Hubble Space Telescope

Cycle 12 GO Proposal

Exploration of the SN Ia Hubble Diagram at z > 1.2

Principal Investigator: Dr. Saul Perlmutter
Institution: Lawrence Berkeley National Laboratory, USA/CA
Electronic Mail: saul@lbl.gov

Scientific Category: COSMOLOGY
Scientific Keywords: COSMOLOGICAL PARAMETERS AND DISTANCE SCALE, SUPERNOVAE
Instruments: NICMOS
Proprietary Period: 0
Cycle 12 primary orbits: 89
Cycle 13 primary orbits: 48
Total primary orbits: 137

Abstract

In the spirit of a Treasury proposal, we propose to organize, and deliver to the astronomical community, non-proprietary follow-up observations of ~ 10 Type Ia supernovae at $1<z<1.7$ that are expected to be discovered in a Cycle 12 Treasury proposal. Together with the currently available sample, this would provide a Hubble diagram with over 20 SNe Ia in this redshift range, where it is possible to test the current cosmological model in the epoch of deceleration. This size sample will show trends and outliers, and permit a more rigorous treatment of the asymmetric amplification distribution from gravitational lensing. This is a key redshift range for the studies of dark energy that will be done with future surveys (and future instruments now being designed); this dataset will lay the ground-work for these studies by establishing the simple properties of the supernovae in this redshift range, including rates, magnitudes, colors, and timescales. If considered more appropriate, this proposal could be treated as a part of a Treasury or Director's Discretionary program, since the data would be available to everybody immediately, and we would welcome others who would want to work with us on it.

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. Isobel Hook	University of Oxford	UK
CoI	Dr. Andrew Fruchter	Space Telescope Science Institute	USA/MD
CoI*	Dr. Reynald Pain	Laboratoire de Physique Nucleaire des Hautes Energies	France
CoI	Prof. Robert A. Knop Jr.	Vanderbilt University	USA/TN
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. Valmiki Prasad	Lawrence Berkeley National Laboratory	USA/CA
CoI	Dr. Brian C. Lee	Lawrence Berkeley National Laboratory	USA/CA
CoI	Dr. Lifan Wang	Lawrence Berkeley National Laboratory	USA/CA
CoI	Prof. Shane Burns	Colorado College	USA/CO
CoI*	Dr. Christopher Lidman	European Southern Observatory - Chile	Chile
CoI	Dr. Susana Deustua	American Astronomical Society	USA/DC

Number of investigators: 15

* ESA investigators: 3

Observing Summary:

Target	RA	DEC	V	Config/Mode/SEs	Flags	Orbits
SN01	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W		7
SN02	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W		11
SN03	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W		11
SN04	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W		11
SN05	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W		10
SN06	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W		16
SN07	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W		16
SN08	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W		13
SN09	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W		21

Target	RA	DEC	V	Config/Mode/SEs	Flags	Orbits
SN10	14 17 54.0	+52 30 31.0	26.0	NIC1/Imaging/F110W, F160W	DUP	21
				Total orbit request:		137

■ Scientific Justification

[ALG comments: We might mention that one reason we that we think we have something special to offer is the possible synergy between this program and SNLS]

Introduction

The accelerating expansion of the universe is one of the more 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, Rei98), the evidence has grown even stronger: complementary CMB measurements have indicated that the Universe has zero curvature (Sie03), 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 (Perc02).

The SN Hubble diagram remains the only direct approach currently in use to study acceleration. There are ongoing studies of the details 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,Rei98,Sul03), any extinction by intergalactic gray dust (Pra03), gravitational-lensing (de)amplification of SN magnitudes (Per99), discovery selection effects (Per99,Rei98), K-correction systematics (Nug02), and population drifts in the SN environment (Sul03).

With these advances in hand, it is now time to pursue the cause of the acceleration — the "dark energy" — be it a simple "energy of the vacuum" (Einstein's cosmological constant, Λ) or a general dynamical scalar field (as is assumed responsible for inflation). Although extremely challenging, we can in fact address this scientific question in several, ordered steps: large projects are just now starting which will test the hypothesis that the expansion is *consistent with* Λ, which is characterized by a constant equation of state ratio $w \equiv p/\rho = -1$. Later projects will tackle the still more difficult goal of detecting changes in w indicative of scalar field models. (The satellite experiment, *SNAP* has been proposed for this work.)

The separate proposal to study SNe Ia at $z \sim 0.5$ submitted by our group for Cycle 12 is aimed at the first key step, testing Λ. However, since there is a Cycle 12 Treasury proposal from Faber et al. that includes a wide-area Groth-field search for SNe at $1 < z < 1.7$, we are also submitting this non-proprietary proposal since there are not many opportunities available to do the exploratory work at these higher redshifts that will lay the necessary groundwork for future steps in the study of dark energy. If the "Tier 3" SN search of the Fabar et al. proposal is approved, that effort and the follow-up of the resulting supernovae represents a total level of investment of HST resources well beyond what we would propose for a regular GO proposal, especially as an addition to our $z \sim 0.5$ proposal. We have therefore designed and will now describe a non-proprietary program in the spirit of a Treasury program to economically follow up each of the supernovae: we would propose to organize this follow-up and obtain the data *for the astronomical community*. All the data would be available to everybody immediately, and we would welcome any others who would want to work with us on this data. The goal would be to treat this follow-up work as a service to the community, and deliver the "standard-ized candle" data that will be important for the community to obtain for these supernovae. **If it would be considered more appropriate, we would be happy**

to run this follow-up as part of a Treasury or Director's Discretionary program.

We have discussed this proposal with Riess, et al., who are also proposing to follow these same supernovae, and both teams recognize the advantages of comparing several approaches to the SN selection and follow-up strategy. The two teams are therefore willing to each observe a fraction of the SNe Ia discovered in Cycle 12, yielding the "right of first refusal" to the other team based on a prearrangement of preferred fields (or any other system the TAC deems appropriate). This will allow a reduction in the telescope allocation needed to achieve fully independent results from the two teams' approaches, as has been so valuable previously. If we share in the allocation for following SNe Ia found by HST, we would also pool our efforts in searching for the supernovae, so that every supernova that could be found will be found (and followed), taking advantage of techniques of both groups.

Simple Scientific Goals

If $\sim$10 new SNe Ia were added to the sample at $1 < z < 1.7$, it would almost triple the number of HST-discovered SNe available for studies in this redshift range. In all, it would become possible to populate the Hubble diagram in this redshift range with over 20 SNe Ia, after adding ~ 5 more ground-based discoveries at $1 < z < 1.3$ that have been followed up with HST. This sample size would allow a more rigorous study of the universe's expansion during a time when it is expected to be decelerating, since the mass density should be dominant over the dark energy. While a half dozen or so SNe provide a suggestive result, a score of SNe makes it possible to begin to look for trends and outliers. (In fact this first, real Hubble diagram extending well into the "epoch of deceleration" is likely to be included in the textbooks as part of the most complete record to date of the history of the expansion of the universe.)

At redshifts significantly greater than $z = 1$ the hunt for trends and outliers is more than an academic exploration. Although the question of gray dust has been well answered by recent Chandra measurements(Pae03), evolution in the properties of SNe Ia is still a much debated question. If $z \sim 0.5$ SNe Ia are fainter due to evolution rather than an accelerating expansion, they should continue to get fainter at even higher redshifts. Since the dark energy cosmology predicts that SNe Ia will be brighter than for an open $\Lambda = 0$ cosmology, it is possible to test the hypothesis of open, $\Lambda = 0$ with evolution versus that of dark energy. With dust being less of a concern, this test of evolution is more powerful than ever because the possibility of a dust/evolution conspiracy has become remote. In addition to this evolution test, we expect to see an asymmetric distribution of residuals from the Hubble line due to the frequent de-amplification, and rarer amplification, of the supernovae's brightnesses by the gravitational lensing of intervening mass density fluctuations (especially amplification by galaxy clusters or deamplification by their absence). This residual distribution will be important to compare with the evidence for overdense and underdense lines of sight to the supernovae — witness the many papers which have tried to understand the lensing of SN 1997ff (Mor01,Ben02). In this way, we can begin to test models of mass distribution and power spectrum in a unique way.

The SN Ia evidence for the acceleration of the universe's expansion can be characterized as resting on the observation that a set of SNe Ia around $z \sim 0.5$ appear to be fainter than would be expected in an empty universe, a universe with no mass and no cosmological constant. It is therefore of obvious interest to see the epoch even further back in time when the SNe should appear to be brighter than expected in an empty universe. The proposed dataset, after correcting for the statistical effects of the gravitational lensing (de)amplifications will provide a much more solid basis for this simple "sanity check" for our cosmological model.

Setting the Stage for Future Studies

The proposed data set of supernova magnitudes should also be understood as a pilot sample to open up many years of future studies. Supernovae at these redshifts are extremely difficult to study even with the current HST instrumentation, so we do not expect to obtain the final, definitive measurements for these SNe, but rather to provide important hints as to how future studies with next-generation instruments should be designed. For example, the WFC3 will be an obvious tool for the SN work in this redshift, with a much wider-field infrared detector. There will not be time for very many major surveys to be performed with this instrument – necessary starting points for any SN studies – so it will be extremely important to make every large survey count. At the most basic level, the current proposed dataset will help establish SN rates in this redshift range, not only for the SNe Ia that are being followed up, but also for the comparable numbers of core-collapse SNe II and Ib/c that will be screened out from the follow up work. (Of course, this will also help current star-formation-history studies.) We will certainly test techniques to screen the non-Ia events that will need to be used in future studies.

In the longer run, we need to test and further develop approaches to constraining systematic uncertainties for supernovae at these extremely high redshifts. This is necessary if we are to reach the more demanding precision requirements of the future studies of changes in the dark-energy equation of state. While this work will ultimately require more advanced instrumentation (such as proposed for *SNAP*), the ground-work needs to be laid by establishing the simple properties of the supernovae in this redshift range, including magnitudes, colors, and timescales. It is important to note that although the dark energy is not a dominant component at these redshifts, the measurement of the Hubble diagram will need to extend through exactly this range to achieve the best sensitivity to the time variation of the equation of state. This is shown in Figure 1. If the current study-phase schedules hold, there are not many more years remaining before the design of the SNAP satellite and mission will be frozen, so this is a particularly timely study.

The Desired Dataset (and its Potential Discontents)

We wish to obtain the dataset of follow-up photometry for each SN Ia discovered that is likely to be of most use to the astronomical community, and do so in the most efficient way possible. The obvious prime interests are (1) to spend orbits primarily on the Type Ia SNe, not on screening out the other types, and (2) to obtain a "standardized candle" magnitude that is corrected for any extinction and for the lightcurve width-brightness relation. To accomplish this, there are a number of important constraints that must be taken into account:

1. In the Faber et al. proposed Tier 3 survey, the candidate supernovae will appear as bright points on the subtraction of one orbit of I band data from another 45 days later. These must be confirmed by at least one more image, because the high HST cosmic-ray rate will cause some coincidence false alarms, even with multiple cosmic-ray splits in the discovery orbit.
2. Of the confirmed supernovae, over 60% will be non-Type Ia (core-collapse) SNe. In a few cases these can be screened out using the Faber et al. proposed V band observation, since Type Ia at peak brightness show no restframe UV flux, while Type II at peak brightness are strong in the restframe

UV. However, it is important to note that after 5 restframe days past peak, the Type II SNe are indistinguishable in the restframe UV from the Type Ia (see Figure 2), so a different screening test must be used – and most of the SNe II in this type of search will be discovered beyond this lightcurve date. We therefore propose to use a combination of host galaxy color constraints (from ground-based data) to identify SN host galaxies in the appropriate redshift range with low star-formation rates (see Description of Observations).

3. To establish a "standardizable candle" magnitude, it is necessary to establish the date of maximum (or some other fiducial date) on the supernova lightcurve. This will require at least two more dates of SN observation beyond the Faber et al. proposal's discovery data points, which only sample a single date on the lightcurve. These data points also make it possible to measure the timescale of the lightcurve (parameterized either by the stretch factor, s, or Δm_{15}), and then "correct" the supernova magnitude using the lightcurve width-brightness relation.

4. At redshifts above $z = 1$, the host galaxy light is usually closely associated with the supernova light, so they cannot be reliably disentangled without subtracting off an image observed a year later, after the SN has faded. This final galaxy image requires an exposure length matched to the longest exposure taken of the supernova. Note that even with this exposure length, all signal-to-noise calculations for the supernovae will be reduced, to account for the extra noise introduced in subtracting the galaxy image. (This degradation is not quite a factor of $\sqrt{2}$, because the noise from the SN signal itself does not enter in twice.) We have included these final galaxy images in the orbit count requested in this proposal, although they will not actually be scheduled in this Cycle, but a year later.

5. The SNe that are not found in E/S0 host galaxies will require color measurements to correct for extinction. Since the color measurement is a subtraction of two magnitudes, each of which in turn is a subtraction of two images (one with and one without the SNe), the color measurement signal-to-noise is a factor of 2 below that of an isolated star with the same magnitude as the SN. Moreover, this large uncertainty gets increased by the R_V ratio of color to extinction. The color measurements therefore become the ones that require the most signal to noise, i.e. the longest exposures both for lightcurve maximum and for the host galaxy image.

6. The SNe discovered in E/S0 host galaxies are particularly important for this work. First, they are very unlikely to be anything but a Type Ia (so far, only SNe Ia have been seen in ellipticals). Second, they are unlikely to have significant extinction. Since the major source of "standardized candle" magnitude uncertainty for the SNe Ia in spiral galaxies will be the extinction correction, the SNe in E/S0's will provide the best points on the Hubble diagram, as we have demonstrated in Sul03. We take best advantage of this chance to obtain much higher precision measurements by using longer exposures for points on the elliptical-hosted SN lightcurves. This extra investment shows up quite directly as improved uncertainty on the Hubble diagram; a comparable improvement for the spiral-hosted SNe would be prohibitively expensive. The expected uncertainties will be as follows:

Follow-up Cases and Orbit Counts

z	Host Type	# of Orbits SN+gal F110W	# of Orbits SN+gal F160W	Orbit Totals	Measurement Uncertainty
1.20	spiral, etc	3+1	2+2	8	0.21 mag
1.70	spiral, etc	6+4	2+2	14	0.27 mag
1.20	E/S0	5+2	0	7	0.11 mag
1.70	E/S0	8+4	0	12	0.18 mag

Note that these uncertainty estimates do not include any dispersion that is intrinsic to SNe Ia after the lightcurve width and extinction corrections are applied. If these intrinsic dispersions are included, effective weight for a cosmology measurement for these SNe would correspond to an uncertainty between 0.15 and 0.21 mag for the E/S0-hosted SNe at redshifts between 1.2 and 1.7, and an uncertainty of between 0.22 and 0.28 mag for the spiral galaxy-hosted SNe at these same redshift extremes.

With these six constraints in mind, we have constructed an optimized follow-up observing program that targets the $\sim$10 SNe Ia expected from the Faber et al. Treasury proposal (Tier 3). The program assumes a spread of redshifts between 1.2 and 1.7; this is the redshift range that is least-well studied using ground-based supernova discoveries. An approximate fraction of SNe Ia in E/S0's is taken to be 30%, based on lower-redshift experience. The actual choice of number of orbits for a given supernova will be made depending on the estimated host-galaxy redshift and the elliptical/spiral classification (both from ground-based host color data).

Total Treasury Type Ia Follow-up Program

z Range	Follow-up Case	Orbits per Range	Cycle 12 Orbits	Cycle 13 Orbits	Total Orbits	Uncertainty (E/S0, spiral)
1.20–1.35	1 E/SO + 3 spiral	$7 + 3\times8$	20	11	31	0.11, 0.21
1.35–1.55	1 E/SO + 2 spiral	$9 + 2\times11$	18	13	31	0.15, 0.24
1.55–1.70	1 E/SO + 2 spiral	$12 + 2\times14$	24	16	40	0.18, 0.27
			62	40	102	Total Orbits

References

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(Per97) Perlmutter, S., *et al.* 1997, ApJ, 483, 565.

(Per99) Perlmutter, S., *et al.* 1999, ApJ, 517, 565.

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(Phi99) Phillips, M., *et al.* 1999, AJ, 118, 1766,

(Rie98) Riess, A. G., *et al.* 1998, AJ, 116, 1009.

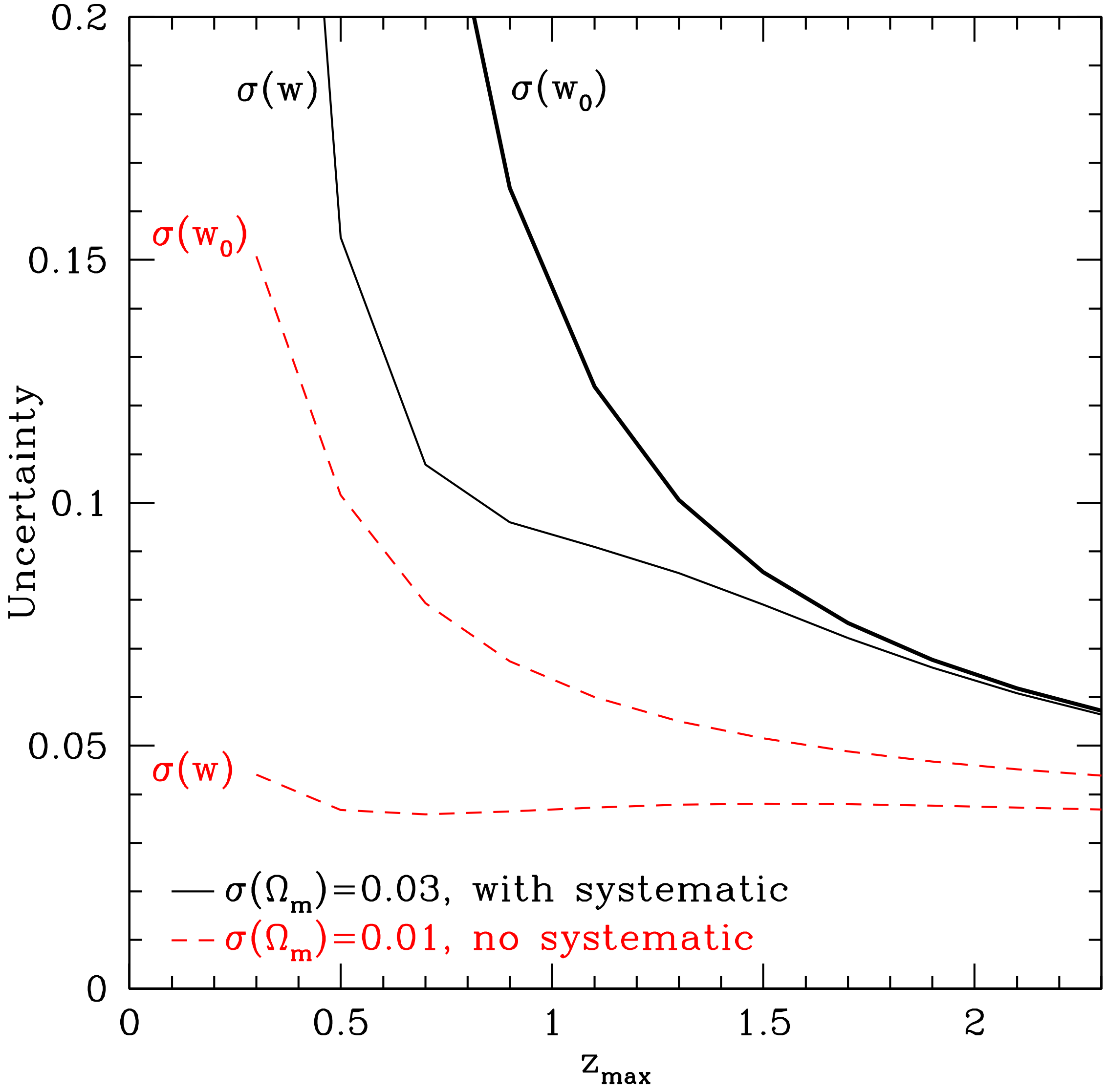

Figure 1: CAPTION FIGURE 1

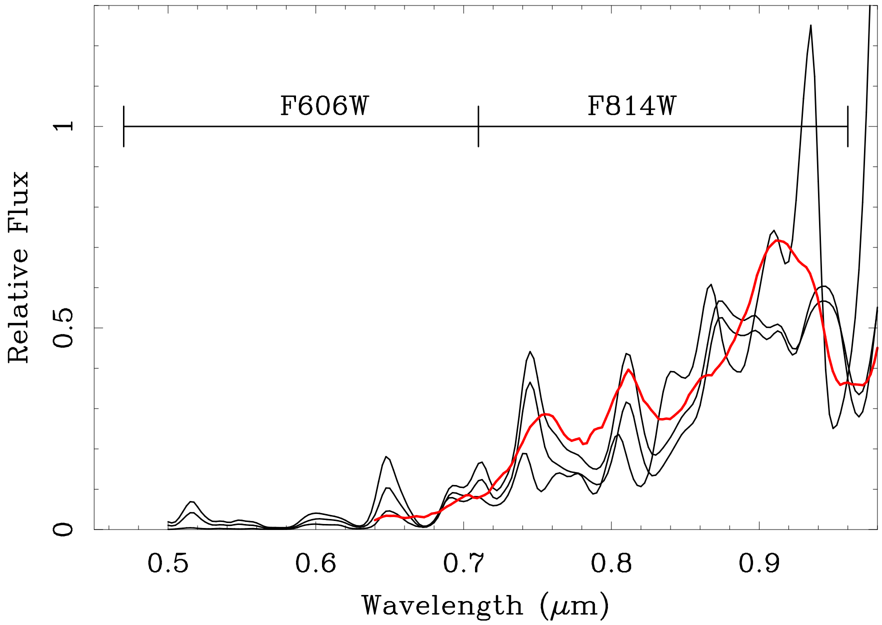

Figure 2: Comparative spectral energy distributions for redshifted Type Ia and Type II SNe. The thick red line shows the maximum-light spectrum of an SN Ia redshifted to $z = 1.56$. The series of black curves show the spectrum of an SN II at maximum, at +5 days, and and +25 days, in this case redshifted to $z = 1.50$. The wavelength ranges of the Treasury search filters are overlaid. It is apparent that the F606W-F814W colors for an SN Ia at maximum and an SN II just a few days after maximum (for Type IIp) will be similar when these objects have similar redshifts. Most of the SN II will be detected after maximum (the most probable date is 10 days after maximum). Thus, Treasury F606W images — of 1 orbit duration — will generally not detect the $z > 1.2$ SNe II, and it will be impossible to screen out the SNe II based on the signal in this band. Fortunately, as described in the text, other methods can be used to distinguish SNe Ia and SNe II.

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Description of the Observations

The Search: In coordination with the Faber et al. Treasury team we will plan the execution of the SN search in a way that optimizes the number of SNe Ia beyond the acceleration/deceleration transition epoch, $z > 1.2$, while providing discrimination against core-collapse SNe. The basic strategy is to obtain pairs of F814W images roughly 45 days apart, with a matching F606W image at the second epoch. The search gap is matched to the risetimes of $z > 1.2$ SNe Ia. (For example, at $z = 1.5$, this is an 18 day gap in the SN restframe.) The F606W image will allow only some discrimination against SNe II near maximum (see below). As the $z \sim 1.7$ redshift limit of the search is reached, the range of dates around maximum light over which an SN Ia can be detected will narrow. Thus the search guarantees that the SNe Ia of interest will be near maximum light when found — a feature we can exploit in selecting candidates and scheduling follow-up. All observations will have CR-SPLITS so that the number of spurious detections is small. As demonstrated by the $100+$ SNe Ia out to $z = 1.3$ that we have discovered, we have extensive experience with deep ACS imaging and with SN searches using data of all types. In preparation for this project, we will tune our software with the GOODS dataset, and compare our results with the reported transient discoveries.

Discrimination against core-collapse SNe: Our simulations based on current estimates of the $1 < z < 2$ star formation history (Sul02) indicate that for each SN Ia, the Treasury search will detect one Type II-P and a Type II-L SN. Some Type Ic may also be detected, but their rates and spectral properties are too poorly known for a believable simulation. The UV spectra of SNe Ia are such that for $z > 1.2$ they will not be detected in F606W. At maximum light, bright SNe II can be detected in F606W because they are much hotter — this has been advertised as an easy way to discrimate between these two types of SNe. However, SNe IIp experience a long plateau phase, during which they are only slightly less luminous than at B-band maximum. Thus, it is more probable that the F814W detections will find an SN IIp on the plateau phase (our simulations show the most probable detection is at 10 days after B-band maximum). As shown in Fig. 2, the spectrum of a Type II will look very much like that of a Type Ia, and in particular, the Type II will not be detected in F606W. Therefore, additional techniques are required to eliminate SNe II.

The CFHT SuperNova Legacy Survey (*SNLS*) will be running a continuous SN search with multiband data every other night in the Extended Groth Strip during the 5-month period when the Treasury search would be scheduled. This means that most $z < 1.2$ SNe Ia, and $z < 0.8$ core collapse SNe will have several ground-based lightcurve points which can be combined with the Treasury observations to exclude the $z < 1.2$ SN Ia candidates for follow-up by the program proposed here. The *SNLS* SNe Ia in the range $1 < z < 1.2$ would also be suitable as backup targets. Note that we are participants in *SNLS*, and thus have access to this proprietary data set for this purpose (although note that the rules of the CFHT Legacy Survey precludes this ground-based data from being made public as part of this HST proposal).

Essential additional ingredients for discriminating against core-collapse SNe are the SN redshift and the star-formation rate of the hosts. The HST/DEEP team (a collaboration closely associated with the Faber et al. Treasury proposal collaboration)will supply photometric redshifts able to discriminate $z < 0.85$ from $z > 0.85$ host galaxies. Unfortunately, such a redshift cut is insufficient for identifying the host galaxies at $z > 1.2$. (By the time of the Treasury search the DEEP team may also be able to supply some spectroscopic redshifts as well.) Our strategy is therefore to use deep colors from CFHT multi-band imaging of the Groth strip to provide further redshift selection and star-formation-rate selection. These colors can determine photometric redshifts for more than two-thirds of the SN host galaxies with $1.2 < z < 1.7$, with improved reliability when coupled with additional deep K-band imaging being obtained by members of the DEEP team. Since core-collapse SNe occur in actively star-forming galaxies — most of which will be UV-bright and therefore detectable in the optical — we should have photometric redshifts for most of the $1.2 < z < 1.7$ core-collapse SNe. In addition, CFHT colors will allow us to estimate the UV spectral slope and star-formation rates, making it possible to discriminate against actively star-forming galaxies and their attendent core-collapse SNe. We estimate that the corresponding fraction of Type Ia SNe eliminated by this same cut will be small (Cap99).

We should also note that as one of the goals is to blaze the trail for future experiments in this redshift range, knowing the rate of core-collapse SNe is important in itself. And of course, there is a great deal of interest within the astronomical community is using these SN rates to trace the evolution of the star-formation rate.

HST Follow-up Strategy: The basic information needed to put a SN Ia on a Hubble diagram are a standardized, extinction-corrected magnitude and a redshift. Most methods use the lightcurve width, Δm_{15} or stretch s, to standardize SN Ia magnitudes, as follows:

$$M_{B_{corr}} = C + B_{max} + 1.7(s-1) + R_B E(B-V)$$

(see Per97 or Phi99). We will use this standardization techniques for Treasury SNe with E/S0 hosts, for which we can assume that $E(B-V)$. This conserves much of the exposure time needed for the color measurements for SNe in spiral hosts.

Using nearby SNe Ia, we have demonstrated a method which can standardize to 0.08 mag in restframe B-band. In its fullest form this method requires a restframe B-V color 10–25 days after maximum light, an estimate of the lightcurve width (Δm_{15}, or stretch); a measurement of the peak brightness is also needed to correct for dust extinction. The full relation is

$$M_{B_{corr}} = C + \beta_{BV}(B-V)_{obs} + 1.0\Delta m_{15}......$$

We will apply this technique to Treasury SNe in spiral hosts. The principle advantage of this method is that $\beta_{BV} = 2.1$ — which means that the error in B-V is half has important is in the standard approach. Moreover, the stretch dependence is much weaker so the lightcurve shape does not need to be known as well.

By obtaining F110W photometry near maximum and about a week after maximum, along with a F110W-F160W color about 15 days after maximum, we can obtain adequate estimates of the restframe B-band peak brightness, the lightcurve width, and the post-maximum restframe B-V color. Using the fact that the Treasury search will only find $z > 1.2$ SNe Ia near maximum, we can predict the appropriate observing epochs to within a few days. Near maximum light the SN brightness changes slowly, so a small error in the date of the at-maximum observations will cause only a small error in the peak brightness. By combining the five observing epochs (reference, discovery, at-maximum, week post-maximum, and two weeks post-maximum), we will get a rough estimate of the lightcurve timescale and we will also be able to refine our estimate of where our observations fall with respect to maximum. Note that the all-important color point can be taken over a wide range of lightcurve phase, so timing errors are not important. We believe this is the most efficient possible set of observations that HST could make and still produce a SN Ia that can be plotted on a Hubble diagram. It has the important advantages that it has half the sensitivity to errors in lightcurve width and extinction as other methods (Δm_{15}, MCLS, etc). All of these data combined will also provide the last line of defense against core-collapse interlopers.

To be more quantitative, our simulations (using code that has done well in modeling our Subaru searches out to $z \sim 1.5$) indicate that the Treasury search will find SNe Ia from -12 to $+9$ days from maximum light at $z \sim 1.2$, and from -7 to $+5$ days from maximum at $z \sim 1.7$. Therefore, we would schedule our first F110W observation shortly after discovery to obtain a point near maximum light. This observation would take 1 orbit in F110W and would yield $S/N \sim$12–19, depending on redshift and exact lightcurve phase. The next observation would be scheduled two observer weeks later — 5–6 restframe days. With this two week gap we would be able to use the discovery point and our first F110W point to refine our estimate of the lightcurve phase. For SNe Ia discovered later than $+5$ days, we would take F110W and F160W observations at the second follow-up epoch, and F110W only at the third follow-up epoch. These observations would require 2 orbits each in F110W and F160W and a third F110W visit of 4 orbits. For those found prior, we would take a second F110W-only observation, and then at the third epoch with F110W and F160W. In this case the second epoch requires 2 orbits in F110W and the third epoch requires 4 orbits in F110W and 2 orbits in F160W. We will schedule half the SNe Ia into the first sequence and half into the latter sequence in order to minimize changes to the HST schedule. All SNe Ia will require matching final reference images of 4 orbits in F110W and 2 orbits in F160W in order to subtract host-galaxy light. The exposures given will give photometry with $S/N \sim 12$ or better (but, no greater than 19) at all epochs over the targeted $1.2 < z < 1.7$ redshift range. In all, each SN requires 15 orbits for full follow-up, include final reference images.

Special Requirements

This program is a ToO for follow-up of high-redshift supernovae to be discovered by a proposed Treasury program, PI-Faber. As such, it will be necessary to coordinate the scheduling of this proposal with the scheduling of the Treasury program. Once the timing of the Treasury program is established, we will consult with the HST schedulers concerning the likely plan for the execution of our program. We note that if the supernova search portion of the Treasury program is scheduled into a monolithic slot such that several candidate SNe are guarenteed in any given week, then our follow-up could be scheduled months in advance. All targets would be in the Extended Groth Strip, and thus within the ±3600 arcsec offsetting range of HST. This enables all details of the observations to be scheduled well in advance, and then a week before the necessary calendars are built we would provide the schedulers with the exact target location. Alternately, if the Treasury search is broken into small portions for scheduling reasons, we would try to interweave all the time-critical aspects of the follow-up observations from this program with those of the $z \sim 0.5$ SN Hubble Diagram HST proposal that we have submitted, which is following *SNLS* SNe Ia discovered in the same field (assuming that is approved). In this mode, we would either observe a Treasury supernova or an SNLS supernova with one orbit on NICMOS, with only a change between NIC1+F110M and NIC2+F110W required. All of the NIC2+F160W observations associated with the current proposal would take place at least three weeks later, which, as with our previous SN programs, gives the schedulers plenty of time to adjust the schedule. Therefore, these observations would be a very low impact ToO if the Treasury search is concentrated in time and/or if our SNLS $z \sim 0.5$ SN follow-up proposal is approved.

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Coordinated Observations

As described under Description of Observations, supporting photometric and/or spectroscopic redshifts of host galaxies from the *DEEP* team will be employed to aid to evaluating the probable redshift and type of Treasury SN candidates. Deep multi-band CFHT photometry will also be essential for selecting the high-redshift SN candidates that are Type Ia. These observations will be performed in advance of the Treasury search, and therefore should not constrain the HST schedule.

Equally important, we will have *SNLS* detections of many of these same SNe, including SNe Ia out to $z \sim 1.2$. This will be extremely powerful in eliminating lower redshift SNe Ia and many core-collapse SNe. We would aim to schedule the Treasury search during the 5-month period during which *SNLS* will be observing the Extended Groth Strip in a continuous SN search mode.

Justify Duplications

All targets are unique transient objects, and therefore are not duplicated by other programs.

Previous Related HST Programs

This proposal builds on our previous HST programs that have studied ~ 30 mid to high redshift SNe, providing multi-epoch lightcurves and images of host galaxies using WFPC2, NICMOS, STIS, and most recently, ACS.

GO-9705: In this program, we pushed our SNe Ia studies to the highest redshifts that are feasable 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 past - 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 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 with a publication in press (Sul03), 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. (Sul03) 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 and preliminary results were presented in Nobili, S. *et al.* 2001, AAS, 199,1611N.

DD-8088: WFPC2 and NICMOS (cycle 7) observations were obtained for SN1998eq at $z = 1.20$ (a record-breaking redshift for a spectroscopically confirmed Type Ia supernova; 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 recently obtained in December 2002, 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 are about to be submitted for publication in Knop, R., *et al.* 2003, (in preparation). A preliminary Hubble diagram was presented January 2002 AAS meeting. The cosmological results from these SNe are in close agreement with results from the first supernova results (Per99) that gave direct evidence for a cosmological constant. 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 color information provided by NICMOS (Burns, S., *et al.*, 2001,AAS,199.1610B), was only possible with HST. The improvement of the confidence limits on the cosmological parameters Ω_M and Ω_Λ are as good as we had previously predicted.

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. Also from this program, HST observations of two $z = 0.83$ 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.