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Hubble Space Telescope

Cycle 14 GO Proposal

Dark Energy and Cosmology with SNe in $z > 1$ Clusters

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Instruments:	
Proprietary Period:	12

	3 Gyro Mode Orbit Request		2 Gyro Mode Orbit Request	
	Prime	Parallel	Prime	Parallel
Cycle 14	181	0	181	0
Cycle 15	6	0	6	0
Total	187	0	187	0

Abstract

Abstract here

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Target Summary:

Target	RA	Dec	Magnitude

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
		Total orbit request:	0

■ Scientific Justification

The signature project of the most ambitious cosmology projects being designed and/or built this decade (LSST/LST/Panstarrs, Dark Energy Camera, JDEM/SNAP/Destiny, South Pole Telescope,...) is the detailed, accurate measurement of the universe's expansion history, from deceleration through acceleration, to look for clues of the properties and identity of dark energy. Of the small handful of known measurement techniques (SN Ia, cluster counts, S-Z, weak lensing, and baryon oscillations), only Type Ia supernovae (SNe Ia) have actually been developed to the point of routine use; and at the highest redshifts, $z \gtrsim 1$, where the transition from deceleration to acceleration can be studied, only HST observations can provide the required signal-to-noise. Even with the HST the first studies in this decelerating redshift range from both the Higher-Z Team and the Supernova Cosmology Project (Reiss et al 2004, Fadeev, Aldering et al 2004) clearly point to the limiting factor for both statistical and systematic uncertainties: extinction correction.

We propose a new approach to the measurements in this difficult decelerating redshift range: by studying "clean" supernovae discovered specifically in galaxy-cluster ellipticals, we can remove this primary statistical and systematic uncertainty — and do so with a dramatically more efficient use of HST time (see Obs. Strategy section). Moreover, the resulting data set also provides a deep z-band survey of $z \gtrsim 1$ rich clusters, allowing us to take important steps forward with several more of the above-mentioned cosmological measurement techniques. In particular, cluster counting is an extremely sensitive measure of expansion history, but also extremely sensitive to the limiting cluster masses of the survey; we here propose to measure these cluster masses with weak lensing. The South Pole Telescope and the Sunaev-Zeldovich (S-Z) Array are both being built to perform S-Z cosmological-distance measurements, but these have never been calibrated against other distance measurements; the SN Ia measurements of this proposal will provide a sample of distance-calibrated clusters to cross-compare the two techniques. Finally, this proposed data set will open an entire range of clusters studies, addressing cluster formation and [...], with comparisons between optically-selected, IR-selected, and X-ray selected subsamples, and across redshifts. This proposal addresses the questions for the new SN approach first and then those for the other dark energy techniques and cluster studies.

How problematic is the extinction correction uncertainty at $z \gtrsim 1$? The large multiplier between color excess and extinction, e.g., $R_B \sim 4$, inflates the statistical error budget (including uncertainties in intrinsic zero-extinction SN colors) so dramatically that the best HST color measurements at $z > 1$ yield extinction corrections with uncertainties greater than 0.3 [check] mag [cites]. All current results at these redshifts thus depend on the application of a strong prior on SN extinction — a large source of systematic uncertainty because the prior cannot be tested at $z > 1$. In fact this correction is currently the dominant source in both the statistical and systematic uncertainty budget. Fig.1 shows the size of this statistical effect if the errors are propagated with no extinction prior[...], and the systematic effect due to the use of a one-sided extinction prior.

How is this problem solved using SNe Ia in ellipticals? In Sullivan et al (2003) we showed that the dispersion about the Hubble diagram for elliptical-hosted SNe is half that of later-type galaxy hosts [give numbers], primarily due to the absence of dust. Thus SNe Ia in ellipticals are statistically each worth *four times* as many SNe in spirals, when making cosmological measurements

– and without the aforementioned systematics associated with extinction correction. This extra weight is even more dramatic at $z > 1$ where color measurements are weaker. Without an extinction prior, the $z > 1$ data in Riess et al. (2004) would give a dispersion of [...], compared with [...] for elliptical hosts, implying an elliptical advantage of [...] to 1.

At lower redshift the lack of significant difference between the central value of the elliptical-host sample's distance modulus at, e.g., $z = 0.5$ and that of the other host-galaxy types gave confidence that evolution of SN environment population is not affecting the shape of the Hubble diagram (because ellipticals would be expected to evolve much more monotonically with redshift than spirals). This would be key test to apply at $z \gtrsim 1$, by comparing the proposed elliptical-hosted sample to the existing GOODS-discovered sample in spirals. This test of population evolution addresses one of the biggest purely systematic uncertainties in a w–w' measurement that depends on these $z > 1$ SNe. Note that for ellipticals the age of [...] goes from [...] to [...] as the redshift varies from [...] to [...].

How is it known that the targeted $z \gtrsim 1$ cluster ellipticals are dust free? There are three clear lines of evidence that the clusters we are targeting are dust free. (1) The Spitzer 3.4 and 4.5 um measurements show.... [at what level]. (2) The x-ray studies of cluster all show x-ray emission... [at what level, and providing what level of guarantee of dust-free ellipticals]. (3) The dispersion on the cluster color-magnitude diagram is so small [quantify] (see Figure XXX?) that dust can not be contributing more than [quantify?] (unless there is a conspiracy that gives all ellipticals exactly the same amount of dust in their line of sight!).

In addition, the HST images themselves will provide...

Why is this cluster search much more efficient at finding (and studying) SNe Ia at $z >\sim 1$ than the previous HST searches in the GOODS fields? In a given ACS image, the number and total luminosity of the potential-host-galaxy ellipticals at $z \gtrsim 1$ is approximately 5 times larger in a field with a rich cluster than in an average GOODS field. This can be seen most clearly in Figure YYY, where we show.... It is therefore significantly more efficient to search in a cluster field (and of course the SNe Ia expected in a typical GOODS field would be found in addition!). Since there were [approximately five times?] more SNe Ia discovered in non-elliptical hosts than in ellipticals in the previous GOODS searches, the cluster search is only expected to yield 5 times more SN Ia in ellipticals at $z \gtrsim 1$, and an increase of approximately 2 times in SNe altogether. [Reword to make this a positive.] In terms of restframe B-band total luminosity (where SN rates have been calibrated), the expected rate is similar... This rate is also consistent with the rate seen in previous searches of clusters below $z = 1$, including one we (SCP) performed with ground-based telescopes (Perlmutter 1995, Pain 1997) and the search of archival HST data by Gal-Yam et al (2002, who rediscovered one of our cluster SNe).

In addition to discovering more SNe Ia per HST orbit, there is another set of major efficiency gains in the *follow-up* of these SNe due to the knowledge that the host is elliptical, the knowledge of the redshift of the cluster, and the higher rate per field. First, the follow-up observations need significantly less signal-to-noise and fewer bands, since the extinction correction no longer dominates the requirements, and the bands can be pre-chosen to match each cluster's known redshift. Second, with the higher discovery rate, we can pre-schedule series of observations for each cluster with a cadence guaranteed to well sample the lightcurves for every supernova discovered. For all but the highest redshift clusters this eliminates the need for expensive TOO follow-up observations! **What is the optimal redshift range, and what limits on w_0 and w' are expected?** The two key goals of the SN Ia work at these redshifts is (1) to map the expansion history back in time to the epoch in which matter dominated over dark energy and the universe was decelerating, and (2) to use this epoch to begin to constrain the time derivative of the equation-of-state of dark energy, w', together with its value today, w_0. These measurements are most sensitive beyond $z \gtrsim 1$, but not much more is gained above $z \sim 1.7$ since then the matter density completely dominate. In this 0.9 – 1.7 redshift range, however, the magnitude distribution of a standard candle is distorted by weak-lensing amplification and deamplification due to mass concentrations in the intervening path. Linder & Holz 2004 showed that this distortion can be averaged out if sufficient SNe are averaged in one redshift bin, so all the supernovae in the $z =$ 0.9 – 1.7 range will need to be binned together for a robust measurement. We have therefore chosen the richest clusters in this redshift range for this search, and with the resulting ~10 cluster SNe Ia the statistical and systematic uncertainties due to extinction can be reduced to the level that the dashed contours of Fig 1 can be "recovered."

2.0: Developing other Dark Energy Techniques using this Cluster Data.

2.1: Weak lensing estimates of cluster masses.

Volume-redshift relation for clusters.

What is our target error for the masses?

Explain why this is a good sample. It spans redshifts 0.9 to 1.4, and spans selection techniques (not just x-ray selected clusters).

What is the tie-down to clusters in the local universe?

HST is the only viable instrument for doing this at z=1!

Question: Can we use WFPC2 in parallel mode for measuring the shears 5 arcmin away from the cluster center?

In Section 9.1: Discuss observing strategy, depth, FOV, bands.

2.2: Cluster masses from X-rays.

2.3: Sunyaev-Zeldovich estimates of cluster masses and D_A

Cosmic Microwaev Background (CMB) photons passing through the hot intracluster medium of a massive galaxy cluster interact with the energetic electrons trapped in the potential well through inverse Compton scattering. On average, the CMB photons are scattered to higher energies causing a distortion in the 2.73 K blackbody spectrum through a process known as the Sunyaev-Zel'dovich Effect (SZE). The SZE signal is proportional to the integrated pressure along the line of sight ($\int n_e T_e d\ell$) while X-ray emission from the same distribution of electrons is $\int n_e^2 \Lambda_{eH} d\ell$, where Λ_{eH} is X-ray cooling function. Using SZ observations along with X-ray observations of a single galaxy cluster, one can decouple the dependence of the signals on electron density and determine the angular diameter distance (D_A) to the cluster. To date, the method has been used to determine distances to 26 different clusters. For a detailed description of the analysis, see Reese et al 2004. A fit to the sample of SZE and X-ray determined distances yields a Hubble constant $H_0 = 60 \pm 3$ km/s/Mpc where error bars represent statistical uncertainty assuming a $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ cosmology. Systematic uncertainties, which include, among many other contributions, absolute calibration, point source contamination, and substructure within the cluster, are expected to be of order 30%, clearly dominating the statistical uncertainty.

The Sunyaev-Zel'dovich Array (SZA) is one instrument in the next generation of dedicated telescopes designed for observations of galaxy clusters which can be used to perform SZ cosmological-distance measurements. However, this method has never been calibrated against other distance measurements. The SN Ia measurements described in this proposal will provide a sample of distance-calibrated high redshift galaxy clusters. The sample is being studied extensively in X-ray observations and will provide a list of high priority targets for observations with the SZA. Comparing the SZ/X-ray distance measurements to the SNe distance measurements, we can determine the extent of systematic uncertainties in the two methods.

3.0: Science with clusters at $z \gtrsim 1$ (Note that our present ignorance of some cluster properties does not impact upon the main science driver with SNe.)

Luminosity function and morphology-density relation
Fundamental plane (requires high-S/N spectroscopy too)
Luminosity evolution (M/L ratios) for cluster galaxies
Relation of everything to cluster mass!

4.0: Supernovae rates and star formation

The rate of supernovae in galaxy clusters will address oustanding questions about the intra-cluster medium (ICM). Specifically, the high metal abundances and the high energetics of the ICM are as-yet unexplained. The metals seen in luminous elliptical galaxies is explained by Type Ia supernovae rates and mass loss from evolving stars (which were originally enriched by Type II supernovae).

However, the mystery arises when one looks at the iron abundances in the ICM. The iron produced from Type II SNe of a Salpeter IMF do not produce enough iron, nor do Type I SNe. It has been suggested by Brighenti & Mathews 1999 that a higher rate for Type Ia supernovae can explain the ICM metal abundances as well as the "entropy floor" seen in the X-ray gas (e.g., Lloyd-Davies, Ponman & Cannon 2000).

The only observational measures of SN rates in $z \sim 1$ clusters is from the work of Gal-Yam *et al.* (2002). Searching the HST archive for repeated WFPC2 pointings of galaxy clusters, they identified 2 or 3 supernovae in 18 pointings (with overlaps of 1.3 to 4.7 square arcminutes). The derived SNe rate of $0.41^{+1.23}_{-0.39} h^2_{50}$ SNu in clusters at $z \sim 1$ argues against SNe Ia being the dominant source of iron in the ICM. However, these statistics from a mere 2 or 3 detections could clearly use improvement.

References (to be TeX'ed)

Brighenti, F. & Mathews, W.G. 1999, ApJ, 515, 542
Gal-Yam, A., Maoz, D. & Sharon, K. 2002, MNRAS, 332, 37
Lloyd-Davies, E.J., Ponman, T.J. & Cannon, D.B. 2000, MNRAS, 315, 689
Reese, E.D., Carlstrom, J.E., Joy, M., Mohr, J.J., Grego, L., and Holzapfel, W.L. 2002, ApJ, 581: 53-85.

Description of the Observations

The supernova observing strategy

The high rate of SNe Ia produced by the clusters *in addition* to the SNe Ia in the fore/background field galaxies makes possible an elegantly simple combined search-and-follow-up scheduling strategy. Generally, we observe each cluster with the ACS F850LP filter every ∼24 days for ∼8 visits, with the exact cadence depending on the cluster redshift and the exact number of visits depending on HST observing constraints for the cluster. This means that every supernova that appears in these clusters during the entire period, modulo small end effects, will have a lightcurve measured — without the need for expensive Target of Opportunity (ToO) observations. We obtain ground-based spectroscopy of the supernovae's host galaxies after the fact, for precise redshifts and confirmation of elliptical galaxy type, which also confirms the SN Ia identification. For only the three highest redshift SNe, we supplement this basic lightcurve with an additional ToO follow-up observation sequence with NIC2 F110W, to provide restframe B band lightcurve data — since the NICMOS fields are too small to be used in the pre-scheduled search. (The very lowest redshift clusters are observed as part of the pre-scheduled cadence in ACS 814W to match the restframe B band.)

Figure YYY shows this strategy. Note that this is a dramatically more efficient approach than the previous ACS/GOODS searches, performed by both our team and the Riess et al team, for several reasons. First, there is a large net savings in the number of search-plus-follow orbits necessary to study ∼10 SNe Ia; the previous method required ∼35% more orbits. Second, the number of required ToO's is reduced from 10 to 3, in itself equivalent to many orbits of observing time. Third, the resulting data has much smaller statistical uncertainties, since the large contribution from extinction correction is removed, making each of these SNe worth four SNe not found in ellipticals. Fourth, there is an additional population of useful SNe that have their lightcurves obtained, which previously could not be followed given the limited number of ToO's.

This observing strategy is also considerably simpler to schedule than the previous GOODS searches. The observing simulations show that there is flexibility in the exact choice of repetition dates; the cluster observations can be at any orient (unlike the contiguous GOODS tiles); there are clusters on the target list observable at different times of the year, and they do not need to be observed in the same cadence like the GOODS tiles, so the observing load is spread.

The observing requirements for this program are based on our experience with ACS and NICMOS measurements of supernovae in precisely this redshift range (with even a few in ellipticals), so we have direct tests of our exposure time, filter, and cadence requirements. For the bulk of the target clusters, between $z = 1.1$ and 1.4, we require a single ACS orbit with the 850LP filter every 24 observer days (i.e., ∼10.5 SN-restframe days) over the lightcurve. After propagating errors for the fit of the lightcurve timescale (used to calibrate the peak magnitude), this yields a SN Hubble-diagram point with uncertainty below the ∼0.15 mag intrinsic SN Ia uncertainty (in fact, 90 % of the SNe will have distance modulus uncertainties below 0.10 mag). At redshift smaller than 1.1 one can afford to increase the cadence to 28 observer days and still meet the criterion that 95 % of the SNe observed will have an uncertainty in the distance modulus of less than 0.15 mag. Correspondingly, for redshifts $z > 1.4$ we use choose a shorter cadence of 20 days to compensate for the increase of the photometric errors. The fluxes/magnitudes, cadences and error bars shown in Figure YYY demonstrate the range that are expected for this program.

[CHECK ALL THE NUMBERS IN THIS PARAGRAPH – they are currently estimates.]

For an elliptical host galaxy, with its symmetric smooth morphology, the images before and/or after the SN lightcurve generally provide a fit of the host galaxy light that gets subtracted from each image of the SN-plus-galaxy. However, for ∼2 of the targeted ∼10 SNe Ia we expect the SN to be so close to the core of a bright host that we will need an additional final image the following year, with a 3-orbit depth so as not to degrade the signal-to-noise after subtraction. More than offsetting this requirement for 6 additional orbits is the probability of cancelling the final cadence observations for clusters that have not produced a SN in time to be followed for sufficient lightcurve points. This will happen, on average, for 15 of the 25 clusters, saving 15 orbits from the total required. (The cancellations would be more than three weeks in advance, so will not introduce scheduling complications.) The total number of orbits thus required for this program is: 12 clusters x 7 planned 1-orbit ACS visits + 13 clusters x 8 planned 1-orbit ACS visits + 3 SNe x 5 NICMOS orbits (primarily TOO) + 2 SNe x galaxy-only 2-orbit ACS visit the following year -15 final cancelled orbits = 194 orbits.

Observing requirements for the cluster science.

Strategy for Two-Gyro Observations

Special Requirements

Coordinated Observations

Justify Duplications

Previous Related HST Programs

To be updated

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

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

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

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

GO-9075: In this program, we pushed our SNe Ia studies to the highest redshifts that are feasible for a ground-based discovery and spectroscopic identification campaign. HST follow-up observations for this program started after servicing mission 3B in March 2002 and have been completed for the most part — final reference images are still to be taken. Coordinated with three large search campaigns using the Subaru 8.2 m and also with simultaneous smaller searches using the CTIO 4 m and CFHT 3.6 m, we obtained ACS/WFC and NICMOS/NIC2 photometry for multi-epoch lightcurves of eight Type Ia SNe at high redshift $(0.9 < z < 1.3)$. For two of the highest redshift SNe, ACS grism spectra were taken. Analysis of this ACS data is in progress. With the refurbished NICMOS, we obtained final reference images of the host of SN1998eq, which we had previously studied in G0-8088, and these images will allow us to complete that analysis.

GO-8585: In GO 8585 we observed six Type Ia supernovae with HST using WFPC. The supernovae were discovered in ground based searches at the CTIO 4-m, CFHT and Subaru telescopes. We obtained both U- and B-band restframe photometry (using either F814W or F850LP depending on the redshift) for each supernova for a period of 2 months. Analysis of this data is presented in the PhD thesis of J. Raux (Univ. of Paris, 2003), presented at the January 2004 AAS meeting. A publication is in progress.

GO-8313: The objective of this project, which has now been completed with the publication (Sul03) mentioned above, was to obtain snapshot unfiltered STIS images of distant galaxies of known redshift which have hosted supernovae (SNe) of Type Ia found by the SCP, 20 of which are used in the Hubble diagram of 42 type Ia SNe (Perlmutter *et al.* 1999). The internal extinction implied is small, even for late-type systems ($A_B < 0.3$), and the cosmological parameters derived from those SNe Ia hosted by (presumed) dust-free early-type galaxies are consistent with our previous determination of a non-zero Λ. The brightness scatter about the Hubble line for SNe Ia in these early-type hosts is also significantly smaller than for the SNe Ia in late-type galaxies. This result was based on HST STIS "snapshot" images and Keck spectroscopy of SNe spanning the range $0.3 < z < 0.8$.

GO-8346: We had the unique opportunity of following up SN2000fr, which had been discovered *14 days prior* to maximum light in its restframe. Because this supernova at z=0.54 was discovered so early we were able to obtain excellent light curves from HST in F555W, F675W and F814W spanning the period from one week prior to maximum light to 6 weeks after Several spectra of the supernova were taken at VLT and Keck along with NIR photometry at VLT.

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

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

GO-7336 and **DD-7590**: Perlmutter *et al.*, 1998, Nature, 391, 51 reported the results of our HST and ground-based imaging and Keck spectroscopic observations of SN1997ap. The HST portion is based on a total of 4 orbits. Also from this program, HST observations of two $z = 0.83$ SNe Ia are included in the analysis in Per99 which reports on the results from our HST and ground-based imaging and Keck spectroscopic observations of 42 type Ia supernovae with $0.18 < z < 0.86$. The paper rules out a flat $\Omega_M = 1$ universe and presents very strong evidence for a positive cosmological constant.