Scientific Justification

[page limits: 8 total, sci just may not extend beyond p 3, no limits on figures, tables, refs but total must not be exceeded.]

[FROM KECK03A PROPOSAL].

The Hubble diagram for Type Ia supernovae (SNe Ia) at high-redshift (Fig. 1), provides the most direct current measurement of the expansion history of the universe—and hence the most direct evidence for an accelerating expansion. The "first generation" of supernova cosmology work developed a systematic approach to this measurement (Perlmutter *et al.* 1997, 1998, 1999) that resulted in a determination, based on 42 SNe at $0.18 < z < 0.83$, of $\Omega_M = 0.28^{+0.09}_{-0.08}$ for a flat universe (Perlmutter *et al.* 1999; see also Riess *et al.* 1998). These measurements indicate the presence of a new, exotic "dark energy" that can cause acceleration, and which current theories of fundamental particle physics are unable to explain. This conclusion is strongly supported by current CMB measurements of Ω_k.

There is a fundamental difference between a Cosmological Constant and other potential forms of dark energy. This distinction can be addressed by constraining the dark energy's average equation-of-state, $\langle w \rangle \equiv \langle p/\rho \rangle$. The importance and possibility of determining $\langle w \rangle$ well enough to rule out the $w = -1$ of a cosmological constant has led to a new second generation of supernova cosmology studies: large multi-year multi-observatory programs with major commitments of dedicated time for "rolling searches," which can find and follow SNe over many months of repeated wide-field imaging, and identify them with coordinated spectroscopy. The challenging second-generation goals are: (1) to constrain $\langle w \rangle$ well enough to potentially rule out $w = -1$, by building an order-of-magnitude larger statistical sample (i.e. $\sim$500) of SNe in the redshift range z = 0.3 – 0.8 where $\langle w \rangle$ is best measured; (2) to study the transition to deceleration by building a first significant sample ($\sim$15) of SNe Ia in the redshift range z = 1 – 1.4; and (3) to improve the systematic uncertainties by studying low-redshift supernovae in detail and comparing specific SN properties between low- and high-redshift. Fully exploiting samples from (1) and (2) to improve the *statistical* uncertainties will depend on (3) reducing the *systematic* uncertainties correspondingly.

These goals clearly require an ambitious effort on the part of the SN Ia community to build up the necessary SN dataset, and we have developed a coherent program to carry this out. We have developed the Nearby Supernova Factory to carry out (3), and are continuing our Subaru/HST SDF and SXDF programs to generate the $z > 1$ sample (2). To address (1) we are now beginning work with the new SN search portion of the Megacam CFHT Legacy Survey (SNLS) to begin to generate the large z = 0.3–0.8 sample, and it is the SNLS SNe which are the target of this 2003A proposal. By strategic HST studies of these samples to determine the value of $\langle w \rangle$, we aim to answer the key question: Is the dark energy something other than Einstein's Cosmological Constant?

An Unprecedented SN Ia Dataset to Measure Dark Energy: [CMAGIC approach]. The SN Ia redshift-magnitude diagram in the redshift range z = 0.3– 0.8, (where dark energy dominates over dark matter) is one of the only known ways to constrain the physics of the dark energy. The simplest measurement to characterize this dark energy is to measure $\langle w \rangle$ averaged over the expansion history from the observer to the source. As shown in Fig. 2, the current constraints on $\langle w \rangle$ are consistent with a very wide range of dark energy theories, including Einstein's Cosmological Constant (Perlmutter *et al.* 1999, Garnavich *et al.* 1998).

The CFHT Legacy Survey is the most ambitious of the planned wide-field surveys, with an imager field 4 times larger than the next largest survey camera (at CTIO), and twice as much time devoted to the survey. The full five-year CFHTLS dataset, when combined with a large sample of well-measured nearby SNe from the Nearby Supernova Factory, will provide a major improvement in the determination of the dark energy parameters. First, assuming $w = -1$, we can provide even stronger confirmation of the existence of dark energy by measuring $\{\Omega_M, \Omega_\Lambda\}$ to $\{\pm 0.06, \pm 0.10\}$. Alternately, assuming a flat universe errors on $\{\Omega_M, \langle w \rangle\}$ of $\{\pm 0.07, \pm 0.18\}$ can be achieved. With further future improvements on Ω_M from LSS and CMB, our constraints on $\langle w \rangle$ can be significantly improved, e.g., to $\sigma_{\langle w \rangle} = 0.07$ for a prior of $\sigma_{\Omega_M} = 0.03$ as shown in Fig. 2. Thus, even with the first few years' statistics from this survey, we will be able to see evidence for a non-Cosmological Constant dark energy if $\langle w \rangle$ is more than ~ 0.1 away from -1. It is important to note that these results assume a precision on z of better than 1% and so spectroscopic redshifts are needed for all SNe.

[REPLACE WITH HST-RELATED TEXT]

Groth Strip

Addressing Systematic Uncertainties with this Proposed Dataset

Perlmutter *et al.* (1997, 1999) discuss systematics in the measurement of Ω_M, Ω_Λ; we found that uncertainties due to K-corrections, gravitational lensing, and Malmquist bias are quite small compared to the statistical error of the current SN samples. We showed that SN Ia evolution and abnormal dust within, or even between, galaxies were possible, but unlikely. The large SNLS sample will reduce the statistical errors to the point that some systematics such as Malmquist bias will again be important. The SNLS data set itself will allow more powerful tests and constraints on several of these key systematics.

Multi-color Lightcurves. The rolling search with multiple filters will generate the first SN Ia dataset with complete color coverage throughout the lightcurves. This will enable more comprehensive extinction studies than previously possible. This is key because SNe Ia show a color-luminosity relation — currently taken from low-redshift SNe, which can be checked in the SNLS sample independent of extinction. It will also be possible to examine the consistency of the stretch-corrected peak magnitudes in restframe B with those in redder bands, where the intrinsic luminosity range of SNe Ia is smaller. SNLS lightcurves will also allow better K-corrections since extrapolation of the SN SED will not be necessary.

High-statistics Subsamples. Fig. 1 shows our recent study (Sullivan *et al.* 2002) in which our 42 SNe were divided into subsamples based on host galaxy morphology. This is an important first test of evolutionary and dust effects that will differ in different host galaxy environments. The large SNLS sample will allow us to perform such tests with much better statistics and in much more detail. As in Sullivan *et al.*, the narrow galaxy emission and absorption lines detectable with Keck spectroscopy of SN+host provide valuable constraints on host galaxy stellar populations. (See Progress to Date for more details.)

Conclusion. This proposal focuses on the unusual science opportunities presented beginning

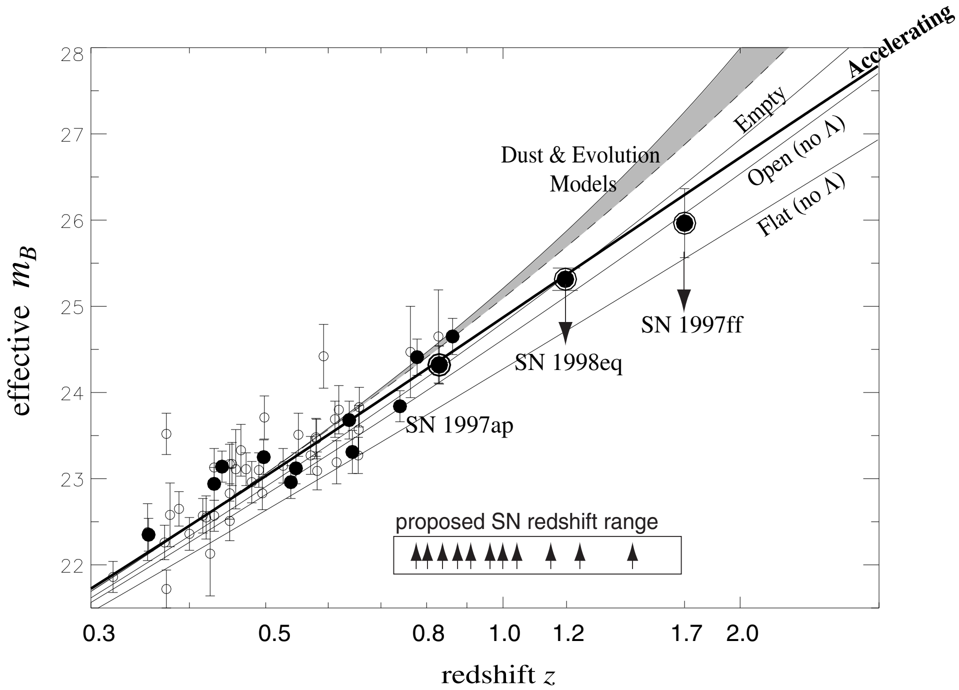

Figure 1: Open points show Hubble diagram for 42 high-z SNe (Perlmutter *et al.* 1999) including SN1997ap at z=0.83 for which HST observations were used, along with comparable non-host-extinction-corrected points (filled circles) for our HST SNe (Knop *et al.* 2000). The Einstein-de Sitter, "Flat (no Λ)" case $(\Omega_M, \Omega_\Lambda)$ = (1.0, 0.0) is strongly excluded by the current data. The "Open (no Λ)" case (0.28,0.00) indicates that some contribution from a cosmological constant is required for values of Ω_M favored by dynamical measurements. The magnitude difference between the best-fit "Accelerating (Λ)" world model (0.28, 0.72) and suitable ones with Ω_Λ=0 show redshift dependencies which would be very hard to mimic within the context of SNe evolution or gray dust hypotheses (the gray shaded region is an example model with uniform dust). 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.

with the Semester 2003A by the CFHT Legacy Survey. With a large increase in statistics for the mid-redshift range, we will make major strides in our ongoing multi-semester campaign to build a well-measured SN Ia Hubble diagram. These data are crucial for studying the cosmological parameters and the nature of dark energy. They also serve to refine our evolution/dust checks on systematics. This second-generation of SN studies provides our first chance to test whether the dark energy is consistent with a Cosmological Constant. Its conclusions and refinements in the use of large, well-studied SN Ia samples will shape future third-generation projects, such as *SNAP*, designed to probe the variation of w with time. With this program Keck will continue to play a leading role in this fundamental science.

References

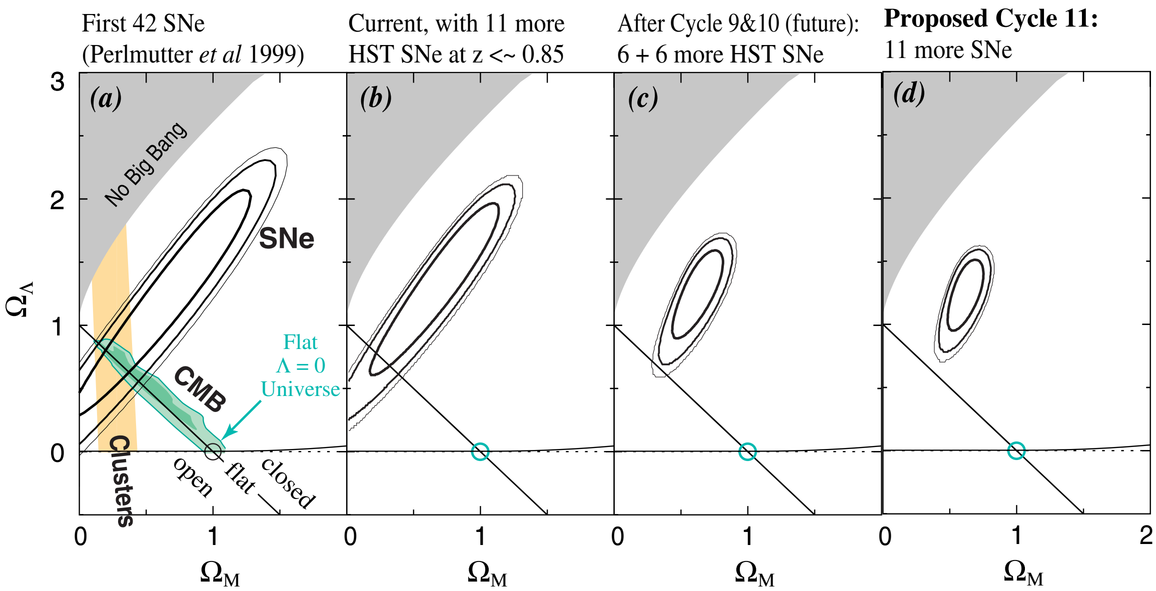

Figure 2: *(a)* 68%, 90%, and 95% confidence regions in the Ω_M—Ω_Λ plane from the 42 distant SNe Ia in Perlmutter *et al.* 1999 (including two observed with HST). These results indicate $\Omega_\Lambda > 0$, in agreement with the overlap of the recent combined CMB results (Jaffe *et al.* 2001) with the Ω_M measurements from galaxy clusters. *(b)* Results presented by Knop *et al.* (2000) for the confidence region after including our additional 11 SNe Ia which have lightcurves from WFPC and NICMOS. *(c)* Expected confidence region size after including six SNe 1a observed in Cycle 9 and an additional six (4 with $z \sim 0.85$ and 2 with $z \sim 1.2$) projected for Cycle 10, which is underway. *(d)* Now including the 11 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)*.

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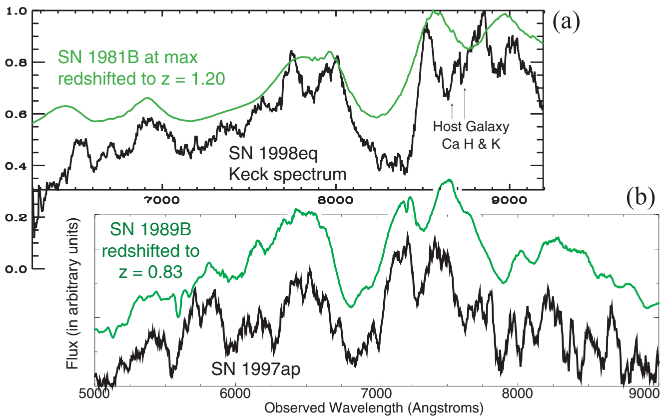

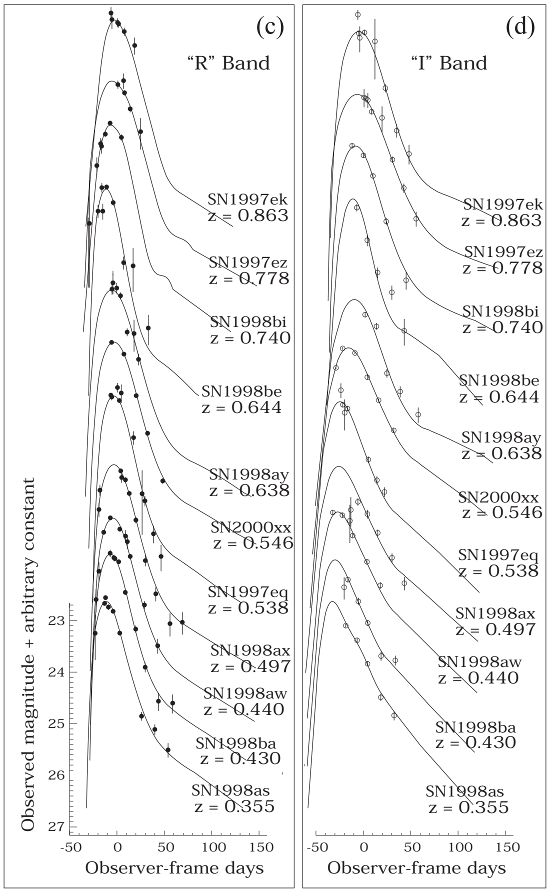

Figure 3: (a & b): Keck spectra for SN1997ap (at z = 0.83; Perlmutter et al. 1998) and SN1998eq (at z = 1.2, our most distant confirmed SN Ia; Aldering et al.). *Lower curves*: the spectrum of the high-z SN Ia. *Upper curves:* a spectrum of a nearby SN Ia for comparison. (c & d): Lightcurves in R and 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.

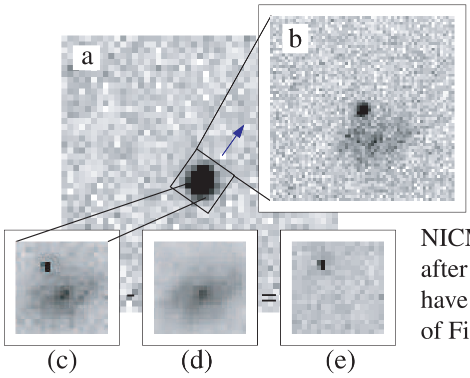

Figure 4:(a) In this R-band ground-based discovery image, SN 1998as is blended with the host galaxy. The host galaxy is clearly separated from the supernova in (b) the WFPC2 F675W image and in (c) the NICMOS F110W image. After subtracting off (d) the NICMOS final image after the SN faded away, only the 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 (Knop et al. 2001).

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Description of the Observations

[FROM CYCLE 11 PROPOSAL] **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 $1.3 \lesssim z \lesssim 1.7$ 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 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

[FROM CYCLE 11] For $z \lesssim 1.2$ 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 $1.3 \lesssim z \lesssim 1.7$ 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/SuprimeCam, 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. $z \lesssim 1.2$ SNe can be discovered with any of these facilities. HST+ACS is able to discover SNe in the $1.3 \lesssim z \lesssim 1.7$ 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 $z \lesssim 1.2$ 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 $0.85 \lesssim z \lesssim 1.2$ 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 Related HST Programs

GO-9705: Observations for this large (100-orbit) program started after servicing mission 3B in March 2002 and have mostly been completed, although some final reference images are still to be taken. Coordinated with three large search campaigns with the Subaru 8.2 m and also with smaller searches with the CTIO 4 m and CFHT 3.6 m, we used ACS/WFC and NICMOS/NIC2 photometry to obtain multi-epoch lightcurves of eight Type Ia SNe at high redshift $(0.9 < z < 1.3)$. For two of the highest redshift SNe, ACS grism spectra were taken. Analysis of this ACS data is in progress. With the refurbished NICMOS, we obtained final reference images of the host of SN1998eq, which we had previously studied in G0-8088, and these images will allow us to complete that analysis.

GO-8585: In GO 8585 we observed six 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. Analysis of this data will be completed when the final reference images are available, scheduled for spring 2003.

GO-8313: The objective of this project, which has now been completed and submitted for publication, was to obtain snapshot unfiltered STIS images of distant galaxies of known redshift which have hosted supernovae (SNe) of Type Ia found by the SCP, 20 of which are used in the Hubble diagram of 42 type Ia SNe (Perlmutter *et al.* 1999). In Sullivan *et al.* (2002, submitted) we present these new results on the Hubble diagram of SNe Ia as a function of host galaxy morphology that demonstrates that host galaxy extinction is unlikely to systematically dim distant SN Ia in a manner that would produce a spurious cosmological constant. The internal extinction implied is small, even for late-type systems ($A_B < 0.3$), and the cosmological parameters derived from those SNe Ia hosted by (presumed) dust-free early-type galaxies are consistent with our previous determination of a non-zero Λ. The brightness scatter about the Hubble line for SNe Ia in these early-type hosts is also significantly smaller than for the SNe Ia in late-type galaxies. This result was based on HST STIS "snapshot" images and Keck spectroscopy of SNe spanning the range $0.3 < z < 0.8$.

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

DD-8088: WFPC2 and NICMOS (cycle 7) 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. With the final NICMO image of the galaxy without the supernova recently obtained in cycle 11, this analysis can now be completed.

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 results are about to be submitted for publication. A preliminary Hubble diagram was presented January 2002 AAS meeting. The cosmological results from these SNe (Knop *et al.*) are in close agreement with results from the first supernova results (Perlmutter *et al.* 1999) that gave direct evidence for a cosmological constant.

[UPDATE THE FOLLOWING] These data are included in Figures 1 and 2 in this proposal. The lightcurves provided by WFPC2 for these supernovae (Figure 3 c& d) were excellent; at the higher redshifts, these lightcurves provide a substantially better measurement of the calibrated supernova magnitude than those for comparable supernovae observed only from the ground. The color information provided by NICMOS (see Figure 4) was only possible from HST. The improvement of the confidence limits on the cosmological parameters Ω_M and Ω_Λ (Figure 2b) are as good as we had previously predicted. Papers presenting the cosmological results from these data will be submitted in 2001.

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.