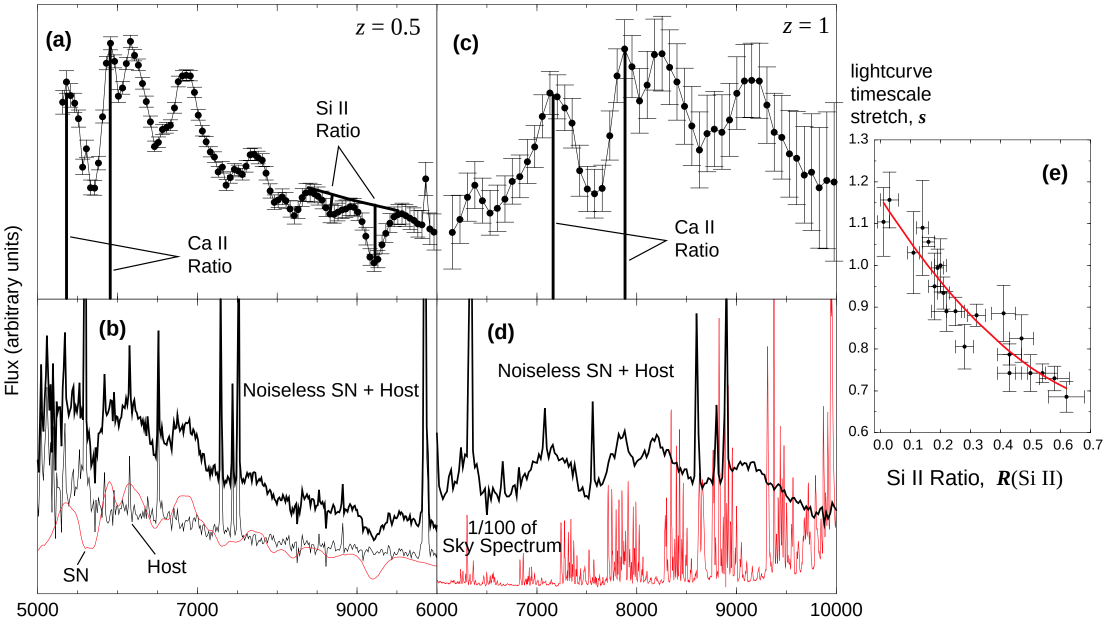

Figure 4: *(a)* Simulated STIS G750L spectrum of a $z = 0.5$ SN Ia near peak with the error bars denoting the S/N ratio per 50 Å for an 8 orbit total exposure (STIS ETC1624004). Note that STIS, due to its small slit size of $0.2''$, removes almost all of the host galaxy ($\approx$4% remains compared to the SN Ia) making it possible to measure the indicated spectroscopic ratios $\mathcal{R}$(Ca II) and $\mathcal{R}$(Si II). *(b)* A noiseless spectrum of a $z = 0.5$ SN Ia near peak with an equal contribution from a Sc host galaxy (a typical high-z case). Below are plotted the individual contributions of the SN Ia and the Sc galaxy. *(c)* STIS G750L spectrum of a $z = 1.0$ SN Ia near peak with the error bars denoting the S/N ratio per 75 Å for a 12 orbit total exposure (STIS ETC1629504). Again, with negligible host galaxy in the slit, the $\mathcal{R}$(Ca II) can be measured to the required accuracy (see text). *(d)* A noiseless spectrum of a $z = 1.0$ SN Ia near peak with an equal contribution from a Sc host galaxy. Note that the Ca II and Fe II spectral features are overwhelmed by the galaxy lines. Plotted below is the (scaled) sky spectrum from Keck showing the strength of the atmospheric lines. At the locations of these lines the ground-based spectrum is unusable (also see Fig. 3b). *(e)* The tight relationship between the spectroscopic ratio $\mathcal{R}$(Si II) and the lightcurve timescale stretch for well-observed low-redshift SNe Ia (see N95 for a similar $\mathcal{R}$(Ca II) plot).

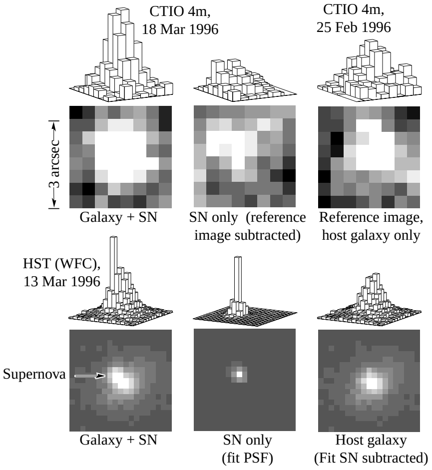

Figure 5: A comparison of ground-based and HST WF images of SN1996cl, a second $z = 0.83$ SN found by our project. This SN lies in the cluster MS1054.4-0321 which happened to be observed with HST when the SN was close to maximum light (HST image courtesy of Megan Donahue).

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).

(2) Exploiting a Cosmology Tool: Filling a SN Ia Hubble Diagram to $z \sim 1.2$

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.

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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.

Host Galaxy Extinction Corrections: Extinction correction significantly decrease the intrinsic dispersion (from ~ 0.17 to ~ 0.12 mag), giving each SN 2× 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.

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.

Spectroscopic Requirements: The goal of STIS spectroscopy of a $z \sim 0.55$ and a $z \sim 1$ SN Ia is to measure key spectral indices free of host-galaxy spectral contamination and the deleterious effects of sky lines. The exposures are set by the requirement that $\mathcal{R}$(Ca II) and $\mathcal{R}$(Si II) be measured to an accuracy better than their intrinsic dispersion as indicators. This requires S/N∼4–10 per 6.5Å in the restframe (the S/N range is due to the strong undulations in the spectrum). Exposures were determined using the STIS ETC (see etc1246804). Real spectra of SNe Ia and potential host galaxies were used in the calculations. Readout noise (also dark current) is a dominant source of noise, and SN features are very broad, so we have chosen to bin by 4× in the dispersion direction. SNe Ia are point sources, so we have not binned in the spatial direction. According to the STIS ETC, 8 orbits are needed to measure $\mathcal{R}$(Ca II) and $\mathcal{R}$(Si II) for a typical SN Ia at $z \sim 0.55$, while 12 orbits are required to measure $\mathcal{R}$(Ca II) at $z \sim 1$. The ETC assumes a 3-pixel aperture in the spatial direction, and does not consider optimal extraction of points sources which might improve the S/N somewhat. Note that one STIS orbit is required to obtain in advance the offset between nearby peak-up stars (selected from search images) and the two SNe. This allows offsetting to $\pm 0.02''$and the use of the narrowest possible ($0.2''$) slit.

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∼ 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.

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.