Hubble Space Telescope

Cycle 13 GO Proposal

Is Lambda the dark energy? Answering with NICMOS systematics controls for high-redshift SNe Ia

Principal Investigator:	Dr. Saul Perlmutter
Institution:	Lawrence Berkeley National Laboratory
Electronic Mail:	saul@lbl.gov
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Cycle 13 primary orbits:	62	Cycle 14 primary orbits:	25
		Total primary orbits:	87

Abstract

The cause of the accelerating expansion of the universe is one of the key scientific questions of our day. While other cosmological studies (CMB, LSS) have provided complementary measurements, the Supernova (SN) Ia Hubble diagram remains the only direct approach currently available to study the acceleration. HST can make major contributions to constraining whether the ``dark energy'' is Einstein's cosmological constant or some other general dynamical scalar field. By obtaining strategic HST NICMOS observations for a sample of 30 z~0.5 SNe Ia found in on-going multi-year ground-based SN searchs, and employing new standardization techniques focused on redder wavelengths compared to the ground-based programs, the efficacy of the next-generation SN Hubble diagram for testing Lambda can be dramatically improved.

Investigators:

	Investigator	Institution	Country
PI	Dr. Saul Perlmutter	Lawrence Berkeley National Laboratory	USA/CA
CoI	Dr. Greg Aldering	Lawrence Berkeley National Laboratory	USA/CA
CoI*	Dr. Reynald Pain	Laboratoire de Physique Nucleaire des Hautes Energies	France
CoI*	Prof. Ariel Goobar	Stockholm University	Sweden
CoI*	Dr. Isobel Hook	University of Oxford	UK
CoI	Dr. Lifan Wang	Lawrence Berkeley National Laboratory	USA/CA
CoI	Prof. Robert A. Knop Jr.	Vanderbilt University	USA/TN
CoI*	Dr. Christopher Lidman	European Southern Observatory - Chile	Chile
CoI	Dr. Gerson Goldhaber	Lawrence Berkeley National Laboratory	USA/CA
CoI	Dr. Anthony L. Spadafora	Lawrence Berkeley National Laboratory	USA/CA
CoI	Dr. Rachel A. Gibbons	Lawrence Berkeley National Laboratory	USA/CA
CoI	Dr. Vitaliy Fadeyev	Lawrence Berkeley National Laboratory	USA/CA
CoI	Prof. Shane Burns	Colorado College	USA/CO
CoI	Dr. Andrew Fruchter	Space Telescope Science Institute	USA/MD
CoI*	Dr. Nino Panagia	Space Telescope Science Institute	USA/MD
CoI	Dr. Susana Deustua	American Astronomical Society	USA/DC

Number of investigators: 16

* ESA investigators: 5

Target Summary:

Target	RA	Dec	Magnitude
SN01A+B	22 15 31.7	-17 44 5.7	V = 23.0
SN02A+B	22 15 31.7	-17 44 5.7	V = 23.0
SN03A+B	22 15 31.7	-17 44 5.7	V = 23.0
SN04A+B	22 15 31.7	-17 44 5.7	V = 23.0
SN05A+B	22 15 31.7	-17 44 5.7	V = 23.0
SN06A+B	02 26 0.00	-04 30 0.00	V = 23.0
SN07A+B	02 26 0.00	-04 30 0.00	V = 23.0
SN08A+B	02 26 0.00	-04 30 0.00	V = 23.0

Target	RA	Dec	Magnitude
SN09A+B	02 26 0.00	-04 30 0.00	V = 23.0
SN10A+B	02 26 0.00	-04 30 0.00	V = 23.0
SN11A+B	02 26 0.00	-04 30 0.00	V = 23.0
SN12A+B	02 26 0.00	-04 30 0.00	V = 23.0
SN13A+B	10 00 29.0	+02 12 21.0	V = 23.0
SN14A+B	10 00 29.0	+02 12 21.0	V = 23.0
SN15A+B	10 00 29.0	+02 12 21.0	V = 23.0
SN16A+B	10 00 29.0	+02 12 21.0	V = 23.0
SN17A+B	10 00 29.0	+02 12 21.0	V = 23.0
SN18A+B	10 00 20.0	+02 12 21.0	V = 23.0
SN19A+B	10 00 29.0	+02 12 21.0	V = 23.0
SN20A+B	10 00 29.0	+02 12 21.0	V = 23.0
SN21A+B	14 19 28.0	+52 40 41.0	V = 23.0
SN22A+B	14 19 28.0	+52 40 41.0	V = 23.0
SN23A+B	14 19 28.0	+52 40 41.0	V = 23.0
SN24A+B	14 19 28.0	+52 40 41.0	V = 23.0
SN25A+B	14 19 28.0	+52 40 41.0	V = 23.0
SN26A+B	14 19 28.0	+52 40 41.0	V = 23.0
SN27A+B	14 19 28.0	+52 40 41.0	V = 23.0
SN28A+B	14 19 28.0	+52 40 41.0	V = 23.0
SN29A+B	22 15 31.7	-17 44 5.7	V = 23.0
SN30A+B	22 15 31.7	-17 44 5.7	V = 23.0

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
SN01A+B	NIC1 Imaging F110M		6 (1x6)
SN02A+B	NIC1 Imaging F110M		4 (1x4)
SN03A+B	NIC1 Imaging F110M		3 (1x3)
SN04A+B	NIC1 Imaging F110M		2 (1x2)
SN05A+B	NIC1 Imaging F110M		2 (1x2)
SN06A+B	NIC1 Imaging F110M		5 (1x5)
SN07A+B	NIC1 Imaging F110M		4 (1x4)

Target	Config Mode and Spectral Elements	Flags	Orbits
SN08A+B	NIC1 Imaging F110M		3 (1x3)
SN09A+B	NIC1 Imaging F110M		3 (1x3)
SN10A+B	NIC1 Imaging F110M		2 (1x2)
SN11A+B	NIC1 Imaging F110M		2 (1x2)
SN12A+B	NIC1 Imaging F110M		2 (1x2)
SN13A+B	NIC1 Imaging F110M		6 (1x6)
SN14A+B	NIC1 Imaging F110M		4 (1x4)
SN15A+B	NIC1 Imaging F110M		2 (1x2)
SN16A+B	NIC1 Imaging F110M		2 (1x2)
SN17A+B	NIC1 Imaging F110M		2 (1x2)
SN18A+B	NIC1 Imaging F110M		2 (1x2)
SN19A+B	NIC1 Imaging F110M		2 (1x2)
SN20A+B	NIC1 Imaging F110M		2 (1x2)
SN21A+B	NIC1 Imaging F110M		4 (1x4)
SN22A+B	NIC1 Imaging F110M		4 (1x4)
SN23A+B	NIC1 Imaging F110M		5 (1x5)
SN24A+B	NIC1 Imaging F110M		2 (1x2)
SN25A+B	NIC1 Imaging F110M		2 (1x2)
SN26A+B	NIC1 Imaging F110M		2 (1x2)
SN27A+B	NIC1 Imaging F110M		2 (1x2)
SN28A+B	NIC1 Imaging F110M		2 (1x2)
SN29A+B	NIC1 Imaging F110M		2 (1x2)
SN30A+B	NIC1 Imaging F110M		2 (1x2)
		Total orbit request:	87

■ Scientific Justification

Introduction

The accelerating expansion of the universe is one of the most captivating "key scientific questions of our day" identified by the NRC Committee on the Physics of the Universe (Tur02). In the few years since the acceleration was first seen in the Type Ia supernova (SN Ia) Hubble diagram (Per99, Rie98), the evidence has grown even stronger: complementary CMB measurements have indicated that the Universe has zero curvature, making the SN Ia result more determinative, and – in combination with the SNe — pointing to a $[\Omega_M \approx 0.3, \Omega_\Lambda \approx 0.7]$ cosmology. This is also consistent with other astronomical mass density measurements (Sper03).

The SN Hubble diagram remains the only direct approach currently in use to study acceleration. There are ongoing studies of all known relevant sources of systematic uncertainty, but none show any biases at a level that might affect the basic acceleration results. These include: any changes with z in host-galaxy extinction by ordinary dust (Per99,Rie98,Sul03; see in particular our large, comprehensive HST-based study in Kno03), any extinction by intergalactic gray dust (Mor03), gravitational-lensing (de)amplification (Per99), discovery selection effects (Per99,Rie98), K-correction systematics (Nug02), and population drifts in SN environment (Sul03). Moreover, the extensive HST programs focused on $z > 1$ are showing the transition to deceleration which would be hard for dust or evolution to mimic.

With these advances in hand, it is now time to aggressively pursue the cause of the acceleration be it Einstein's cosmological constant, Λ, or a general dynamical scalar field (like that assumed for inflation). Large ground-based projects are underway whose aim is to test the hypothesis that the expansion is *consistent with* Λ. In general this is done by measuring the time-averaged equation of state ratio $w \equiv p/\rho$ of the "dark energy", which is $w = -1$ for a cosmological constant. We propose a program which will leverage off of these ambitious new ground-based SN projects to enable a powerful complementary test of Λ having high-quality HST NIR data at its core. This program employs a methodology which is less sensitive to several types of systematics, which would limit the ground-based programs. Large scale structure data and CMB data are needed as complements to this SN measurement, but they themselves have little sensitivity to the dark energy's equation of state; see Fig. 1b. Moreover $z > 1$ SNe Ia programs which HST has undertaken to date place few constraints on w. Thus, improved SNe Ia measurements are essential for measuring w, and given the possible cancellation of SM4, this program may be the principle means by which HST can have a lasting impact on the study of the "dark energy."

Importance of Systematic Uncertainties

Redshift optimization studies (Hut01) have shown that for the case of a constant equation of state, and assuming that systematic uncertainties can be sufficiently controlled, the easiest test of a *constant* Λ can be accomplished with a well-measured Hubble diagram around $z \sim 0.5$, with SNe Ia at higher redshifts serving mostly as checks. Large ground-based dedicated projects have now begun with the goal of collecting from 200 (CTIO *Essence* project) to 500 (CFHT SuperNova Legacy Survey, *SNLS*) SN Ia lightcurves with $0.2 < z < 0.7$. These surveys employ now-classical standardization methods based on lightcurve width. The photometric uncertainty for each of these SNe will contribute statistical errors that are significantly smaller than the current estimates of intrinsic peak magnitude dispersion ($\sigma_{\rm peak} < 0.15$ mag, Phi99), after correcting for extinction and lightcurve timescale (e.g. stretch or Δm_{15}). The statistical error for the Λ test will scale as $\sqrt{N}$, giving a statistical uncertainty of less than 0.01 mag for $N \sim 200$ SNe. Since the current systematic uncertainties are much larger than this (Per99, PeSc03, Knop03) the measurements from these large projects will be entirely limited by systematic errors.

These major ground-based efforts (and, for that matter, any further space-based higher-redshift SN efforts like SNAP) are therefore only meaningful if the dramatic improvement in statistical uncertainty is matched by corresponding improvement in systematic uncertainty. The *Essence* and *SNLS* projects both use discovery and follow-up strategies, and target redshifts, such that there will be negligible systematics from Malmquist bias, gravitational lensing, or K-corrections. Complicated lightcurve templates which only approximate the SNe lightcurves are needed to model the data. Moreover, there are not good constraints on systematic errors in extinction correction arising from any small changes to $z \sim 0.5$ in the intrinsic B-V color of SNe Ia or the value of the reddening ratio, $R_B \equiv A_B/E(B\text{-}V)$. In Fig. 1c we show an example where a realistic systematic error of $\Delta m \sim 0.03$ over this redshift range would lead these experiments to incorrectly conclude that dark energy is not Λ. We here propose to constrain these systematics by observing a significant sub-sample of 30 of the $z \sim 0.5$ *SNLS* or *Essence* SNe Ia with NICMOS F110M imaging at maximum light and during a key post-maximum period – a unique HST contribution. These observations correspond to rest-frame R-band to I-band (depending on redshift). In the following we refer generally to rest-frame I, although the exact improvement will depend somewhat on the restframe wavelength that is being observed.

Proposed Measurement — How NICMOS Constrains Systematics

Restframe I-band photometry at maximum light from NICMOS can be used in conjunction with the full ground-based lightcurves in B and V, to obtain an $I_{\rm max}$ SN Ia Hubble diagram at $z \sim 0.5$, which is dramatically less affected by extinction, or by the uncertainty in the intrinsic SN color and R_B or R_I values needed to correct this extinction. As a complement to the standard I_{max} method, we propose to employ a powerful new technique we have developed for standardizing SNe Ia: The CMAGIC method (Wan03) calibrates SNe Ia magnitudes at a fixed post-maximum color — rather than at maximum light — using a simple *linear* relation between magnitude and color which has a known, fixed slope for all SNe Ia (see Fig. 2 and Wan03). In I-band, the dependence on lightcurve width is very small (and consistent with zero). Wan03 showed that this technique has worked for every well-measured SN Ia and has achieved standardization with a remarkably small dispersion of only 0.08-0.11 mag (depending on the band used). In I-band this method works at least as well as I_{max} standardization using Δm_{15} (Phi99), and may be up to 50% less noisy. Spectroscopically, SNe Ia appear much more uniform after maximum light, while spectropolarimetry indicates that any asymmetry in the photosphere is confined to earlier epochs. This suggests that the post-maximum period during which our technique is applicable ($+14$ to $+28$ restframe days after maximum in I-band) represents a period when the behavior of SNe Ia is more homogeneous. The linear color-magnitude relation shown in Fig. 2 makes I-band CMAGIC much less sensitive to extinction uncertainties, and less sensitive to any evolution in the luminosity-width relation, thus providing better homogeneity for distance measurements.

Constraining systematic drift in extinction-related quantities
As a quantitative example of how the proposed I-band observations can address systematic errors due to drifts in extinction-related quantities, let us take the current uncertainty in intrinsic SN Ia color (after calibration for lightcurve width), which is $\sigma(B\text{-}V)_0 \approx 0.03$ mag (Phi99). If there were a systematic change with redshift in this color of only half this dispersion it would produce an error in the extinction correction of $\Delta A_B = R_B\ \Delta(B\text{-}V)_0 \approx 0.06$ mag for a restframe B-band Hubble diagram. For an I_{max} Hubble diagram this error would be only $\Delta A_I = R_I\ \Delta(B\text{-}V)_0 \approx 0.03$ mag. We would be able to use the $B\text{-}I$ color rather than $B\text{-}V$, dropping the systematic uncertainty in I_{max} to almost half this value, $\Delta A_I = R_I \Delta(B\text{-}I)_0/(2.4) \approx 0.02$ mag (where $E(B\text{-}V) = E(B\text{-}I)/2.4$), even accounting for the less certain intrinsic $B\text{-}I$ color ($\sigma(B\text{-}I)_0 \approx 0.045$ mag (Phi99)). With our post-maximum technique the systematic uncertainty would be only 0.02 mag for $B\text{-}I$ or $B\text{-}V$. Systematic errors due to changes in R would be reduced in an analogous way. The drop in systematic uncertainty gained with the NICMOS data is the factor of ∼3 needed to begin to match the statistical improvement from the two major ground-based projects.

Constraining systematic drift in intrinsic SN progenitor populations
An important test for a drift from $z = 0$ to 0.5 in the properties of SN Ia progenitors can be made by separately studying the Hubble diagrams for E/S0 and spiral hosts, which are expected to follow very different evolution histories. Using several years worth of our HST data, we have recently published the first implementation of this test (Sul03), which showed the same cosmological results for a Hubble plot of 12 E/S0 galaxies as for a Hubble plot of 45 spiral galaxies (see Fig. 1b). The two subsamples agree within their ±0.1 uncertainties for Ω_M or Ω_Λ in a flat cosmology. An important ancillary benefit of our proposed program will be NICMOS images, which will double the sample size of morphologically-typed high-redshift SN Ia hosts required for this important test. Together with the accompanying larger low-redshift sample (discussed in the section on sample size below)— and more accurate SN measurements than were possible for the earlier SNe Ia — this test can be bring the constraint on this source of systematic uncertainty down below the 0.05 level in Ω_Λ.

We propose to perform two additional powerful tests of population drift: (1) For nine of the SNe (chosen to cover a spread of lightcurve widths), we will study the consistency of the CMAGIC color-magnitude slope between high- and low-redshift SNe Ia, by obtaining one additional point during the CMAGIC period. This subsample is sufficient to measure the slope at the necessary (~ 0.1 on slope) precision. (2) For four of these same SNe, we will measuring the height of the second lightcurve peak (Fig.2a), which is known to correlate strongly with luminosity.

Conclusion
The HST has a key opportunity to test the possibility that dark energy is Λ, by taking advantage of the two ground-based supernova projects that are committing very large amounts of dedicated telescope time with wide-field instruments. We here propose a highly efficient use of NICMOS — based on two complementary techniques — to achieve this goal, and thereby provide the crucial improvement in control of systematic uncertainties necessary to measure w at the best currently possible level of precision.

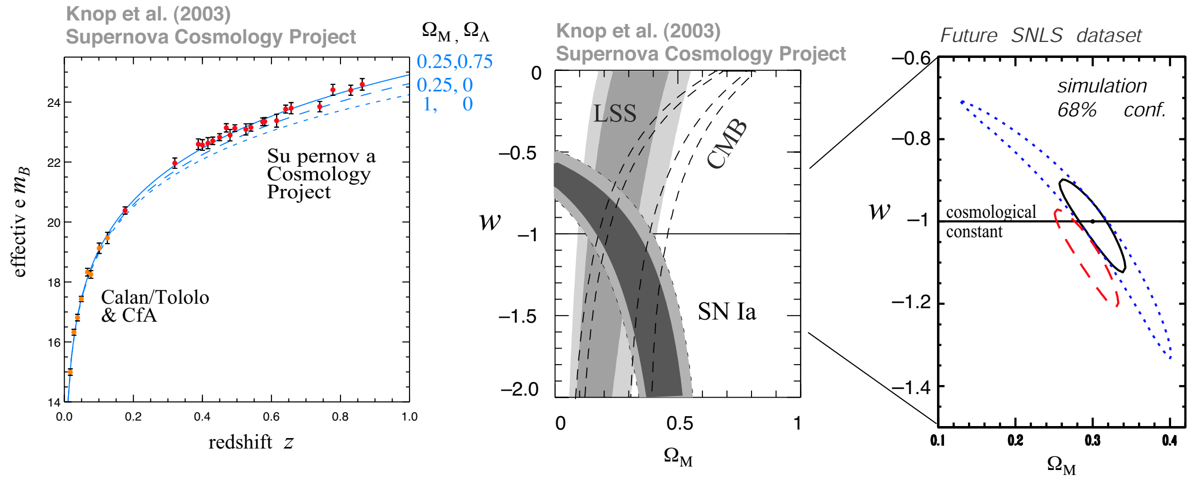

Figure 1: (Left): Our major new result based on several cycles of HST data showing the averaged Hubble diagram (SNe within $z < 0.01$ of each other have been combined) for all supernovae from our low-extinction subsample. The solid curve overlaid on the data represents our best-fit flat-universe model, $(\Omega_M, \Omega_\Lambda = (0.25, 0.75)$. Two other cosmological models are shown for comparison. (Center): Our latest joint measurements of Ω_M and w assuming $\Omega_M + \Omega_\Lambda = 1$ and that w is not time-varying. Confidence regions (68% and 90%) are shown for the SCP SN Ia data overlaid with LSS measurements and combined CMB measurements. (Right): 68% statistical confidence intervals on the dark energy equation of state possible from *SNLS* when it is completed 5 years from now, assuming a flat universe (from CMB measurements), and with (solid) and without (dotted) a prior on Ω_M from Large-Scale Structure. If a small systematic error is introduced, the statistical confidence interval will miss the correct simulated Λ ($w = -1$) solution by 2σ (long-dash).

References

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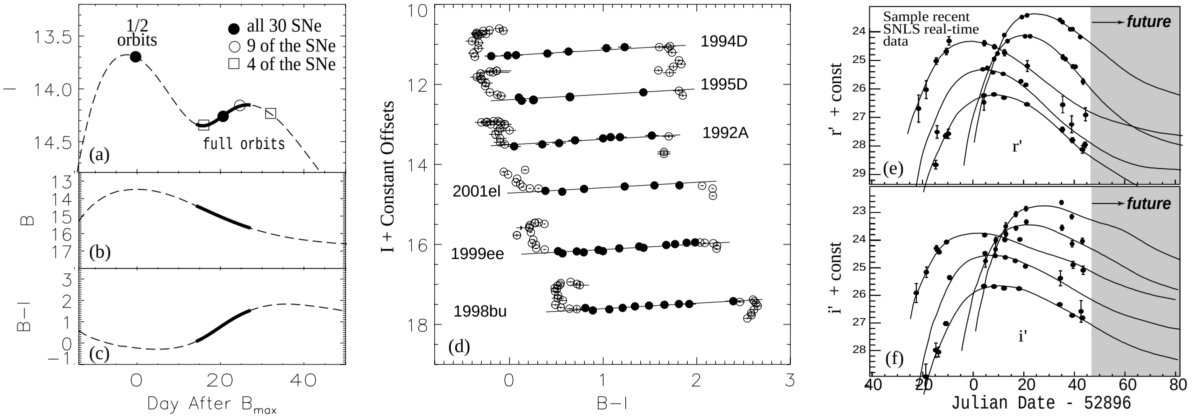

Figure 2: *Left:* I-band, B-band lightcurves and B-I color curve for a normal supernova. The solid line segment indicates the region where I vs B-I can be described by a linear relation. Plotting points show the proposed NICMOS observations. *Center:* The I vs B-I Color-Magnitude diagram showing data between 0 to 35 days after B_{max} for several SNe Ia, in order of increasing host-galaxy extinction. Filled circles correspond to epochs in the linear B-I CMAGIC region (typically 14–28 days after B_{max}). Wan03 showed that a universal slope fits the linear relation for all well-observed nearby SNe Ia. *Right:* A sample of recent SNLS "raw" r- and i-band data as seen in real time (not shown here: g- and z-bands) for five SNe Ia at $z \sim 0.5$. Note the early discoveries and the comprehensive high signal-to-noise follow up.

Description of the Observations

This proposal requests NIC1 F110M observations of 30 SNe Ia in the redshift range $0.4 < z < 0.6$ at maximum light, and ∼3 weeks after maximum to obtain a CMAGIC magnitude. From previous HST work in this redshift range, we have found that for most of the SNe (typically 25 out of 30) it is necessary to observe final images of the host galaxy after the SN has faded to ensure the proper subtraction of the host-galaxy light, as our goal is to limit systematics at the few-percent level. This will require one orbit per SN for these 25 SNe. The density of SNe Ia in each *SNLS* field is high enough that two nearby (separation less than 1 degree) targets can be observed in the same orbit for the maximum-light observations (which requires only 1/2 orbit each SN). We have used this approach in previous programs and have confirmed the efficacy of this procedure using RPS2. The full observing strategy is described under Coordinated Observations.

Exposure Times: The 1/2-orbit at-maximum photometry point will provide the measurement of restframe I_{max}. The NICMOS ETC, as well as scaling from our Cycle 11 NIC2 photometry, indicates that the at-maximum photometry point will have $S/N \sim 25$ after subtraction of a reference image. This meets our requirement for a B-I color with uncertainty better than 0.05 mag, which enables our check for color evolution and keeps the extinction correction below the intrinsic dispersion among SNe Ia. The post-maximum photometry point will provide the CMAGIC magnitude. During this period the SNe Ia will be roughly half as bright and the full-orbit photometry will have $S/N \sim 18$ after subtraction of final reference images, which will roughly match the best CMAGIC intrinsic dispersion. Nine SNe will be observed with more complete sampling of the lightcurves, an additional one or three full-orbit observations. These observations will span a period on the lightcurve during which the I-band changes by only $\sim$10% compared to the post-maximum photometry point (Fig 2d), so the S/N will remain comparably good throughout this period.

Filter Choice: The F110M filter provides a good match to restframe I over most of the targeted redshift range (the same techniques will also be used with restframe R-band at the highest targeted redshifts). The F110W filter is more sensitive, but it is so broad that on the red side it will contain SN light for which there is no reference data, while its blue side extends into the restframe V and B thereby negating the decreased sensitivity to extinction which is central to our program. F110M is available only on NIC1 — the superior resolution of NIC1 will help in separating host light from SN light.

Sample Size: *SNLS* is now producing roughly 60 well-measured SNe Ia per year in the $0.4 < z < 0.6$ redshift range. The nominal statistical uncertainty in the mean SN brightness in a bin of $\Delta z = 0.1$ at $z = 0.5$ will be ~ 0.02 mag from this sample. However, a systematic error of $\Delta m \sim 0.03$ over this redshift range would limit the *systematic* accuracy to the *statistical* accuracy achievable from a sample of roughly 30 SNe Ia. We take this as a suitable sample size for our systematics-suppressed I-band Hubble diagram. With this sample and our target color uncertainties we will be able to compare B-I intrinsic colors between low- and high-redshift SNe Ia in E/S0 and spiral subsamples at a level of 0.01 mag (for low-redshift versus high-redshift spiral) to 0.02 mag (comparing high-redshift E/S0's with high-redshift spirals). With regards to extinction, our methodology allows us to suppress systematics in our dataset below this level. (It is important to note that the low-redshift I-band data will improve during Cycle 13 with the advent of the Nearby Supernova Factory (Ald02), so better calibration, and tighter constraints from the proposed NICMOS data, are expected.)

The Need for HST: Our targets have $J \sim 22.2$ at maximum and $J \sim 22.9$ during the post-maximum period; were we to attempt this program using ground-based 8-m telescopes roughly 11 hrs per SN would be required to obtain comparable data (two lightcurve points plus matching final reference). Moreover, even on queue-scheduled 8-m's we have found that NIR instrumentation is often relegated to bright time. The SNe which would come to maximum light at that time will have poor ground-based optical data, which is a necessary complement to the restframe I-band data and needed to obtain the lightcurve width and the peak B-band magnitude. The proposed space-based follow-up will not suffer from this problem and will be homogenous and robust. In contrast, our experience with ground-based follow-up programs carried out over the last several years with comparable NIR requirements has been that problems of instrument availability, schedulability at the correct epochs, cross-telescope calibration, etc., result in a significant reduction of the sample that is ultimately usefully observed. Even our top-ranked NIR proposals at VLT and Gemini have been unable to get good data on more than a couple of SNe Ia in a semester. Thus, attempting 30 SNe Ia from the ground at 11 hrs each would be unlikely to succeed even if all the requested time (~ 45 nights per year) were granted. (Note that adaptive optics techniques have not been developed for precision photometry – this is expected to be a difficult future challenge – and that the observing conditions needed for adaptive optics observations are even more restrictive.)

Special Requirements

As described below, we will arrange with the HST schedulers to put on the HST calendar three orbits for each field every lunation (one just after new moon, and two three weeks later)throughout this observing Cycle. Depending on the time of year, we will be monitoring 1 or 2 fields, so this is a very minor load on the schedule. Prior to the building of the flight calendar we will provide HST with the precise coordinates of each target. This will be similar to, but even simpler than, arrangements we have made with HST over the last several Cycles for the observation of high-z SNe Ia. For nine of the SNe, we will add an additional orbit, and for four of those SNe we will add three orbits – all in the same lunation scheduled at least three weeks in advance.

Coordinated Observations

Both the *SNLS* and *Essence* projects are discovering supernovae in a "rolling search" mode, in which the same fields are revisited every few nights (with observations in multiple filters) over several months (Fig. 2e,2f). This means that any supernova in the field can be discovered within a few days of explosion, and all the SNe in the field are followed with photometry every few nights over the following few months. Most (or all) of the SNe that will be used for this current proposal will likely come from the *SNLS* since most of the proposers are either affiliate or members of the *SNLS* team (in particular, Reynald Pain is a leader of that project); the *Essence* data and discovery announcements are available publicly as part of the NOAO Science Archive and we would follow those SNe as appropriate.

There are several advantages for this proposal from this mode of discovery and follow-up. First, there will be a continuous rate of supernova discoveries in the redshift range around $z \sim 0.5$ — approximately 60 per year from the *SNLS* search. This allows just a few orbits to be scheduled per month for this HST program (to follow two or four SNe at maximum and post-maximum), providing more HST scheduling flexibility. These discoveries will all be in one of the few predetermined *SNLS* survey fields, which are small enough that the HST can be scheduled many weeks in advance to observe a target in the field and then the final exact coordinates given one week in advance of the observation. This observing mode (which we have used extensively for HST follow up of high-redshift SNe) avoids the inefficiency of ToO observations.

The discoveries are triggered about two observer-weeks before the supernova reaches maximum light in restframe I-band (which is just a couple of days before the B-band maximum). We are obtaining Keck, VLT and Gemini spectroscopy to determine the redshift, type (Ia, II, etc.), and lightcurve phase for each SN. *SNLS* photometry provides photometric redshifts to help with the selection of spectroscopic targets, and can provide photometric redshifts as back-up (galaxy redshifts are also becoming available from the Keck/DEEP study of the Groth Strip and the VIMOS study of the SNLS Fall field). The SN spectroscopy and photometry will provide predictions of the date of maximum, allowing the selection of just the right $z \sim 0.5$ SNe Ia and a ±3 day prediction of the date of I-band maximum. The "rolling search" and follow-up yields sufficiently high S/N observations in restframe B- and V-band throughout the lightcurves of these SNe that the $B_{\rm max}$, B-V color, date of maximum light (in B-band, and hence in I-band), and lightcurve timescale stretch (or Δm_{15}) will all be known to a precision that is better than needed for the known intrinsic dispersion of the standardization methods.

As each $z \sim 0.5$ SN Ia is identified, it will be ranked against the other new SNe Ia, and the best choice will be placed into the next available observing slot closest to its date of maximum light. The post-maximum observations at $+14$ to $+28$ restframe days ($\sim$ 21–42 observer days) will then be assigned as well. This program is powerful, yet robust to weather and as simple an HST SN program as is possible.

In addition, we have an independent program to obtain extensive $0.34 < \lambda < 1.0$ μm spectrophotometry of nearby Hubble-flow SNe Ia, which will greatly improve the calibration in the restframe R- and I- bands and provide the reference for obtaining relative distances to the high-z SNe Ia from this HST program.

Justify Duplications

None - these are all unique observations of transient events.

Previous Related HST Programs

By combining observations from a series of GO programs over a number of HST cycles we have obtained a cumulative sample of high redshift SNe which has yielded new determinations of cosmological parameters $(\Omega_M, \Omega_\Lambda, w)$. Equally important, these HST observations have been the basis for studies of possible systematics of the SN technique, such as host-galaxy extinction or evolution. Two such multi-cycle HST studies were published in the past year and both provided confirmation and improved precision on the earlier ground-based acclerating universe results. Knop *et al.*, 2003 (based on G0-7336, GO-7590, GO-8346) presented an analysis of an independent set of 11 high redshift SNe. The high-quality lightcurves available from photometry on WFPC2 make it possible for this sample alone to provide measurements of the cosmological parameters comparable in statistical weight to the previous results. In addition to high-precision lightcurve measurements, this data offered greatly improved color measurements of the high-redshift supernovae, and hence improved host-galaxy extinction estimates. These extinction measurements show no anomalous negative $E(B-V)$ at high redshift. The precision of the measurements is such that it was possible to perform (for the first) time a host-galaxy extinction correction directly for individual supernovae without any assumptions or priors on the parent $E(B-V)$ distribution.

Sullivan *et al.* 2003 (based on GO-8313, GO-9131) presented the Hubble diagram of distant type Ia supernovae (SNe Ia) segregated according to the type of host galaxy. This allowed us to confirm our previous evidence for a cosmological constant by explicitly comparing SNe residing in galaxies likely to contain negligible dust with the larger sample. These data provide a key test of evolutionary systematics.

Other such multi-cycle analyses, described below, are in progess. In particular, this year we are completing final observations of host galaxies after the SNe faded for SNe discovered in GO-9075 and GO-8585.

GO-9727: This cycle 12 program will begin observations in April 2004 using ACS to do a new search for very high redshift $(1.2 > z > 1.6)$ SNe Ia in the GOODS-N field. In coordination with Riess (GO-9728), images from 15 ACS pointings will be taken approximately every 45 days and searched for candidates. Followup photometry will be obtained with ACS and NICMOS for approximately three very high redshift SNe.

GO-9075: In this program, we pushed our SNe Ia studies to the highest redshifts that are feasible for a ground-based discovery and spectroscopic identification campaign. HST follow-up observations for this program started after servicing mission 3B in March 2002 and have been completed for the most part — final reference images are still to be taken. Coordinated with three large search campaigns using the Subaru 8.2 m and also with simultaneous smaller searches using the CTIO 4 m and CFHT 3.6 m, we obtained ACS/WFC and NICMOS/NIC2 photometry for 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 is presented in the PhD thesis of J. Raux (Univ. of Paris, 2003), presented at the January 2004 AAS meeting. A publication is in progress.

GO-8313: The objective of this project, which has now been completed with the publication (Sul03) mentioned above, 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). 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 SN2000fr, 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.

DD-8088: WFPC2 and NICMOS (cycle 7) observations were obtained for SN1998eq at $z = 1.20$ (Aldering, *et al.*, 1998,IAUC,7046). The preliminary photometry is consistent with the previous results for Ω_M, Ω_Λ. With the final NICMOS image of the galaxy without the supernova obtained, this analysis can now be completed.

GO-7850 and balance of **GO-7336** and **DD-7590**: WFPC2 and NICMOS observations were obtained for 11 Type Ia supernovae in the redshift range 0.36—0.86. These observations, including final references where necessary, are now complete, and the results were published in Knop, R., *et al.* 2003 as mentioned above. The color information provided by NICMOS (Burns, S., *et al.*, 2001,AAS,199.1610B), was only possible with HST.

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. The HST portion is based on a total of 4 orbits. Also from this program, HST observations of two $z = 0.83$ SNe Ia are included in the analysis in Per99 which reports on the results from our HST and ground-based imaging and Keck spectroscopic observations of 42 type Ia supernovae with $0.18 < z < 0.86$. The paper rules out a flat $\Omega_M = 1$ universe and presents very strong evidence for a positive cosmological constant.