Hubble Space Telescope Cycle 11 General Observer Proposal

Cosmological Parameters from Type Ia Supernovae at High Redshift

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Scientific category: COSMOLOGY
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Cycle 11 primary orbits: 167
Cycle 11 parallel orbits: 83

Abstract

Over 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 detailed SN Ia studies, we here propose to measure 11 SNe Ia in the ranges of redshifts where the Hubble diagram is still poorly constrained ($0.85 \lesssim z \lesssim 1.2$) or nearly unconstrained ($1.3 \lesssim z \lesssim 1.7$). ACS and NICMOS now make it possible to obtain strong constraints on SN Ia evolution and (ab)normal dust extinction within or between galaxies—revealing all but the most contrived 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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Total number of investigators: 15
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 23 13	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-1	14 23 13	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z08-2	14 23 13	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-2	14 23 13	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z08-3	14 23 13	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-3	14 23 13	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z08-4	14 23 13	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-4	14 23 13	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z08-5	14 23 13	05 01 01	23	ACS IMAGE F625W,F814W	5	
SN11Z08-5	14 23 13	05 01 01	23	NIC2 IMAGING F110W	2	
SN11Z10-1	14 23 13	05 01 01	24	ACS IMAGE F814W,F850LP	6	
SN11Z10-1	14 23 13	05 01 01	24	NIC2 IMAGING F110W	3	
SN11Z10-2	14 23 13	05 01 01	24	ACS IMAGE F814W,F850LP	6	
SN11Z10-2	14 23 13	05 01 01	24	NIC2 IMAGING F110W	3	
SN11Z10-3	14 23 13	05 01 01	24	ACS IMAGE F814W,F850LP	6	
SN11Z10-3	14 23 13	05 01 01	24	NIC2 IMAGING F110W	3	

Observing Summary:

Target	RA	DEC	V	Configuration,mode,aperture spectral elements	Total orbits	Flags
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SN11Z12-1	14 23 13	05 01 01	25	NIC2 IMAGING F110W	20	
SN11Z12-1P	14 23 13	05 01 01	25	ACS IMAGING F814W,F850LP	20	CPAR
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	
SN11Z12-2P	12 31 31	62 01 01	25	ACS IMAGING F814W,F850LP	20	CPAR
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
SN11Z15-1P	12 31 31	62 01 01	26	ACS IMAGING F814W,F850LP	43	CPAR
SN1998EQ	23 00 00	20 01 01	25	NIC2 IMAGING F110W	7	
				Grand total orbit request	250	

■ 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.* 2001) 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 our newest completed high-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. Our additional 11 WFPC2/NICMOS-observed SNe Ia out to $z = 0.86$ (cf. Figs. 2b,3c,3d) strengthen these results (Knop *et al.* 2000, 2001).

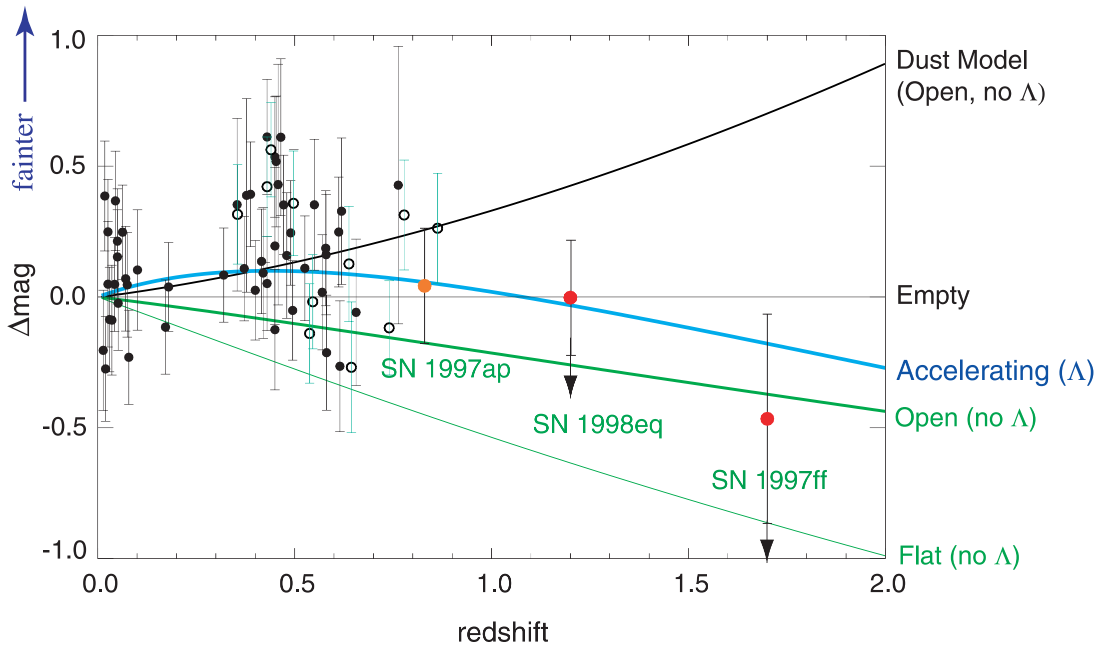


Figure 1: Hubble diagram plotted as deviations from "Empty" universe, $(\Omega_M, \Omega_\Lambda)$ = (0,0). Filled points show 42 high-z SNe (Perlmutter *et al.* 1999) including SN1997ap at z=0.83 for which HST observations were used, and 18 Calan/Tololo Search low-z SNe. The Einstein-de Sitter, "Flat (no Λ)" case (1.0, 0.0) is strongly excluded by the current data. The "Open (no Λ)" case (0.28,0.00) indicates that some contribution from a cosmological constant is required for values of Ω_M favored by dynamical measurements. The magnitude difference between the best-fit "Accelerating (Λ)" world model and suitable ones with Ω_Λ=0 show redshift dependencies which would be very hard to mimic within the context of SNe evolution or gray dust hypotheses (the upper curve is an example model). 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 estimates of our highest redshift SN1998eq at $z = 1.2$ and the serendipitous data for SN1997ff at $z = 1.7$ are suggestive, but more analysis and significantly more SNe in these redshift ranges (as proposed here) are necessary.

The stage is now set for significant new advances in exploiting SNe Ia as cosmological probes at redshifts twice those of our earlier work. Indeed, our discovery and WFPC2/NICMOS follow-up of SN1998eq extend 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/NICMOS data for SN1997ff at $z \sim 1.7$ (Riess *et al.* 2001; R01).

(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.

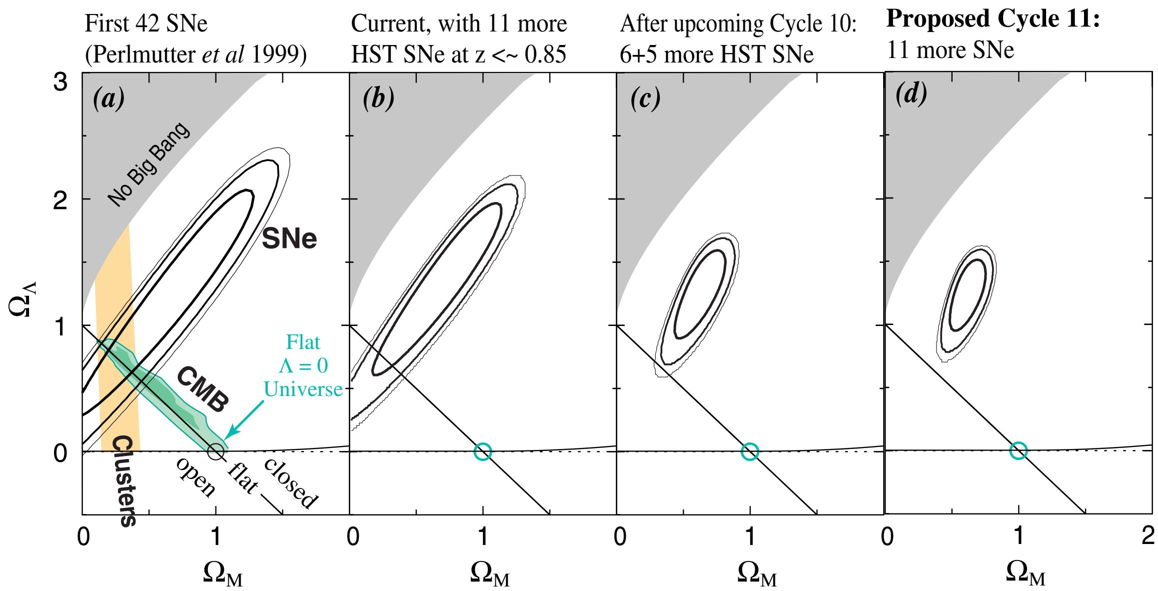
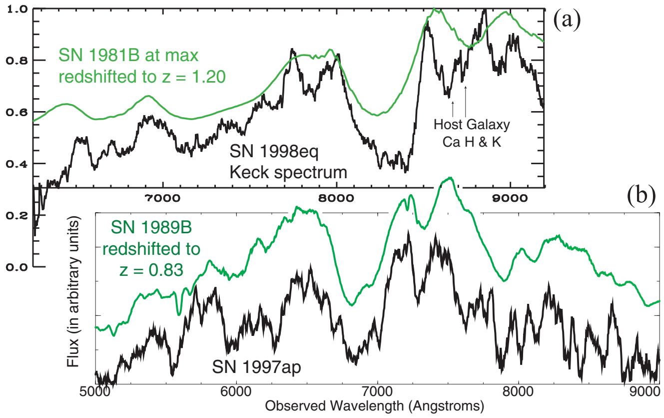


Figure 2: *(a)* 68%, 90%, and 99% confidence regions in the Ω_M—Ω_Λ plane from the 42 distant SNe Ia in Perlmutter *et al.* 1999 (including two observed with HST). These results indicate $\Omega_\Lambda > 0$, in agreement with the overlap of the recent combined CMB results (Jaffe *et al.* 2001) with 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)*.

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. As a start we have obtained extensive observations of a new sample of nearby Hubble-flow SNe Ia (Aldering 2000b), detailed spectroscopy of two $z \sim 0.5$ SNe Ia (Lidman *et al.* 2000), and have begun a program of UV STIS spectroscopy of additional Hubble-flow SNe (GO-8618). In this proposal we focus on two key tests possible at higher redshifts: 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 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 to diverge monotonically from the magnitude-redshift relation for the *true* combination of Ω_M, Ω_Λ. Fig. 1 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 $z \sim 1.7$ where we propose to



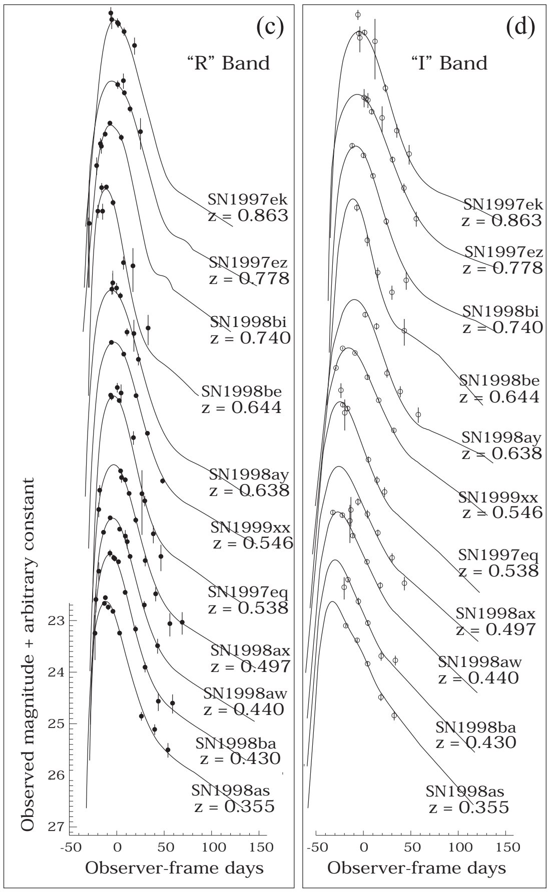


Figure 3: (a & b): Keck spectra for SN1997ap (at z = 0.83; Perlmutter et al. 1998) and SN1998eq (at z = 1.2, our most distant confirmed SN Ia; Aldering et al.). *Lower curves*: the spectrum of the high-z SN Ia. *Upper curves:* a spectrum of a nearby SN Ia for comparison. (c & d): Lightcurves in R and I bands for 11 SNe from previous work in this HST program (Knop et al., 2001) For these SNe, the five latest points, which constitute most of the lightcurve, are almost all from HST (fewer R-band points for z ~>0.7). Except for the very faintest points, the HST error bars are smaller than the symbols plotted.

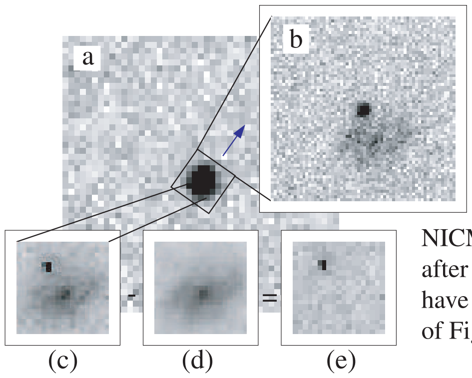


Figure 4:(a) In this R-band ground-based discovery image, SN 1998as is blended with the host galaxy. The host galaxy is clearly separated from the supernova in (b) the WFPC2 F675W image and in (c) the NICMOS F110W image. After subtracting off (d) the NICMOS final image after the SN faded away, only the SN is seen in (e) the difference image. We have obtained and analyzed NICMOS near-IR photometry for six of the SNe of Figure 3 in this HST program (Burns et al.2001).

observe — our best-fit prediction becomes brighter. Thus, extension of the Hubble diagram out to $z \sim 1.7$ 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 $z \sim 0.85$, 1.2, and 1.7 will be fainter by 0.14 mag, 0.27 mag, and 0.45 mag than the cosmology with Λ. *Preliminary* data for SN1998eq falls on the brighter (no dust) curve, as does the SN1997ff data, (although with significantly larger error bars); Fig. 1.

Our recent discovery and HST follow-up of an additional six $0.5 \lesssim z \lesssim 1.1$ SNe Ia in Cycle 9 (GO-8585), plus an additional six $0.85 \lesssim z \lesssim 1.2$ SNe Ia expected in Cycle 10 (GO-9705) will allow the $\Omega_M, \Omega_\Lambda = 0.3, 0.0$ dust model to be distinguished at 3.5σ. The additional SNe Ia we will pursue in Cycle 11 can increase these confidence limits to 5σ. Moreover, even one SN in the $z \sim 1.5$ range measured with 0.2 mag uncertainty (i.e., better than was possible with SN1997ff's serendipitious observations) will provide a check of $\sim 2.5\sigma$ accuracy at the highest redshift. With such accuracies over the entire 0.85 to 1.7 redshift range 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 (cf. Croft *et al.* 2000). (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).

These refinements/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 2000b), and showing consistency between the lightcurves of low- and high-z SNe (Aldering *et al.* 2000a; Goldhaber *et al.* 2001). Moreover, SN1997ff is consistent with extrapolation of the results from lower-redshift SNe Ia (R01).

(2) Exploiting a Cosmology Tool: Filling a SN Ia Hubble Diagram to $z \sim 1.7$

SNe Ia have passed the tests of their efficacy as cosmological probes, and as described above, significant ($\sim 2\times$) improvements are being made in decreasing many systematic uncertainties. 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 $\sim$100 SNe Ia. This is about the number that could reasonably be expected to be found and spectroscopically confirmed at $0.8 < z < 1.7$ by all SN teams with ground- and space-based telescope resources over the remaining lifetime of the HST.

This Hubble diagram is a crucial record of the expansion history of the universe over the past $\sim$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 $z \sim 0.8$ (a situation which will improve slightly 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. The study of high-redshift SNe is therefore a key task for the HST to pursue, if possible, at as rapid a rate as is manageable. As discussed in the observation details below, 11 such SNe can be reliably discovered and confirmed with current space- and ground-based facilities during Cycle 11, including the NICMOS-enabled study of one SN beyond $z \sim 1.3$.

The 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 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 (2001) 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, $\mathbf{1.3 \lesssim z \lesssim 1.7}$,** the era in which the universe was much smaller and denser, we expect the universe's expansion history to be completely dominated by the value of Ω_M. Any deviations from the ($\Omega_M \sim 0.7$, $\Omega_\Lambda \sim 0.3$)

line of Fig. 1 would then be due either to systematic effects of dust and SN Ia evolution, or to the gravitational lensing by intervening mass over/under-densities. However, using estimates of the intervening masses (e.g., from galaxy redshifts and velocity widths, and inclinations measured from our HST images) 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 spectroscopy necessary to estimate mass over/underdensity.

There are several new or upcoming developments that make this the first HST proposal cycle in which this part of the Hubble diagram could be included in the SN Ia work. First, is the resurrection of NICMOS, enabling us to obtain restframe B and V photometry necessary to calibrate the highest redshift SNe Ia and place them on the Hubble diagram.

Second, there are exciting new SN-search capabilities at these redshifts. This Cycle's proposed Legacy/Treasury ACS surveys ("GOODS" and "HTS"), have the potential to find several pre-maximum $1.3 \lesssim z \lesssim 1.7$ SNe Ia per year (along with discovery of lower redshift SNe Ia only days after explosion which we would follow from the ground). (HTS in particular offers valuable coordinated spectroscopic follow-up which would include SN candidates.) The HST Director may also add orbits to GO and GTO multi-orbit imaging programs to make it possible to search these fields for SNe, and we will use our deep ACS coordinated parallels for further searching. In addition to these promising options for HST-discovered SNe, our collaboration has demonstrated for the first time that the newly-commissioned wide-field SuprimeCam on Subaru can reach very deep, with $z \sim 1$ spectroscopically-confirmed SNe Ia detected at $S/N \sim 40$ in 50 minutes (Doi *et al.* 2001). Even our searches at CFHT are finding reliable candidates at $I \sim 25$ (equivalent to a $z \sim 1.3$ SN Ia at max), but beyond the reach of spectroscopic capabilities of the recent past. Thus, there are credible ground-based alternatives if the proposed ACS surveys do not materialize. Together these new capabilities can provide scheduled, "guaranteed" SN discoveries at $1.3 \lesssim z \lesssim 1.7$, with the predictability and reliability that previously was only possible at lower redshifts.

Finally, by Cycle 11 ultra red-sensitive LBNL CCD's and laser guide-star AO NIR spectroscopy will be available to us at Keck (and possibly VLT), enabling determination of redshifts and types for the highest redshift SNe Ia.

With all of these new capabilities, it is now possible to obtain a 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 comphrehensive dataset 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 ∼0.12–0.15 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 $0.8 \lesssim z \lesssim 1.7$, 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.

References

Aguirre, A. N. & Haiman, Z. 2000, ApJ, 532, 28.
Aldering, G., *et al.* 1998, IAUC 7046.
Aldering, G., Knop, R. A. and Nugent P 2000a, AJ, 119, 2110.
Aldering, G. 2000b, in AIP Conference Proceeding: Cosmic Explosions.
Bahcall, N. A., *et al.* 1999, Science, 284, 1481.
Croft, R., *et al.* 2000, ApJ, 534, 123.
Doi, M., *et al.* 2001, IAUC 7649.
Goobar, A., & Perlmutter, S. 1995, ApJ, 450, 14 (GP95).
Garnavich, P., *et al.* 1998, ApJ, 509, 74.
Goldhaber, G., *et al.* 2001, ApJ, in press.
Hamuy, M., *et al.* 1996, AJ, 112, 2438 & 1995, AJ, 109.
Jaffe, A. H., *et al.* 2001, Phys. Rev. Lett. 86, 3475.
Knop, R., *et al.* 2000, B.A.A.S., 197, 950.
Knop, R., *et al.* 2001, in preparation.
Lidman, C., Goobar, A. & Pain, R. 2000, ESO Messenger, 101, 18.
Nugent, P., *et al.* 1995, ApJ, 455, L147.
Perlmutter, S., *et al.* 1997, ApJ, 483, 565.
Perlmutter, S., *et al.* 1998, Nature, 391, 51.
Perlmutter, S., *et al.* 1999, ApJ, 517, 565.
Riess, A. G., *et al.* 1995, ApJ, 438, L17 & 1996, ApJ, 473, 88 (R96).
Riess, A. G., *et al.* 1998a, AJ, 116, 1009.
Riess, A. G., *et al.* 2000, ApJ, 536, 62.
Riess, A. G., *et al.* 2001, ApJ, in press (R01).
Weller, J. & Albrecht, A., 2001, Phys. Rev. Lett., 86, 1939.

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. 4 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. This must be done within the constraints imposed by available spectroscopy and photometry follow-up capabilities and resources. 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.*, 1998) and HST's discovery of SN1997ff at $z \sim 1.7$ (R01) have demonstrated that SNe Ia in the matter-dominated era can be found and followed. HST is needed to follow all SNe Ia with $z > 0.7$, where, as Fig 1 shows, the Hubble diagram is sparsely populated. 5 SNe Ia at $z \sim 0.85$, 3 at $z \sim 1.0$, 2 at $z \sim 1.2$, and 1 at $1.3 \lesssim z \lesssim 1.5$ offer the greatest scientific gain while balancing statistical accuracy, systematics test power and exploration without unduly taxing HST or ground-based resources and capabilities.

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. (Four points is a minimum 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 forming the basis for luminosity-width and color corrections. 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 0.12–0.15 mag accuracy after lightcurve 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 $0.85 \lesssim z \lesssim 1.7$ 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, HTS, 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 $1.3 \lesssim z \lesssim 1.7$ 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 shortly 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.

Coordinated Parallels: By holding a fixed ORIENT for our multi-epoch NICMOS observations we have the opportunity to conduct deep SN searching using ACS parallel observations. The temporal coverage planned for the NICMOS observations will provide free ACS lightcurves for the $\sim 1 - 3$ SNe expected to occur. These observations will be sensitive to other types of optical transients. (Note that coordinated parallels for SN-searching on WFPC2 with ACS as prime are not appealing due to the single-orbit duration of those observations and WFPC2's lower sensitivity, hot pixels, and CTE).

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, as presented in Table 1. 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.

Table 1: Table 1: Synopsis of Requested Primary Orbits

Target	ACS Orbits per SN	NICMOS Orbits per SN	Subtotal per SN	Number of SNe	Total Orbits
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

Special Requirements

For $z \lessapprox 1.2$ SNe our search strategy guarantees the date of discovery, lightcurve phase, and possible sets of coordinates. We discover sufficient numbers of SNe to screen for those with preferred redshifts. Thus, we specify our observing plan well before the actual discovery of the new SNe. However, pursuit of $1.3 \lessapprox z \lessapprox 1.7$ 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 being invested. 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. The probability of occurrence for a suitable SN is near 100%. The observations should begin 5–7 (2–3 restframe) days after discovery.

Coordinated Observations

We will use SNe discovered in coordinated ground-based observations (with Subaru/Suprime-Cam, CFHT/MegaCam, and CTIO4m/MOSAIC), those found in our coordinated parallels or in any Director's program – and more importantly – from the SN-search portions of the HTS and GOODS Treasury proposals. $z \lessapprox 1.2$ SNe can be discovered with any of these facilities. HST+ACS is able to discover SNe in the $1.3 \lessapprox z \lessapprox 1.7$ range, and SuprimeCam will serve as back-up. We will arrange our ground-based searches to coincide in time and on the sky with the HTS and GOODS SN searches so that the best SNe from ground or space can be chosen for follow-up. HTS has offered to schedule Keck/DEIMOS and VLT/VIMOS spectroscopy time for spectroscopic confirmation of $z \lessapprox 1.2$ SNe. We will use our Keck, VLT, Gemini, and Subaru time to spectroscopically confirm more distant candidates using, e.g., laser guide star AO-fed NIR spectrographs and red-enhance spectroscopy detectors. 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 $0.85 \lessapprox z \lessapprox 1.2$ SNe.

We anticipate an abundance of HST-discovered SNe well beyond what we propose to follow, but will be sure to coordinate the choice of follow-up targets with any other HST SN cosmology programs to avoid accidental duplication.

Justify Duplications

None - these are all unique observations of transient events.

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 10 Type Ia supernovae in the redshift range 0.36—0.86. These observations, including final references where necessary, are now complete, and the data are in the final stages of preparation. A preliminary Hubble diagram including these supernovae was presented at the January 2001 AAS meeting in San Diego, CA, and these data are included in Figures 1 and 2 in this proposal. The lightcurves provided by WFPC2 for these supernovae were excellent; at the higher redshifts, these lightcurves provide a substantially better measurement of the calibrated supernova magnitude than those for comparable supernovae observed only from the ground. The improvement of the confidence limits on the cosmological parameters Ω_M and Ω_Λ are as good as we had previously predicted. Papers presenting the cosmological results from these data will be submitted in 2001.

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). 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 a supernovae at z=0.54 which was discovered *14 days prior* to maximum light in its restframe. 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:

In GO 8585 we observed 6 Type Ia supernovae with HST using WFPC. The supernovae were discovered in ground based searches at the CTIO 4-m, CFHT and Subaru telescopes. We obtained both U- and B-band restframe photometry (using either F814W or F850LP depending on the redshift) for each supernova for a period of 2 months. The data is currently being analyzed to determine which supernovae need final reference images.

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.