Hubble Space Telescope

Cycle 16 GO Proposal

Addressing Dark Energy Systematics with the First I-band Hubble Diagram to z=0.9

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Scientific Category:	COSMOLOGY
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Instruments:	NICMOS
Proprietary Period:	12

Orbit Request	Prime	Parallel
Cycle 16	87	0

Abstract

The cause of the acceleration 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 most effective and precise approach currently available to study the acceleration. By obtaining strategic NICMOS observations of 30 high-redshift SNe Ia found in the final year of the ground-based Supernova Legacy Survey (SNLS), we will construct the first I-band Hubble diagram extending to z=0.9. This Hubble diagram will be much less sensitive to extinction, and thus much less affected by this dominant source of systematic uncertainties, than the already powerful SNLS B-band Hubble diagram. Since the statistical uncertainties of the full multi-year SNLS data set are already limited by these systematics, HST has an opportunity with this program to help dramatically improve the best current constraints on dark energy.

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Target Summary:

Target	RA	Dec	Magnitude
D1	02 26 0.0000	-04 30 0.00	V = 23.0
D2	10 00 29.0000	+02 12 21.00	V = 23.0
D3	14 19 28.0000	+52 40 41.00	V = 23.0
D4	22 15 31.0000	-17 44 6.00	V = 23.0

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
D1	NIC1 Imaging F110M		1
D1	NIC1 Imaging F110M	TOO	1
D1	NIC2 Imaging F165M NIC2 Imaging F160W NIC2 Imaging F187W NIC1 Imaging F110M		6 (3x2)
D1	NIC2 Imaging F165M NIC2 Imaging F160W NIC2 Imaging F187W NIC1 Imaging F110M	TOO	3
D1	NIC1 Imaging F145M		6 (2x3)
D1	NIC1 Imaging F145M	TOO	4 (2x2)
D2	NIC1 Imaging F110M		1
D2	NIC1 Imaging F110M	TOO	1
D2	NIC2 Imaging F165M NIC2 Imaging F160W NIC2 Imaging F187W NIC1 Imaging F110M		6 (3x2)
D2	NIC2 Imaging F165M NIC2 Imaging F160W NIC2 Imaging F187W NIC1 Imaging F110M	TOO	3

Target	Config Mode and Spectral Elements	Flags	Orbits
D2	NIC1 Imaging F145M		6 (2x3)
D2	NIC1 Imaging F145M	TOO	6 (2x3)
D3	NIC1 Imaging F110M		1
D3	NIC1 Imaging F110M	TOO	1
D3	NIC2 Imaging F165M		6 (3x2)
	NIC2 Imaging F160W		
	NIC2 Imaging F187W		
	NIC1 Imaging F110M		
D3	NIC2 Imaging F165M	TOO	3
	NIC2 Imaging F160W		
	NIC2 Imaging F187W		
	NIC1 Imaging F110M		
D3	NIC1 Imaging F145M		8 (2x4)
D3	NIC1 Imaging F145M	TOO	6 (2x3)
D4	NIC1 Imaging F110M		1
D4	NIC1 Imaging F110M	TOO	1
D4	NIC2 Imaging F165M		3
	NIC2 Imaging F160W		
	NIC2 Imaging F187W		
	NIC1 Imaging F110M		
D4	NIC2 Imaging F165M	TOO	3
	NIC2 Imaging F160W		
	NIC2 Imaging F187W		
	NIC1 Imaging F110M		
D4	NIC1 Imaging F145M		6 (2x3)
D4	NIC1 Imaging F145M	TOO	4 (2x2)

Total prime orbits: 87

■ Scientific Justification

By combining HST near-IR observations with the CFHT Supernova Legacy Survey (SNLS) we can make important progress on one of the key cosmology goals of this decade: the detailed, accurate measurement of the universe's expansion history to study the dark energy. The primary tool currently in use for this measurement is the type Ia supernova (SN Ia) luminosity distance, and the unprecedented SNLS photometric and spectroscopic dataset of ~500 SNe Ia is likely to be the most complete study from z = 0.3 to 0.9 for years to come. However, the SNLS statistical uncertainties are already so small that it is clear the dominant uncertainties for this five-year project will be systematic. While some systematics like photometric calibration can and will be improved, the single most important inherent systematic is due to the host-galaxy-dust extinction correction. It is thus crucial to reduce this systematic uncertainty, if the full potential strength of this cosmological measurement is to be realized.

We propose here to address this dominant systematic, due to extinction, by constructing the first I-band Hubble diagram out $z \sim 0.9$, using strategic NICMOS observations of ~30 SNe Ia from the SNLS.

SNLS: A Comprehensive SN Ia Dataset to Measure Dark Energy

Cycle 16 will coincide with the final year of the very successful five-year SNLS program. A major investment of telescope time on CFHT (202 nights over 5 years with spectroscopic follow-up by VLT, Keck and Gemini) is providing high-quality multicolor $griz$ data. As the name "Legacy" implies, the SN data set will be the best available for many years to come, being a large sample with broad wavelength coverage, comprehensive lightcurve sampling and spectroscopic data. The first-year results from the project (Figure 1a, Astier et al. 2006) combined with measurements of the baryon acoustic oscillations (Eisenstein et al. 2005) and the cosmic microwave background (Spergel et al. 2006) yields a statistical uncertainty of ± 0.09 for w, the equation of state parameter, assuming flat cosmology. The results from the ESSENCE collaboration (Wood-Vasey et al. 2007), released recently, are consistent with this. From Monte Carlo studies of the effects from different sources of systematic errors they concluded that the main contribution, ± 0.08, originates from host galaxy extinction corrections.

SNLS is designed to provide as broad a wavelength coverage as possible from the ground. The $griz$ CFHT data provides useful *rest-frame* B measurements for SNe to $z \sim 0.9$ (Figure 2), V to $z \sim 0.6$, R to $z \sim 0.5$ and I to $z \sim 0.2$. Providing multi-color data for the higher redshift SNe involves observations in the near-IR. Out to $z \sim 0.5$ these NIR measurements are being made from the ground – albeit with great effort on the best nights — as an extension to the SNLS using the PANIC imager on Magellan. However the higher redshift SNe are fainter and require observations at longer wavelengths where the ground-based sky background is bright. Hence for SNe at $z > 0.5$ restframe I-band observations are only feasible from space. This year is the last opportunity to enhance SNLS data with infrared data from NICMOS.

Extending the SNLS Science Reach

To take the full advantage of the statistical power of the SNLS data and reduce the key systematic error we propose to extend the rest-frame I-band Hubble diagram out to $z \sim 0.9$. We will accomplish this with NICMOS F110M, F145M, F160W, F165M and F187W photometry of SNLS SNe that will be continuously discovered in the redshift range 0.4–0.9 during the final year of the SNLS project. These filter/redshift combinations correspond to restframe I and J where dust extinction is significantly smaller than in the B-band. Further, smaller K-correction uncertainties will also be achieved as a result of the SN Ia spectrum being relatively featureless at long wavelengths around peak brightness.

Separately and in combination with the Carnegie Supernova Project (hereafter CSP; CoI on this HST proposal: W. Freedman) that covers the restframe I-band at $z < 0.1$ as well as the sample of SNLS SNe out to $z \sim 0.5$ observed using the Magellan Telescope, these data will allow construction of the first high-z I-band Hubble diagram over the entire redshift range of the SNLS. (Our lowest redshift data will overlap with the CSP redshifts, making it possible to tie together the two programs consistently.) By carrying the I-band Hubble diagram out to $z = 0.9$, the I-band measurement of w improves by a factor of 25–40%, since a broad redshift baseline is particularly important for systematics-limited measurements (Linder & Huterer 2003). Perhaps even more important is that the expected systematic error due to host galaxy extinction corrections in the I-band will be a quarter of the corresponding error for the B-band, as discussed in the following section.

It is not known what fraction of the observed intrinsic dispersion of SN Ia magnitudes is due to extinction (and its correction), but there is evidence that at least some of the intrinsic dispersion would be substantially reduced by working in the restframe I band, making each of these SNe worth several of the SNe measured in the restframe B band. The proposed combined restframe-I-band Hubble diagram is thus likely to have the statistical weight of a much larger sample observed in restframe B.

Reducing sensitivity to dust extinction

A full correction for extinction for data observed in the restframe B band uses $A_B = R_B\mathrm{E}(B-V)$. (The $B - V$ color is available for SNLS out to $z \sim 0.6$.) By contrast, our proposed subsample observed in restframe I-band will be corrected for dust extinction using $A_I = R_I\mathrm{E}(B - I)$ out to $z = 0.9$. For a standard Cardelli et al. (1989) extinction law the extinction in I-band is $2\times$ smaller than in B-band. Moreover, a measurement of this extinction is a further factor of $2\times$ more accurate if a large color baseline, $B - I$, rather than $B - V$, is used to determine it. In other words, $R_I = 0.83$ is a very small multiplier on the $B - I$ uncertainty, whereas $R_B = 4.1$ is a large multiplier on the $B - V$ uncertainty. Therefore, if there are shifts in the intrinsic SN colors or in the values of $R_{B,I}$ between low- and high-z, our measurements will be significantly less sensitive to such discrepancies.

As a quantitative example, let us take the current uncertainty in intrinsic SN Ia color of $\sigma(B - V)_0 \approx 0.03$ mag (Phillips 1999). If there were a systematic change with z in this color of only half this dispersion it would produce an error in the extinction correction of $\Delta A_B \approx 0.06$ mag for a B-band Hubble diagram. For an I_{max} Hubble diagram using E($B - V$) this error would be reduced to $\Delta A_I \approx 0.03$ mag. In Figure 1b we show an example where such a systematic error of $\Delta m \sim 0.03$ would lead these experiments to incorrectly conclude that dark energy is not Λ. Fortunately with rest-frame I data we would be able to use E($B - I$) rather than E($B - V$), decreasing the systematic uncertainty in I_{max} by another $2\times$, even accounting for the less certain intrinsic $B - I$ color ($\sigma(B - I)_0 \approx 0.045$ mag (Phillips 1999)). Systematic errors due to changes in R_I would be reduced in an analogous way.

For part of our sample ($\sim 20\%$) we will obtain full restframe B- to J-band coverage, allowing a self-consistent measurement of the extinction as well as determination of R_V for each individual object with $\sim 10\%$ uncertainty based on simulations and low-z data (c.f., Krisciunas et al. 2006). This is particularly interesting since SN Ia data seem to suggest that R_V on average is lower than what is measured for the Milky Way (see for example Astier et al. 2006). The restframe J-band data will also be combined with data from CSP and the SDSS SN Ia near-IR program at $z \sim 0.2$ (CoI's on this HST proposal: C. Lidman and A. Goobar) to build a Hubble diagram up to $z \sim 0.4$. The well calibrated SNLS data set for the optical bands is particularly well suited for combining with the near-IR data to accomplish this goal.

Complementarity with other HST-SNLS program

A complementary proposal is also being submitted for a study of a smaller sample of SNLS SNe at $z \sim 0.5$, including examination of SN color evolution at late-time. If both programs are approved we will share our observations near maximum brightness that are requested in common for both programs.

Conclusion

The HST has a key opportunity to test the possibility that dark energy is not Λ by taking advantage of the ground-based SNLS project that is committing very large amounts of dedicated telescope time with wide-field instruments. We here propose a highly efficient use of NICMOS to achieve the goal of a restframe I-band Hubble diagram for the full redshift range out to $z \sim 0.9$, and thereby provide the crucial improvement in control of systematic uncertainties necessary to measure w at the best currently possible level of precision.

References

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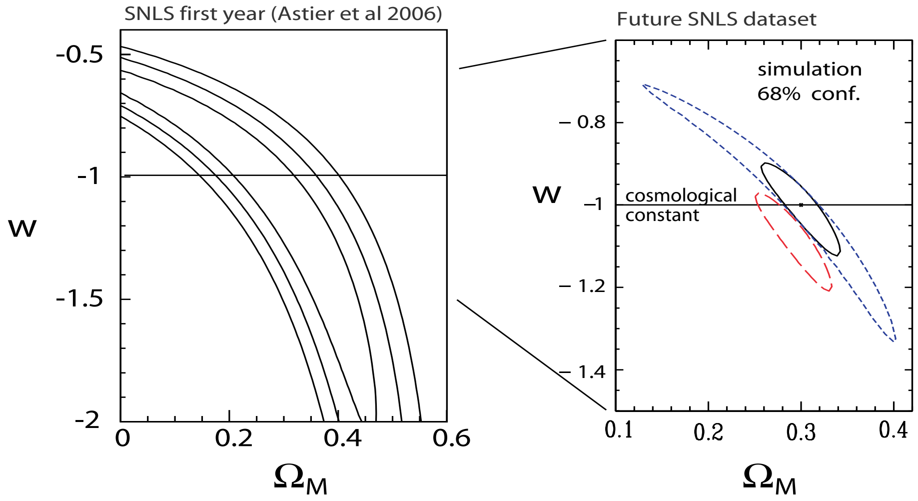

Figure 1: **(a) Left Panel:** The published SNLS first-year confidence region for Ω_M and w assuming $\Omega_M + \Omega_\Lambda = 1$ and that w is not time-varying. Confidence regions (68.3%, 95.5% and 99.7%) are shown. **(b) Right Panel:** 68% statistical confidence intervals on the dark energy equation of state possible when SNLS is completed one year from now, assuming a flat universe (from CMB measurements), and with (solid) and without (dotted) a prior on Ω_M from LSS. If a small systematic error is introduced, as in the example given in the text, the statistical confidence interval will miss the correct simulated Λ ($w = -1$) solution by 2σ (long-dash).

Description of the Observations

In this proposal, we request NIC1 F110M or F145M observations to measure the restframe I-band peak magnitude of ~30 SNe Ia in the redshift range $0.4 \lesssim z \lesssim 0.9$. On average, 60% of these SNe Ia will require two orbits in F145M, while 40% will require one orbit in F110M. For those SNe at $z \sim 0.4$ (we expect ~6 such events), we request two additional orbits using one of the F160W, F165M, or F187W filters (depending on exact redshift) on NIC2 to obtain the restframe J-band peak magnitude.

Using the ground-based data, targets will be selected soon after discovery with sufficient lead time to schedule the HST observation near the peak of the SN lightcurve (see below for details of the selection strategy). We find that $\sim 40\%$ of the selected SNe require "final" images well after the SN has faded to be used in modeling the host galaxy. These final images will be of depth equal to the SN observation. Our total request this cycle is therefore: (12 restframe-I + 5 final)×1 orbit + (18 restframe-I+8 final)×2 orbits + (6 restframe-J + 3 final)×2 orbits = 87 orbits to observe the peak and final images for 30 SNe discovered in the SNLS program.

Redshift Range: Our program will focus on SNe Ia at $0.4 \lesssim z \lesssim 0.9$, where the vast majority of the SNLS SNe Ia are found (see Figure 2 inset), to extend the restframe-I-band Hubble diagram beyond the reach of ground-based observing. We will target SNe at the low end of this redshift range to obtain both restframe J-band peak magnitudes and restframe I-band peak magnitudes.

Filter Choice: The F110M filter provides a good match to restframe I for SNe in the redshift range $0.4 < z < 0.6$ while F145M matches restframe I-band for $0.6 < z < 0.9$. Restframe J-band

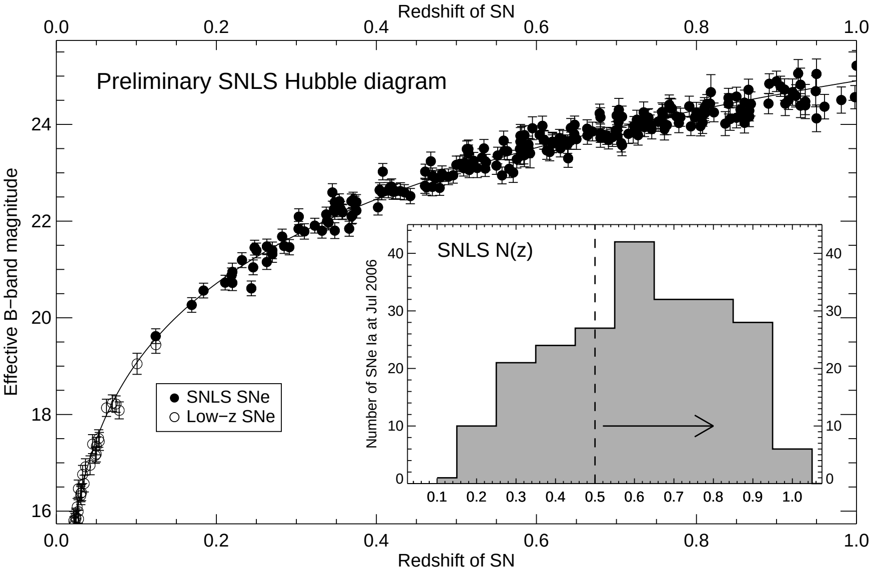

Figure 2: Preliminary B-band Hubble diagram from the first three years of SNLS data. The histogram shows the redshift distribution of the confirmed SNLS SNe Ia plotted in the Hubble diagram and useful for cosmological analysis. Cosmological constraints from this Hubble diagram will be limited by systematic uncertainties.

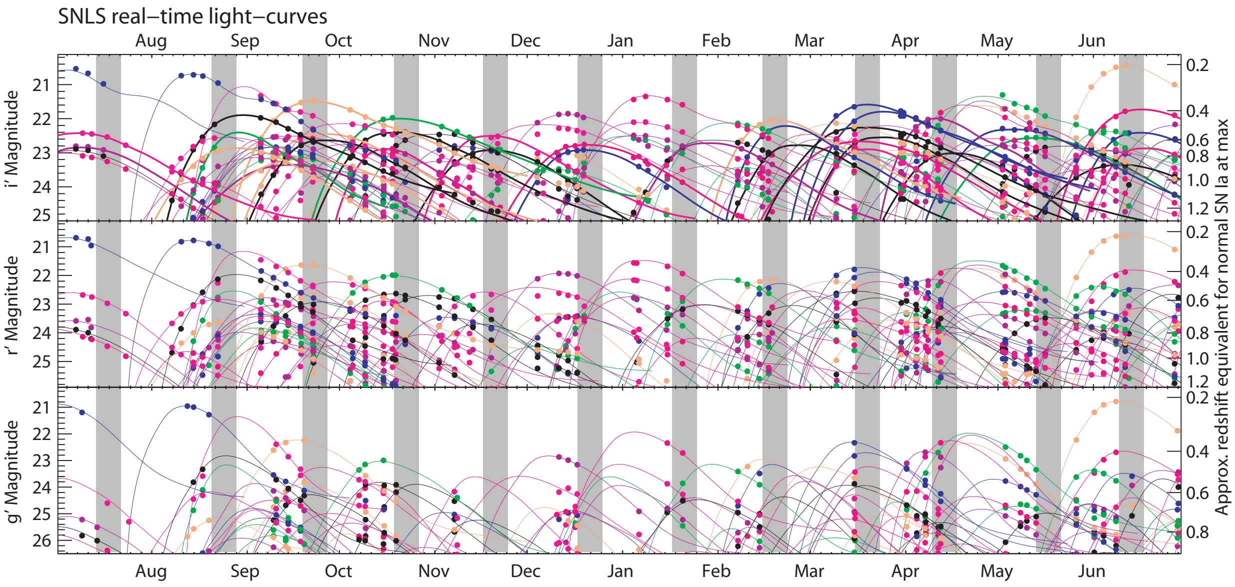

Figure 3: Actual SNLS lightcurves, showing the “rolling” nature of the search (z'-band observations not shown here). Shaded vertical regions indicate example times when HST could be pre-scheduled. The bold lightcurves in the top panel then indicate the example SNe Ia that we could follow using the observing strategy we propose here. Note that suitable SNe are always available in this pre-scheduled mode, so no fast-turnaround ToO is required.

observations will be taken using either the F165M, F160W, or F187W filter on NIC2 depending on the exact redshift and level of host galaxy contamination. Each of these filters provides a good match to restframe J and has the width required to reach a sensitivity well matched to the ground-based B-band observations in two orbits at this redshift range.

Exposure Times: Our data quality goal is to match the SNLS fitted restframe B-band peak brightness uncertainty, which is typically 0.02–0.06 mag for $0.4 < z < 0.9$. Better measurements would not lead to significantly better cosmological constraints or systematics controls since the known intrinsic brightness and color dispersion amongst SNe Ia would then dominate the error budget. Lower quality HST measurements would significantly limit the additional cosmological constraints or systematics controls achievable with this unique SN sample. SNe Ia with $0.4 < z < 0.6$ observed at maximum light in F110M will require one orbit to achieve $\sigma_I \sim$ 0.03 mag. To achieve the requisite $\sigma_I \sim$ 0.04–0.06 mag at $0.6 < z < 0.9$ in F145M will require two orbits per SN. SNe Ia with $z \sim 0.4$ observed at maximum light in F165M will require two orbits to obtain $\sigma_J \sim$ 0.05 mag, those with slightly higher redshift or with higher host contamination will require two orbits in F160W or F187W. These S/N estimates have been determined using the NICMOS ETC, as well as scaling from our Cycle 14 NIC2 photometry of high-redshift SNe.

Sample Size: Our program goal is to achieve a restframe-I-band Hubble diagram having statistical power comparable to, and systematics control exceeding, the one year SNLS B-band Hubble diagram. This is possible because correction for dust dominates the statistical (and the inherent systematic) uncertainties in the B-band Hubble diagram, while our I-band Hubble diagram will have $\sim 4\times$ smaller sensitivity to dust (see Scientific Justification). Because the SNLS program will be completed in Fall 2008, this HST cycle presents the last opportunity to conduct such a survey.

SNLS produces roughly 100 well-measured SNe Ia per year, the majority of which lie in the $0.4 < z < 0.9$ redshift range. Our NICMOS observing strategy will allow us to observe 30 of these SNe in one year in restframe I-band. As the statistical weight of each of our SNe will be substantially greater than that of each point on the SNLS B-band Hubble diagram due to the decreased dust sensitivity, the overall statistical weight of our ground+space restframe I-band Hubble diagram is likely to be at least as strong or stronger than that of a full year of SNLS restframe B-band Hubble diagram. Observing fewer than 30 SNe Ia simply weakens our constraints and underutilizes the tremendous existing investment in ground-based imaging and spectroscopy of the SNLS SNe Ia.

Strategy: The SNLS program monitors four fields, each subtending a solid angle of one square degree. Each field is visible to HST (in 2-gyro mode) for more than 40 minutes per orbit for windows of at least 5 days for periods ranging from 4 to 6 months. Each month roughly 3 SNe Ia are discovered that meet our HST follow-up requirements. Based on our statistics from the previous three years of SNLS, approximately half of the SNe from SNLS are discovered and assigned a photometric redshift and typing at least 10 days before max. The SNLS has previously demonstrated that by fitting lightcurves with two epochs of data it is possible to predict SNe Ia with only an 8% contamination rate (Howell et al. 2005, Sullivan et al. 2005). With the current generation of real-time data, and host galaxy photometric redshifts, it is now possible to predict likely SNe Ia using only one epoch of $g'r'i'$ photometry with >95% success (Poznanski et al. 2006).

We would trigger a $>$2-week-advance-notice ToO for those SNe with a sufficiently early discovery date. Because we find that some ($\sim 35\%$) of SNLS SNe will be discovered 5 to 10 days before max, we would also preschedule visits in the program near the end of dark time in each field (during its prime visibility period) that can observe these SNe near lightcurve peak. A week prior to the pre-scheduled observation we will provide the exact coordinates of the SNe to be observed. The angular separation between the field center and any SN is less than one degree, allowing for the HST scheduler to simply apply a small shift as has been done for the SN programs in the past. Using both pre-scheduled orbits and $>$2-week-advance-notice ToO's allows us the opportunity to take advantage of very productive months without the risk of a large number of pre-scheduled orbits. In addition, the use of both kinds of observation allows us the flexibility to use more or less ToO's depending on the needs of the HST scheduler.

Figure 3 shows actual SNLS lightcurves of SNe from a typical year of the SNLS search. The gray bands indicate example periods when we would have scheduled HST observations and thick lightcurves indicate SNe that would have been chosen. This demonstrates that such a passive scheme allows efficient and effective observations of suitable SNe Ia during each scheduled period without the need for rapid turnaround ToO's.

The Need for HST: Our targets reach $22.0 < J < 23.2$ and $22.6 < H < 23.5$ at maximum light. As stated earlier, ground-based telescopes can reach the brighter end of this range at the requisite S/N with exposures of several hours under excellent conditions. However, beyond z~0.5 such observations become heroic, whereas our program requires that good measurements be obtained for many SNe Ia on a regular basis. 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 homogeneous 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. In these cases the full potential of a substantial number of SNe Ia is lost after an already significant investment to find them and obtain their spectra. (We have recently collaborated on a pilot project to test adaptive optics SN photometry in the near-IR at the Keck observatory. The observing restrictions would be prohibitive for a program such as this: in particular, even with laser-guide-star AO a very nearby PSF reference star is necessary to provide the aperture correction for precision photometry.)

Special Requirements

As described in the observing strategy, we will arrange with the HST schedulers to preschedule orbits during lunation periods (right around 1st quarter moon) throughout this observing Cycle (see the examples in Figure 3). 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 previous Cycles for the observation of high-z SNe Ia. We also request that a fraction of orbits be allocated to allow for 18 $>$2-week-advance-notice ToO's to observe SNe that we expect to discover more than ten days before peak magnitude as has been done in our previous programs. Because of the prescheduled orbits, we also have some flexibility to use more or fewer of these $>$2-week-advance-notice ToO's depending on the needs of the HST scheduler.

■ Coordinated Observations

SNLS is discovering SNe in a "rolling search" mode, in which the same fields are revisited every few nights (with observations in multiple filters) over several months. This means that any SN 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. As each 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. Spectroscopy is also later obtained for more precise redshift and typing. The SNe that will be used for this current proposal will come from the SNLS since most of the proposers are either affiliate or members of the SNLS team.

There are several advantages for this proposal from this mode of discovery and follow-up. First, there will be a continuous rate of SN discoveries — approximately 100 per year from the SNLS search. This allows just a few orbits to be scheduled per month for this HST program (to follow $\sim$2–4 SNe), providing more HST scheduling flexibility. This program is powerful, yet robust to weather and as simple an HST SN program as is possible.

■ Justify Duplications

None - these are all unique observations of transient events.