Cosmological Parameters from Type Ia Supernovae at High Redshift

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Cycle 11 primary orbits: 167
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 10 SNe Ia in the ranges of redshifts where the Hubble diagram is still quite poorly constrained ($z \sim 0.85 - 1.2$) or almost completely unconstrained ($z \sim 1.3 - 1.7$). Using the more sensitive ACS and the NICMOS near-IR data, it is now possible to obtain strong constraints on SN Ia evolution and both normal and abnormal dust extinction within or between galaxies—revealing all but the most contrived evolutionary effects. Accurate measurement of a statistically significant SN Hubble diagram in this redshift range, 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. This Hubble diagram 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: 5 (indicated by * after name)

Observing Summary:

Target	RA	DEC	V	Configuration,mode,aperture spectral elements	Total orbits	Flags
SN11Z08-1	14 01 31	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-1	14 01 31	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z08-2	14 01 31	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-2	14 01 31	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z08-3	14 01 31	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-3	14 01 31	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z08-4	14 01 31	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-4	14 01 31	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z08-5	14 01 31	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-5	14 01 31	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z10-1	14 01 31	05 01 01	24	ACS IMAGE F814W,F850LP	6	
SN11Z10-1	14 01 31	05 01 01	24	NIC2 IMAGING F110W	3	
SN11Z10-2	14 01 31	05 01 01	24	ACS IMAGE F814W,F850LP	6	
SN11Z10-2	14 01 31	05 01 01	24	NIC2 IMAGING F110W	3	
SN11Z10-3	14 01 31	05 01 01	24	ACS IMAGE F814W,F850LP	6	
SN11Z10-3	14 01 31	05 01 01	24	NIC2 IMAGING F110W	3	
SN11Z12-1	14 01 31	05 01 01	25	ACS IMAGE F850LP	5	

Observing Summary: Target	RA	DEC	V	Configuration,mode,aperture spectral elements	Total orbits	Flags
SN11Z12-1	14 01 31	05 01 01	25	NIC2 IMAGING F110W	20	
SN11Z12-2	12 31 31	62 01 01	25	ACS IMAGE F850LP	5	
SN11Z12-2	12 31 31	62 01 01	25	NIC2 IMAGING F110W	20	
SN11Z15-1	12 31 31	62 01 01	26	ACS IMAGE F775W,F814W,F850LP	5	
SN11Z15-1	12 31 31	62 01 01	26	NIC2 IMAGING F110W,F160W	43	TOO
SN1998EQ	23 00 00	20 01 01	25	NIC2 IMAGING F110W	7	
				Grand total orbit request	167	

■ 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, and then continues into the epochs in which the dark matter is dominant.

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

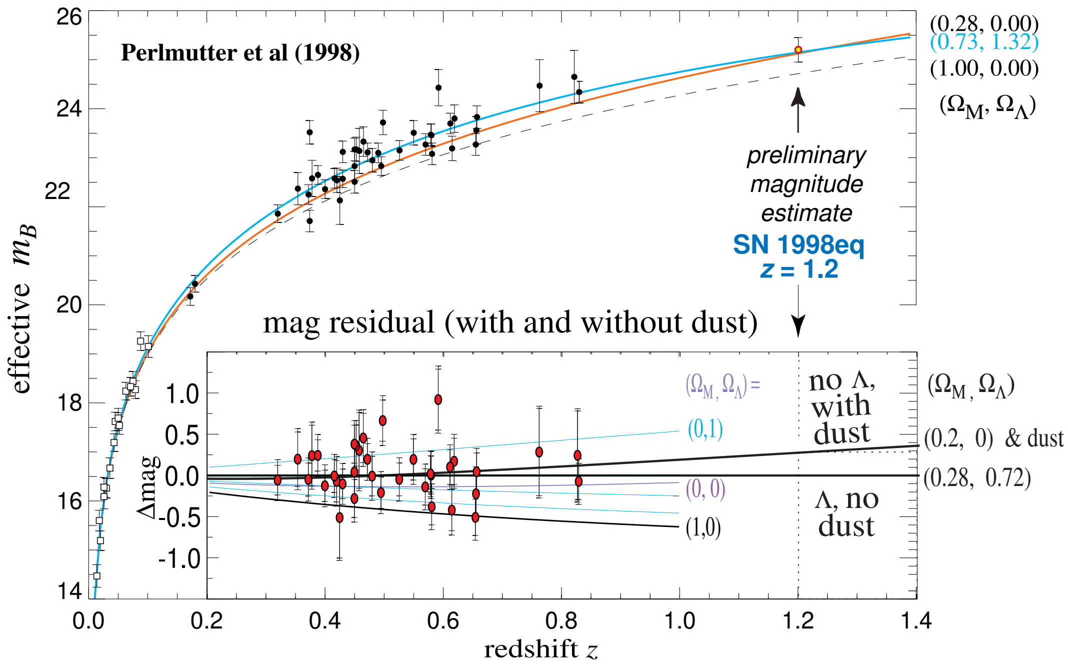


Figure 1: Hubble diagram for 42 high-z SNe (Perlmutter *et al.*1999) including SN1997ap at z=0.83 for which HST observations were used. The best-fit world model with $(\Omega_M, \Omega_\Lambda)$ = (0.73, 1.32) is drawn through the data (solid line). The Einstein-de Sitter case (1.0, 0.0) is strongly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

NICMOS lightcurves (cf. Fig. 2b), and the analysis of these SNe has recently been presented (Knop *et al.* 2001 and publication in preparation). Our discovery and WFPC2/NICMOS follow-up of SN1998eq extends these techniques to $z = 1.2$ (Aldering *et al.* 1998), and a member of our team played a key role in the recent study of the serendipitous WFPC2 and NICMOS data for SN1997ff at $z \approx 1.7$ (Riess *et al.* 2001).

(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

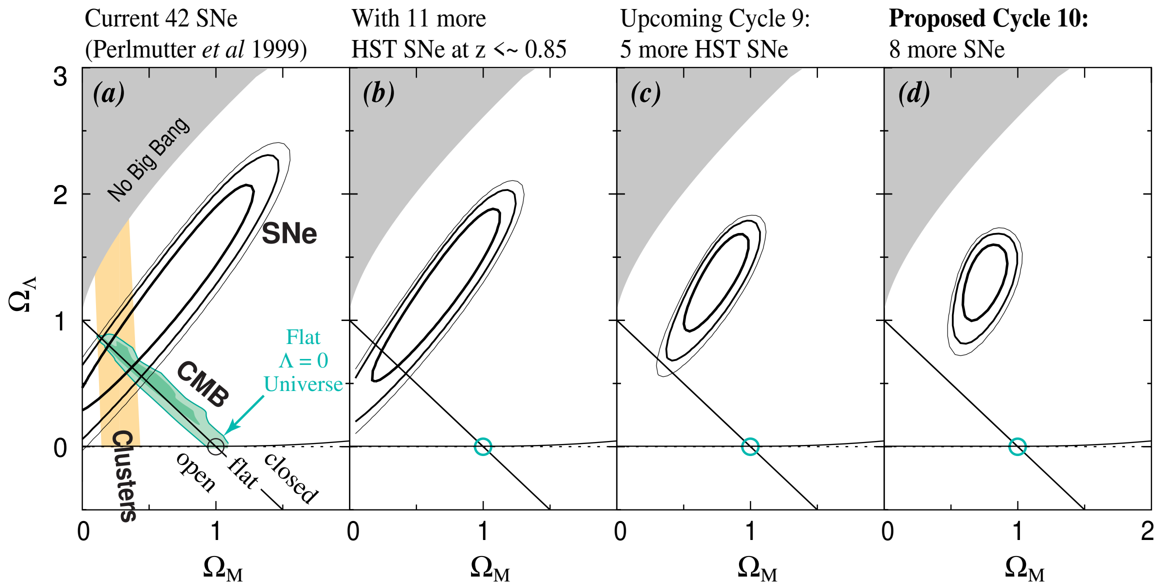


Figure 2: *(a)* 68%, 90%, and 99% confidence regions in the Ω_M—Ω_Λ plane from the 42 distant SNe Ia in Perlmutter *et al.* 1999 (including two observed with HST). These results indicate $\Omega_\Lambda > 0$, in agreement with the overlap of the recent combined CMB results (Jaffe *et al.* 2000) with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

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: near-IR dust measurements, a Hubble-diagram shape test, and a magnitude dispersion test.

Near-IR measurements of normal and "gray" dust 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 could cause a systematic bias in the SNe Ia Hubble diagram. There is some evidence that the extinction law can change from galaxy to galaxy and in particular studies of high redshift galaxies have indicated a range of non-standard values for R_B (Kochanik *et al.* ???). Of even more concern for the measurements of the cosmological parameters would be a diffuse form of gray dust, i.e. a dust that causes extinction without showing the telltale reddening in the optical bands (see Aiguire *et al.* ????). Even these forms of dust, however, will be measurable by their reddening effect, if the measurements are made with a sufficiently broad wavelength coverage and include near-IR measurements.

NICMOS observations are therefore needed to obtain lightcurves suffering less total

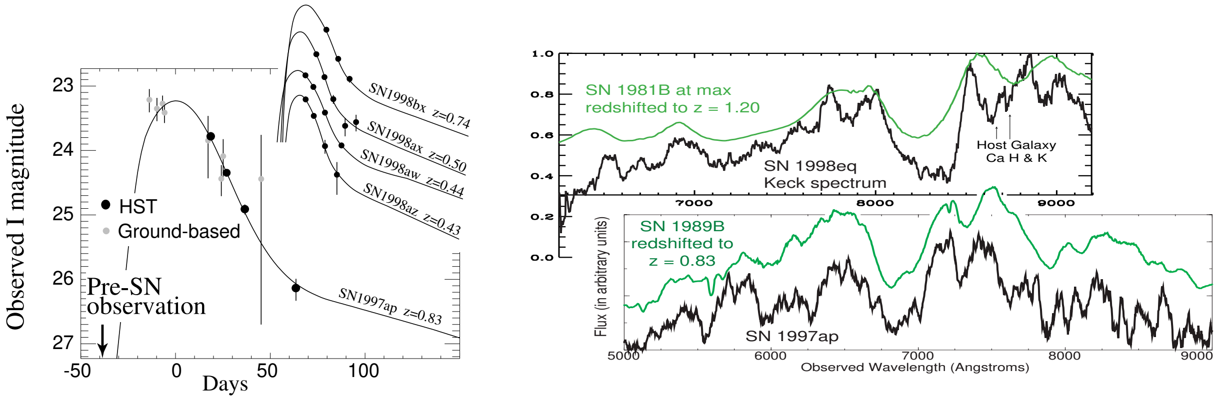
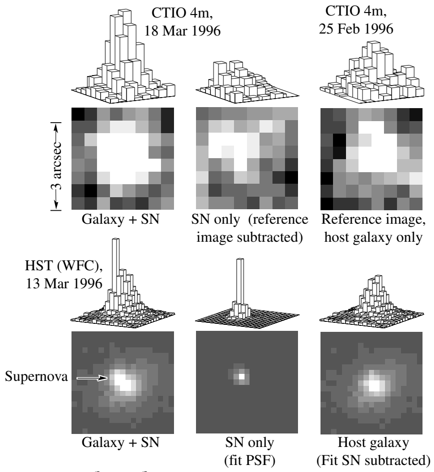


Figure 3: HST and ground-based I-band photometry for SN1997ap and Keck spectra for SN1997ap (at $z = 0.83$; Perlmutter *et al.* 1998) and SN1998eq (at $z = 1.2$, our most distant confirmed SN Ia; Aldering *et al.*, IAUC 7046). (a) Best-fit template lightcurve for SN1997ap. Unlike the ground-based photometry,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



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.

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 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 $z \approx 0.85$, 1.2, 1.5 will be fainter by 0.14 mag, 0.27 mag, 0.45 mag than the cosmology with Λ (Fig. 1b). *Preliminary* data for SN1998eq falls on the brighter (no dust) curve, as does the SN1997ff data, although with significantly larger error bars; Fig. 1a. The addition of five $z \sim 0.85$ and two $z \sim 1.2$ HST-observed SNe Ia from Cycle 9 to the similar number we expect from Cycle 10(GO8585) will allow the dust model to be distinguished at 2.5σ at *both* redshifts. Even one supernova in the $z \sim 1.5$ range measured with 0.2 mag uncertainty (i.e., higher accuracy than was possible with the serendipitous data for SN1997ff) will provide a comparable point. With such accuracies over this entire redshift range from 0.85 to 1.5 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. Out to redshifts $z \sim 1.2$, 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 $z \sim 1.7$

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 to $z \sim 1.2$, and beginning to extend it with new data even beyond this redshift.

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 even beyond redshift $z \sim 0.75$, 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 $0.75 < z < 1.2$ with ground- and space-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, 10 such SNe can be reliably discovered and confirmed with current space- and ground-based facilities during Cycle 11. Just a few supernovae beyond $z \sim 1.3$ can also be discovered and studied with useful photometry.

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 ∼ 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 ∼ 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 $0.85 < z < 1.7$ 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.

In the **highest redshift range of this proposal, $\mathbf{z \approx 1.3 - 1.7}$,** the era in which the universe was much smaller and denser, we expect the universe's expansion histoory to be completely dominated by the gravitational deceleration of dark matter. Any deviations from the ($\Omega_M \approx 0.7$, $\Omega_\Lambda \approx 0.3$) line of Figure 1 would then be due either to systematic effects of dust and SN Ia evolution, or to the gravitational lensing of intervening mass over/underdensities. If we can begin to populate this range of the Hubble diagram with data that is carefully matched (in time-coverage, wavelength coverage, and detection Malmquist bias) to the lower-redshift SNe then we can use the whole SN Ia data set together to isolate the systematic effects from the gravitational lensing effects. If the cosmological history turns out to be as simple as we now expect, then such careful measurements will allow us a first look at the clumpiness of dark matter at redshifts between 0 and 1.5. Of course, the expansion history has surprised us before, and it is possible that we would pick up hints of some dark energy effect with a dramatically deviating Hubble diagram even in this era which is expected to be mass dominated.

Beyond redshift $z \sim 1.2$, the amplifications and deamplifications due to gravitational lensing by intervening over- and underdensities of mass will spread the SN magnitude distribution about the Hubble line. However, using estimates of these intervening masses (e.g., from galaxy spectral velocity curves and redshifts) it is possible to constrain the amplification/deamplification amplitude. Our highest redshift ($z \sim 1.5$) SN will be chosen, if possible, from the fields studied by DEIMOS on Keck, thus providing the galaxy information necessary to estimate mass over/underdensity.

There have been several new developments this year that make this the first HST proposal cycle in which this part of the Hubble diagram could be included in this SN Ia work. First, there are new search capabilities for SNe at these redshifts. The wide-field Suprime-Cam on Subaru was commissioned this year, and our collaboration used it for the first time to find a batch of SNe Ia, with several beyond $z = 1$ (Doi *et al.* 2001). This year, we have also used the new wider-field capabilities on CFHT to find batches of SNe beyond I = 25, i.e. the target magnitudes for this highest redshift range. These ground-based searches now have the capability to provide scheduled, "guaranteed" SN discoveries at $z \approx 1.3 - 1.6$, with the regularity and predictability that previously was only possible at lower redshifts.

Second, with this HST cycle's proposed Legacy/Treasury ACS surveys ("GOODS" and

"HITS"), it will be possible for the first time with HST to discover SNe on the rising part of their lightcurves at scheduled dates. This year the HST Director is further adding some orbitrs to other multi-orbit imaging proposals, to make it possible to search these fields for SNe as well. The SNe Ia expected from the ACS surveys and the Director's additional time will span the redshift range 0.2 – 1.7, but we expect a few in the 1.3 – 1.7 range. Such SNe will have a few advantages, including early HST points on their lightcurves, and SN-free images of the host galaxies to allow precise photometric subtraction from the SN light throughout the lightcurve.

Finally, it should be emphasized that the refurbishment of NICMOS is also an important element of the HST work at these highest redshifts, since almost all of the redshifted SN Ia's spectral energy will be in the near-IR.

With all of these new capabilities, it is now possible to obtain an SN Ia data set in this highest redshift range that will have significantly better controlled measurements than was possible with the random, after-the-fact (and after-maximum-light) discovery of SN1997ff. While the work in this redshift range will procede rather slowly, given the expense of the follow-up on the ground and in space, we see this as an important part of this integrated effort to obtain a uniformly designed data set over the entire available Hubble diagram.

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, and optical-NIR wavelength coverage needed to fully exploit high-redshift SNe Ia for determining the cosmological parameters and realize the full potential of Fig 2d. With the capabilities of ACS and NICMOS in Cycle 11, these accurate HST measurements of SNe Ia in the redshift range $z \sim 0.75$–1.7, 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. This problem is especially acute in the NIR; without HST restframe BV SN Ia lightcurves are impossible to obtain, and even a point at maximum-light requires two nights of integration per SN if done from the ground.

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.

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. It is thought that the properties of "dark energy" are best constrained with SNe Ia with $z \lesssim 1$, while the systematics tests possible with the matter-dominated portion of the Hubble diagram require SNe Ia with $z \gtrsim 1$. Our discovery of SN1998eq at $z = 1.2$ (Aldering, *et al.*, IAUC 7046) and HST's discovery of SN1997ff at z1.7 (Riess, *et al.*2001) have demonstrated that SNe Ia in the matter-dominated era can be found and followed. In any deep search lower redshift SNe are also found – some very early. HST is needed to follow all SNe Ia with $z > 0.7$, where, as Fig 1 shows, the Hubble diagram is sparsely populated. A discrete approximation to the numbers of SNe Ia it is possible to find and follow-up in one year is 5 at $z \sim 0.85$, 3 at $z \sim 1.0$, 2 at $z \sim 1.2$, and 1 at $z \sim 1.5$.

Optimal Sampling of the Lightcurves: As with our previous HST SNe, we plan to observe these SNe Ia in restframe B at five epochs spaced every 5–7 restframe days, starting soon after discovery. 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. (The bare minimum number of points is four since three data points determine the peak date and brightness while the fouth determines the lightcurve width.) After the SNe have faded, observations will be made of their host galaxies to obtain a baseline point.

Host Galaxy Extinction Corrections: Extinction correction significantly decreases 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. These require $S/N \gtrsim 30$ observations near maximum light, and will use a combinations of ACS and NICMOS observations as outlined below.

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 from which the luminosity-width and color corrections can be determined. For SNe Ia at $z \sim 0.85$, restframe U and B map to F625W and F814W on ACS, while F110W covers V on NICMOS. At $z \sim 1.0$ and $z \sim 1.2$, the UBV mapping is F775W,F850LP,F110W and at $z \sim 1.5$ the mapping is F850LP,F110W,F160W. (F140W would be a better choice but would require using the less-sensitive NIC1). NICMOS actually reaches further to the red than restframe V, giving a slightly lower total extinction and a better lever-arm for extinction corrections.

Photometry Exposure Times: The magnitudes of our targets are fairly well constrained. In Perlmutter *et al.* 1999 we find $I \sim 23.5$ at peak for SNe Ia at $z \sim 0.85$, for SN1998eq at $z = 1.20$ we find $I \sim 24.4$, and SN1997ff at $z \sim 1.7$ had $J \sim 24$ at peak. To achieve the requisite 0.15 mag accuracy after width-brightness and extinction corrections requires 5% photometry at five epochs over the -7 to $+20$ 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). The ACS ETC indicates that 1-orbit depth at any epoch is sufficient to achieve this accuracy for $z \lesssim 1.2$ SNe Ia. Indeed, at peak it should be possible to obtain observations in two filters (or screen several SN candidates) within one orbit for $z \lesssim 1$ SNe Ia. According to our past experience and the updated NICMOS ETC, the NIC2 exposures will be significantly larger. We calculate that a 5-epoch J-band NIC2 F110W lightcurve for a $z \sim 1.2$ SN Ia requires 20 orbits. For a $0.85 \lesssim z \lesssim 1.6$ SN Ia, a flux point at peak for color determination requires only 2–6 orbits in F110W or F160W. If the dark current “bump” is not present we will benefit from higher S/N or the ability to follow slightly higher redshift SNe Ia.

Screening: For the specific case of the HST director’s and Treasury SN searches (SNAZ, HITS, GOODS), the relatively small number of exposures means that there is a non-zero chance that multiple cosmic-ray hits could masquerade as a SN candidate. Given the large investment required for follow-up, we have allowed 5 ACS orbits for screening of up to 10 candidates (particularly any $z \sim 1.5$ candidate).

Final references: Our WFPC2 final reference images for SN1998eq indicate that it is located on an edge-on (spiral) galaxy. SN1998eq has extensive NICMOS photometry (from director’s time) taken only two months before the cryogen ran out. To accurately place

SN1998eq on the Hubble diagram requires proper subtraction of the NIR host-galaxy light. Therefore, we have allowed 7 NICMOS orbits to obtain F110W final reference images for SN1998eq.

Synopsis: In summary, we are requesting the following allotment of orbits to obtain ACS and NICMOS HST photometry of very high-redshift Type Ia supernovae:

Target	ACS Orbits	NICMOS Orbits	Subtotal	Number	Total
SN Ia @ $z \sim 0.85$	5 (lightcurve)	2 (color)	7	5	35
SN Ia @ $z \sim 1.0$	6 (lightcurve)	3 (color)	9	3	27
SN Ia @ $z \sim 1.2$	5 (lightcurve)	20 (lightcurve)	25	2	50
SN Ia @ $z \sim 1.5$	1 (screening)		1	5	5
SN Ia @ $z \sim 1.5$		43 (lightcurve)	43	1	43
SN1998eq reference		7	7	1	7
Total:					167

Only HST can provide the deep red and NIR imaging high spatial resolution with a stable PSF, and phase coverage, needed to accurately measure the intrinsic luminosities and colors for high–z SNe needed to determine the cosmological parameters while testing for systematics.

■ Special Requirements

For $z \leq 1.2$ SNe 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. However, pursuit of $z \sim 1.5$ SNe is much riskier due to the difficulty in confirming the Type Ia nature of any given SN candidate and the large number of HST follow-up orbits needed. Therefore, we feel it prudent to schedule HST follow-up of our single highest-redshift SN as a TOO. In practice, we will know the approximate sky location and possible dates for any such SN so the impact to the HST schedule should be much less than for an unconstrained TOO.

■ Coordinated Observations

We will use SNe discovered using coordinated ground-based observations (with Subaru/SuprimeCam, CFHT/MegaCam, and CTIO4m/MOSAIC) along with SNe found by the director's SNAZ program – and more importantly – from the SN-search portions of the HITS and/or GOODS HST treasury proposals. SNe through $z \sim 1.2$ can be discovered with any of these facilities. Subaru/SuprimeCam or HST+ACS are able to discover SNe up to $z \sim 1.8$. We will arrange our ground-based searches to coincide in time and on the sky with the HITS or GOODS SN searches so that the best SNe from ground or space can be chosen for follow-up. HITS has agreed to schedule Keck/DEIMOS and VLT/VIMOS spectroscopy time for spectroscopic confirmation of $z \leq 1.2$ SNe. We will use our Keck, VLT, and Gemini time to spectroscopically confirm candidates beyond the reach of DEIMOS or VIMOS using, e.g., laser guide star AO-fed NIR spectrographs. As back-up in the case of NICMOS problems, we would propose for sufficient ground-based NIR time to obtain peak magnitudes for roughly four $0.85 \lesssim z \lesssim 1.2$ SNe.

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**:

Rob will update 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:

Peter to update

GO-9705:

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: