■ Scientific Justification

Introduction

The accelerating expansion of the universes 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 (Xxx01), 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 (Bah01,Tur01).

The SN Hubble diagram remains the only direct approach currently in use to study acceleration, and there is ongoing close study 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,Sul02), 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, we are now ready 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.) This proposal is aimed at the first key step, testing Λ. By adding strategic HST observations for a sample of SNe Ia from a new, ambitious multi-year ground-based SN project, it will be possible to dramatically improve the efficacy of these next-generation SN Hubble diagrams for testing Λ.

Proposed Measurement: NICMOS constrains systematics

Redshift optimization studies 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 $z \sim 0.5$. 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. The photometric uncertainty for each of these SNe will contribute statistical errors that are significantly smaller than the current estimates (Phi99) of intrinsic peak magnitude dispersion, $\sigma_{\rm peak} \approx 0.15$ mag, after correcting for extinction and lightcurve timescale (e.g. stretch or Δm_{15}). The statistical error for the Λ test will be $\sqrt{N}$ smaller, i.e. a statistical uncertainty of less than 0.01 mag given a $N \sim 7200$ SNe. Since the current systematic uncertainties are much larger than this (Per99, PeSc03) the measurements from these large projects will be entirely systematics limited.

These major ground-based efforts 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 would be negligible systematics from Malmquist bias, gravitational lensing, K corrections, or gray dust (given the Pae03 limit on its density). However, there are not good constraints on the intrinsic $B-V$ color of SNe Ia or the value of the reddening ratio, $\frac{R_B \equiv A_B}{E(B-V)}$ at the levels necessary to remove the systematics arising from any small changes in their values out to $z \sim 0.5$. There are also important tests of intrinsic SN population drift that remain necessary. We here propose to constrain these systematics by observing a significant sub-sample of 30 of the $z \sim 0.5$ SNe with NICMOS F110M imaging at their lightcurve maximum.

The F110M-band measurements correspond to restframe I-band at these redshifts. When used with the full ground-based lightcurves in B and V, this HST observation will thus make it possible to obtain an $I_{\max}$ 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_x values needed to correct this extinction. Quantitatively, the current uncertainty in intrinsic SN color (after calibration for lightcurve width) is $\sigma^0_{B-V} \approx 0.03$ mag (Phi99), so the systematic uncertainty due to changes in this color of order half this disperion is $dA_B = R_B \sigma^0_{B-V}/2 \approx 0.06$ mag if a restframe B-band Hubble diagram is used, but only $dA_I = R_I \sigma^0_{B-V}/2 \approx$ 0.03 mag for restframe I-band. If the $B-I$ color is used rather than $B-V$ the systematic uncertainty in I-band drops to almost half this value, $dA_I = R_I/2.4\sigma^0_{B-I}/2 \approx 0.02$ mag, even though the intrinsic $B-I$ color is somewhat more uncertain, $\sigma^0_{B-I} \approx 0.045$ mag (Phi99). This drop in systematic uncertainty by adding the NICMOS data is the factor of $\sim$3 needed to begin to match the statistical improvement from the two major ground-based projects. Figure 2 shows that this improvement in systematic uncertainty makes possible the measurement precision of a constant w that is targeted by these ground-based projects.

The sample size for this NICMOS study is chosen so that this level of systematics control can be tested by comparing restframe $B-I$ intrinsic SN Ia colors from high- and low-redshift SNe Ia. With intrinsic color dispersions of approximately 0.05 mag in the low-redshift sample, a comparable assumed dispersion in the high-redshift sample, and an additional dispersion of 0.07 mag at high-redshift when the ground-based and NICMOS observation are combined, and, finally, after splitting the sample into 1/3 ellipticals/S0s and 2/3 later-type hosts, a sample of 30 is required. It is important to note that the low-redshift I-band data will improve during Cycle 12 with the advent of the Nearby Supernova Factory (Ald02), so better calibration, and tighter constraints from the NICMOS data, are expected.

Note that one might have considered testing the intrinsic color drift by comparing SN colors in spiral host galaxies with those in ellipticals; however, this color difference would be confused with any population drift out to $z = 0.5$ *within* these host- galaxy subsets. We therefore test for intrinsic color drift separately within each of these host-galaxy subsamples, and then separately test for intrinsic SN population drift, as follows.

Testing intrinsic SN population drift systematics

The possibility of a drift from $z = 0$ to 0.5 in the distribution of SN host galaxy environments remains as a source of systematic uncertainty that must be tested. Elliptical and S0 galaxies would be expected to follow a much different evolution history than spirals, so an important test can be made by separately studying the Hubble diagrams from the two host-galaxy-type subsamples.

Using several years worth of our HST data, we have recently published the first implementation of this test (Sul02), which showed the same cosmological results for a Hubble plot of 12 E/S0 galaxies as for a Hubble plot of 45 late-type galaxies (see Figure 5). The two subsamples agree within their ± 0.1 uncertainties for Ω_M or Ω_Λ in a flat cosmology. With the current proposal's NICMOS observations it will be possible to double the sample size for this important test. Together with the accompanying larger low-redshift sample, this test can be bring the constraint on this source of systematic uncertainty down below the 0.06 level; more of these tests will be needed to reach the final statistical goal, but these can be done with host galaxy Snapshot observations in the following HST Cycle after the supernovae fade. [[[Is there some other way we should quantify the amount of improvement in this test that we get by doubling the sample size???]]] [[LET'S DISCUSS THIS - I'M NOT SURE WHERE THE 0.06 COMES FROM OR EVEN WHAT UNITS IT HAS. ALSO, HAVE WE RULED OUT SEEING THE HOST IN OUR NICMOS IMAGES?]]

Tackling Systematics with a Complimentary Technique

We have developed a new technique for standardizing SNe Ia which is complimentary to the usual lightcurve-width method, and may be even more robust against systematics. The CMAGIC method calibrates SNe Ia magnitudes at a fixed color — rather than at maximum light — using a simple empirically-determined linear relation between magnitude and color (see Fig. 3 and Wan03). In I-band, the dependence on lightcurve width is very small, and the extinction correction is half that required at I_{max} due to correlation between SNe Ia color and extinction. In the B-band, the CMAGIC technique for every well-measured SN Ia, and has achieved standardization with a remarkably small dispersion of only 0.08 mag (Wan03). Although the available I-band test data is limited, CMAGIC in I-band seems to work about as well as I-band standardization using Δm_{15} (Phi99). Spectroscopically, SNe Ia appear more uniform after maximum light, which suggests that the CMAGIC epoch ($+12$–$+25$ days after maximum in I-band) may occur when the behavior of SNe Ia is more homogeneous. Taken together, this suggests that I-band CMAGIC is least sensitive to extinction uncertainties, should be much less sensitive to any evolution in the luminosity-width relation, and may provide better homogeneity.

The control of systematics is so central to efforts to measure whether acceleration is due to a cosmological constant, and we believe that this new method is so promising, that CMAGIC should be implemented as a check on the standard B-band standardization methods and on our own I_{max} standardization method. For the same 30 SNe observed in this program with NIC1 F110M at lightcurve peak, we propose one additional measurement with the same filter $\sim$ 17 days later. This observation is economical, and when combined with the I_{max} observations, makes for a very simple and robust HST observing program.

Conclusion

The two new ground-based supernova projects that have begun are committing very large amounts of dedicated telescope time with wide-field instruments to the goal of testing the possibility that dark energy is Λ. If they are to succeed the ground-based work must be complemented by redder photometry measurements that are only available with HST. 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 match the statistical uncertainty of which *SNLS* and *ESSENSE* are capable.

References

Aldering, G., 2001, AAS, 199.6701A
Bahcall, N. A., *et al.* 2000, ApJ, 541, 2000
Nugent, P., A. Kim, S. Perlmutter, 2002, PASP, 114, 803.
Paerels, F., *et al.* 2003 (in preparation)
Perlmutter, S., *et al.* 1999, ApJ, 517, 565.
Phillips, M., *et al.* 1999, AJ, 118, 1766,
Riess, A. G., *et al.* 1998, AJ, 116, 1009.
Sullivan, M., *et al.* 2003, submitted to MNRAS. astro-ph/0211444
Turner, M.S., *et al.* 2002, Report of the "Turner Panel", National Academies Press
Wang, L., *et al.* 2003, in preparation.

Description of the Observations

This proposal requests three 1/2-orbit NIC1 F110M exposures — near maximum light, 2-3 weeks after maximum, and a year later — for each of 30 SNe Ia in the redshift range $0.4 < z < 0.7$. 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. We have done this in previous prorams and have confirmed the efficacy of this procedure using RPS2.

Exposure Times: The at-maximum photometry point will provide the measurement of I_{max}. The NICMOS ETC 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 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 photometry will have $S/N \sim 14$ after subtraction of final reference images, which will roughly match the best-possible CMAGIC intrinsic dispersion. After the SNe Ia fade (typically a year later), a 900s NIC1 F110M image will be needed to subtract the host galaxy light from both the at-maximum and post-maximum SN+galaxy images.

Strategy: The observing strategy is coupled to coordinated ground-based programs, and is described under Coordinated Observations.

Filter Choice: The F110M filter provides a good match to restframe R and/or I over the $0.4 < z < 0.7$ redshift range of interest. 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 decreaed sensitivity to extinction which is central to our program.

The Need for HST: Our targets have $J \sim 22.1$ at maximum and $J \sim 22.8$ during the CMAGIC period; were we to attempt this program using ground-base 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

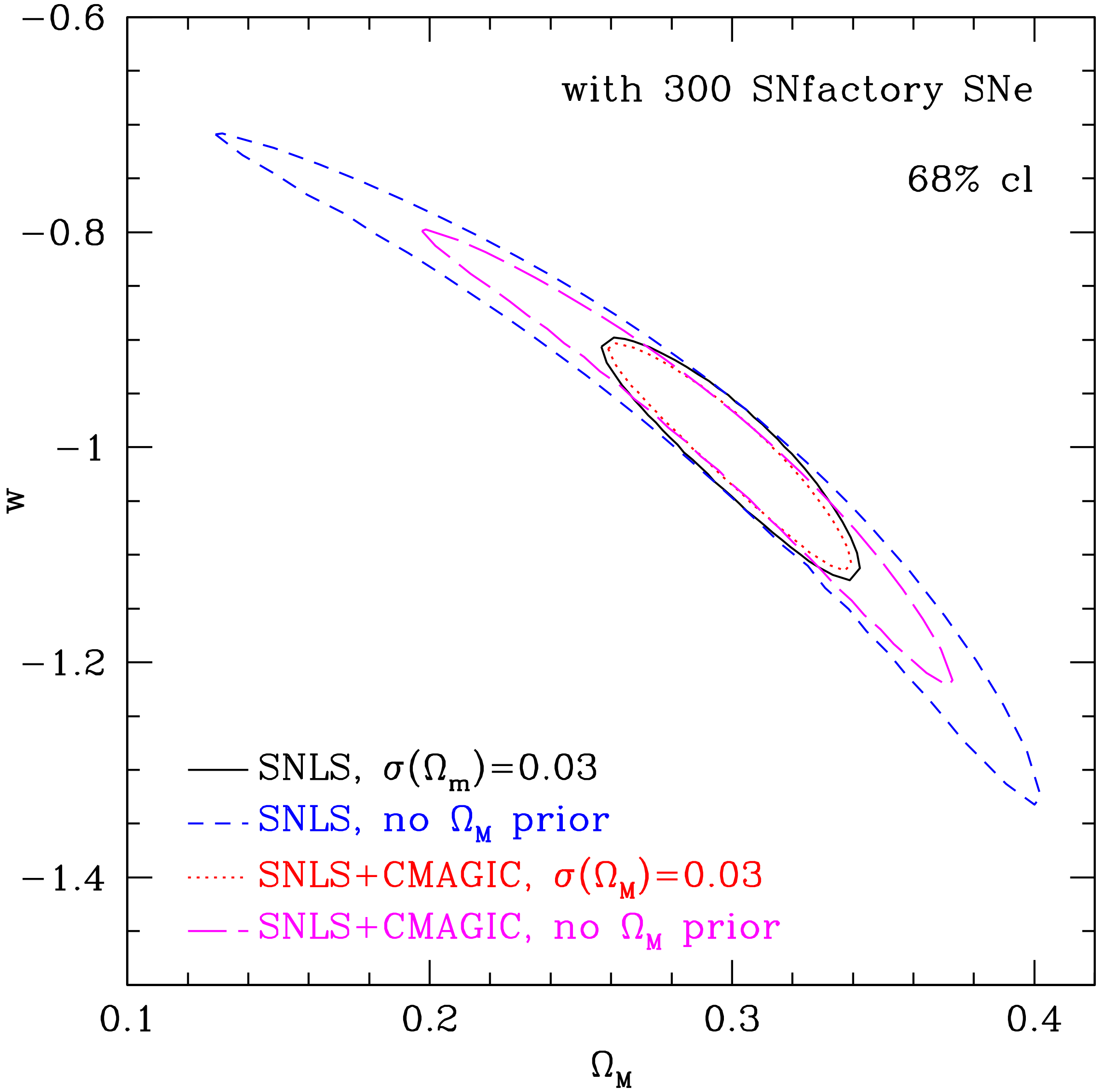

Figure 1: Caption fig 1

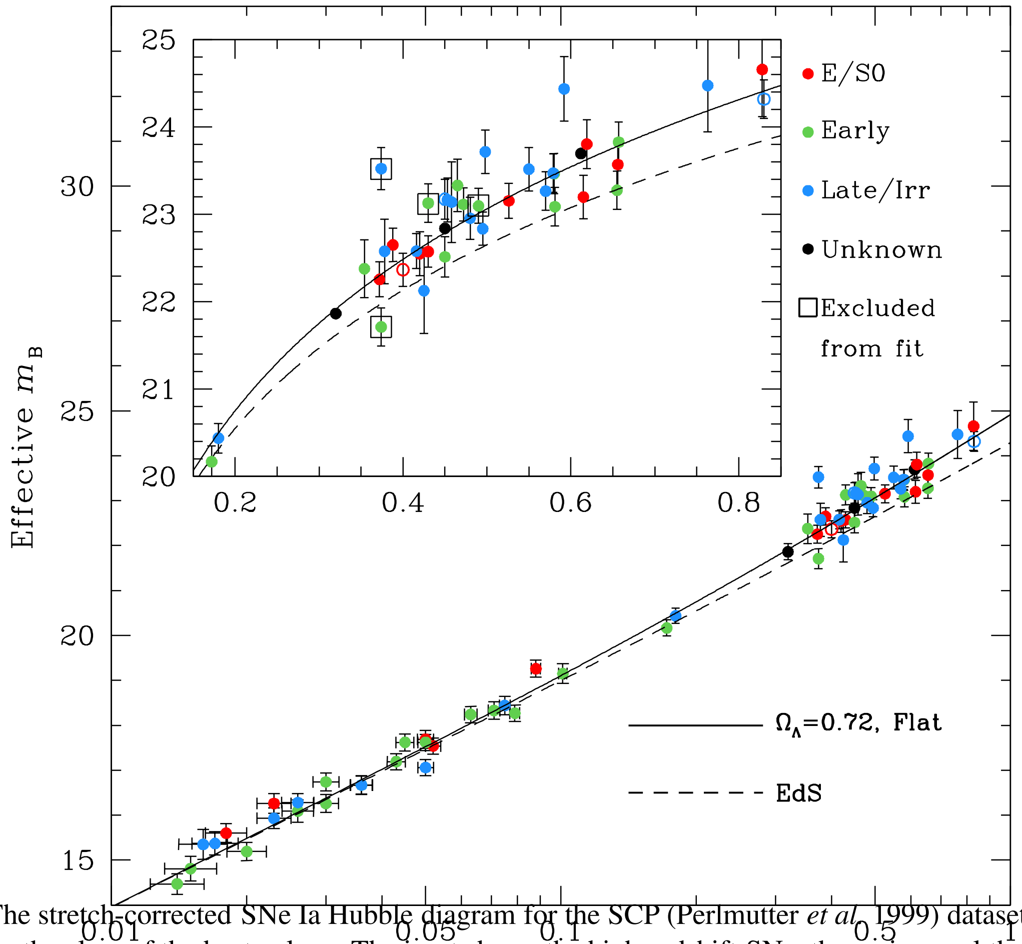

Figure 2: The stretch-corrected SNe Ia Hubble diagram for the SCP (Perlmutter *et al.* 1999) dataset plotted according to the class of the host galaxy. The inset shows the high-redshift SNe, the main panel the Hubble diagram for the entire sample. Boxed points show SNe excluded from 'fit-C' of Perlmutter 1999. Supernovae in elliptical/S0 host galaxies show significantly less scatter than those in later types.

have poor ground-based 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 total requested orbit count would then be [TYPESET TABLE OR TABS] 30 SNe at 1/2 orbit each at max = 15 orbits
30 SNe at 1/2 orbit at $+12$ to $+25$ days = 10 orbits
30 final refs at 1/2 orbit a year later = 15 orbits
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Total: 45 orbits

Note that 30 of these orbits would be scheduled this HST Cycle, and 15 the following Cycle.

Special Requirements

As described below, we will arrange with the HST schedulers to put one orbit every 10 days for a period of 5 months for each field on the HST calendar. Depending on the time of year, the we will be monitoring 2 or 3 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 too, but even simpler than, arrangements we have made with HST over the last several Cycles for the observation of high-z SNe Ia.

■ 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. 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 publicly available publicly as part of the NOAO Science Archive and we would be happy to 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 40 per year from the *SNLS* search. This allows just a couple of orbits to be scheduled per week for this HST program (to follow ~ 4 SNe per week at maximum or 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 in restframe U, B, and V bands 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 will obtain Keck and VLT spectroscopy to determine the redshift, type (Ia, II, etc.), and lightcurve phase for each SN. CFHT photometry will provide photometric redshifts to help with the selection of spectroscopic targets, and can provide photometric redshifts as back-up. The 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-signal-to-noise observations in restframe B- and V-band throughout the lightcurves of these SNe that the $B_{\max}$, $B - V$ 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 placed into the next available observing slot closest to its date of maximum light. The post-maximum observations at $+12$–$+25$ restframe days ($\sim$ 16–40 observer days) for a previously observed supernovae will be used to fill the balance of the orbit. The wide range of suitable post-maximum dates means that post-maximum observations of two SNe Ia can be taken on those occassions when there isn't a suitable SNe at maximum. This program powerful, yet robust to weather and as simple an HST SN program as possible.

In addition, we have an independent program to obtain extensive $0.34 < \lambda < 1.0$ 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 program.

Justify Duplications

None - these are all unique observations of transient events.

Previous Related HST Programs

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

GO-8585: In GO 8585 we observed six Type Ia supernovae with HST using WFPC. The supernovae were discovered in ground based searches at the CTIO 4-m, CFHT and Subaru telescopes. We obtained both U- and B-band restframe photometry (using either F814W or F850LP depending on the redshift) for each supernova for a period of 2 months. Analysis of this data will be completed when the final reference images are available, scheduled for spring 2003.

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

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

DD-8088: WFPC2 and NICMOS (cycle 7) observations were obtained for SN1998eq at $z = 1.20$ (another record-breaking redshift for a spectroscopically confirmed Type Ia supernova; Aldering, *et al.*, 1998). The preliminary photometry (shown in Fig. 1) is consistent with the previous results for Ω_M, Ω_Λ. With the final NICMO image of the galaxy without the supernova recently obtained in cycle 11, this analysis can now be completed.

GO-7850 and balance of **GO-7336** and **DD-7590**: WFPC2 and NICMOS observations were obtained for 10 Type Ia supernovae in the redshift range 0.36—0.86. These observations, including final references where necessary, are now complete, and the results are about to be submitted for publication. A preliminary Hubble diagram was presented January 2002 AAS meeting. The cosmological results from these SNe (Knop *et al.*) are in close agreement with results from the first supernova results (Perlmutter *et al.* 1999) that gave direct evidence for a cosmological constant.

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

GO-7336 and **DD-7590**: Perlmutter *et al.*, 1998, Nature, 391, 51 reported the results of our HST and ground-based imaging and Keck spectroscopic observations of SN1997ap, then the *highest redshift* ($z = 0.83$) *spectroscopically confirmed* Type Ia supernova. The HST portion is based on a total of 4 orbits.

Perlmutter *et al.*, ApJ, 1999 reports on the results from our HST and ground-based imaging and Keck spectroscopic observations of 42 type Ia supernovae with $0.18 < z < 0.86$. HST observations of two $z = 0.83$ are included in the analysis. The paper rules out a flat $\Omega_M = 1$ universe and presents very strong evidence for a positive cosmological constant.

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NOTES FOR US WHILE WRITING THIS PROPOSAL:

List of Topics for Description of Observations and Coordinated Observations

1. Describe the SNLS (and Essence?) projects well enough to make it clear that sufficiently high-signal-to-noise observations in restframe B and V band will be available throughtout the lightcurves of these SNe that the B_{max}, B-V color, date of max (in B and hence in I), and stretch will all be known to a precision that is better than needed for the known intrinsic dispersion of the methods. Also explain how the supernovae will be triggered well before maximum I-band light, and we will be able to predict the date for the NIC F110M observation far enough in advance to schedule the SN.

2. Describe the plan for a couple of SN observation slots per week for 15 weeks (if we are doing two ground-based fields) that will be filled by the appropriate SN as it comes up. Occasionally this slot may become the CMAGIC day 17 slot, if we don't have a new SN at the right time, perhaps?

3. Point out that the final "reference" orbits to image the host galaxy without the SN will not be obtained during this Cycle, but one year later.

4. Make it clear that most (or all) of SNe will likely come from the SNLS set since one of the proposers (Reynald Pain) is a leader of that project, but that the Essence data and discovery

announcements are publicly available and we would be happy to follow those SNe as appropriate.

5. Provide a signal-to-noise calculation from the NICMOS ETC showing that we achieve our desired SNR with two supernovae per orbit for the observations at lightcurve maximum, and one SN per orbit at the CMAGIC day 17, even after the final host galaxy images are subtracted off. Note that the host galaxy images cost another half-orbit per SN for 20 SNe and a full orbit per SN for the 10 that are observed with CMAGIC day 17 observations. The total requested orbit count would then be

30 SNe at 1/2 orbit each at max = 15 orbits
(OR drop this to 24 SNe .... = 12 orbit)
10 SNe at 1 orbit at day 17 = 10
20 SNe at 1/2 orbit final ref = 10
(OR drop this to 14 SNe ... = 7 orbits)
10 SNe at 1 orbit final ref = 10
— — — — — — — — — — — — — — — —
Total: 45 orbits
(OR drop this to total 39 orbits)

[State that this is 25 orbits to be scheduled this Cycle + 20 to be scheduled next Cycle.] (OR .... 22 + 17)

6. [[[NOT YET WRITTEN INTO PROPOSAL]]] Show that we have thought about the "persistent cosmic ray" problem for NICMOS, which at worst will cut out 5% of our SNe (based on our previous experience with NIC2) and at best can be cut out by PSF fitting given the better pixel sampling of NIC1.