1 Scientific Justification

The Hubble diagram for Type Ia supernovae (SNe Ia), extended to redshifts well beyond $z = 0.25$ (Fig. 1), provides perhaps the most direct current measurement of the expansion history of the universe—and hence the most direct evidence for an accelerating expansion. The Supernova Cosmology Project developed an approach to this measurement (Perlmutter *et al.* 1997, 1998, 1999) that resulted in a determination, based on 42 SNe at $0.18 < z < 0.83$, of $\Omega_M = 0.28^{+0.09}_{-0.08}$ for a flat universe, and constrained the combination $0.8\,\Omega_M - 0.6\,\Omega_\Lambda$ to -0.2 ± 0.1 (Perlmutter *et al.* 1999; see also Riess *et al.* 1998). This evidence has been increasingly strengthened, both by tests and improvements of the supernova measurements and by independent, cross-cutting cosmological measurements. In particular the recent balloon-based CMB measurements (Jaffe *et al.* 2001) have strongly indicated that the geometry of the universe is flat, reinforcing this evidence for an accelerating universe by eliminating the possibility of a low-density open universe (see Fig. 2a). There are now two important directions to pursue with the SN Ia cosmology work, which we address in this proposal: (A) extending and filling in the SN Ia Hubble diagram to obtain a more complete and detailed expansion history of the universe, and (B) refining and further testing the SNe Ia as tools for cosmological measurements.

(A) Exploiting a Cosmology Tool: Filling a SN Ia Hubble Diagram to $z \sim 1.2$
We currently have the opportunity to obtain a Hubble diagram that will be of longlasting value as a record of the expansion history of the universe over the last 10 billion years. Significant improvements are now being made in the systematic uncertainties in SN measurements (see later in this proposal), and it is therefore now useful to reduce the statistical uncertainty by almost a factor of two — that is, by studying an additional ~100 SNe Ia. This is about the number that could reasonably be expected to be found and spectroscopically confirmed at $0.5 < z < 1.3$ with ground-based telescope resources over the remaining lifetime of the HST. The study of these SNe is therefore a key task to complete at as rapid a rate as is manageable, and we are therefore proposing a concerted effort in Semester 2002A to discover and study 15 SNe Ia, with the most distant to be followed with 100 HST awarded orbits. Only HST observations can provide photometric accuracy at these higher redshifts, and only the Keck can obtain the spectra that allow these HST observations to be triggered.

This Hubble diagram redshift range that we propose to populate is aimed at addressing several of the more important scientific questions of our day. First, it allows a determination of the curvature of the universe and decoupled measurements of Ω_M and Ω_Λ. While additional SNe Ia over the $z \lesssim 0.85$ range of the current datasets will improve the current statistical uncertainty by $\sqrt{N}$, additional SNe Ia beyond $z \sim 0.85$ can dramatically shorten the major-axis of the current Ω_M—Ω_Λ error ellipse (cf. Goobar & Perlmutter 1995 [GP95] and Fig. 2). After our proposed observations in semester 2002A, $\Omega_\Lambda = 0$ could be ruled out at well over 3σ. For a flat universe, Ω_M and Ω_Λ could be constrained to $\sim 6\%$. The resulting estimate of Ω_M, for *any* Ω_Λ, is still accurate to ± 0.15 in this simulation and would be a first check on the CMB measurements that indicate a flat geometry. This measurement of curvature hinges on the very-highest redshift SNe (GP95); currently, $z \sim 1.2$ is close to the highest redshift that we can confirm with spectroscopy, and these are our most time-consuming observations.

Second, the Hubble diagram out to $z \sim 1$ provides one of the only known ways to constrain the physics of the "dark energy" that apparently is accelerating the universe's expansion. The simplest measurement to characterize this dark energy is the effective equation-of-state ratio, $w \equiv p/\rho$. The current constraints on w are consistent with a very wide range of dark energy theories, including Einstein's Cosmological Constant (for which $w = -1$) (Perlmutter *et al.* 1999, Garnavich *et al.* 1998); the proposed data set, together with data now being analyzed can tighten these constraints by 40%, potentially ruling out several contending theories if the current w value holds. Recent work by Weller and Albrecht (2001) has shown that dark energy theories can be further differentiated on the Hubble diagram at $0.3 \lesssim z \lesssim 1$ by their behavior *over the range* of z. This requires better (and more) photometry measurements than previously obtained in this redshift range (with 4-m telescopes). With this proposal, all Keck SNe discovered will have the necessary photometric accuracy (either from the HST, for the higher redshifts, or from the new generation of 8-m telescopes, for $z < 0.85$) to address this interesting new science.

(B) Refining and Testing a Cosmology Tool: SNe Ia Systematic Uncertainties
Perlmutter *et al.* (1997, 1999) provide extensive discussion of possible systematics in the measurement of Ω_M, Ω_Λ; we find that uncertainties due to K-corrections, gravitational lensing amplification, and Malmquist bias, are quite small compared to the statistical error. Remaining sources of systematic uncertainty that we showed are unlikely, but possible, are SN Ia evolution and abnormal dust within, or even between, galaxies. To proceed with the SN cosmology studies, we have identified a series of refinements and tests that will "sharpen" this cosmological measurement tool, by addressing these two issues. This work seeks to take advantage of an almost unique characteristic of SNe Ia as cosmological tools: they can be studied individually by their light curves and time-varying spectra and hence calibrated individually, not simply statistically. We focus here on three of these refinements/tests:
1) A spectral-feature luminosity indicator. The spectral feature ratios of Ca II and Si II show a tight relationship with the lightcurve timescale parameter (Fig 4a) and may therefore be used as an alternative luminosity indicator (Nugent *et al.* 1995; (N95)). These spectral ratios have not yet been exploited at high-z. As described in the feasibility section, measurement of these features for a SN Ia at $z \sim 0.5$ will allow a better than 3σ detection of evolutionary effects which could sufficiently alter the SN brightness to make the current datasets consistent with a flat, $\Omega_M = 1$ universe.
2) A UV metallicity indicator. Metallicity is an important parameter governing radiative transfer in SN photospheres, and thus it is important to develop a direct measure for metallicity in a given SN Ia. Fig. 4b shows one such measure that would be possible with very deep Keck spectroscopy of a $z \sim 0.5$ SN Ia (see Feasibility).
3) Hubble diagram shape and dispersion tests. As shown in Fig. 1, the form of the Hubble diagram at high-z expected for a Λ-dominated universe would be hard to mimic by systematic effects such as intergalactic gray dust or evolution in SN Ia peak magnitudes. SNe Ia at $z > 1$ will provide a direct test for such possible systematics. A further test, made possible with a set of well-measured high-z SNe, is to check for the increased dispersion in absolute magnitude that would be expected from evolution or abnormal dust extinction.

Conclusion. By concentrating our year's effort on one large campaign (*that is, we intentionally did not request time in 2001B in order to focus on 2002A*; see Telescope Time Request), we can most effectively pursue the goal of a well-measured SNe Ia Hubble diagram at the highest redshifts. These data are crucial for addressing the questions of the cosmological parameters, the curvature, and the identity of dark energy. They also serve double duty by refining our evolution/dust checks on systematics. Having pioneered these techniques and this science, we see this large Keck/HST -led campaign as the key next step. This fundamental science is only possible with Keck.

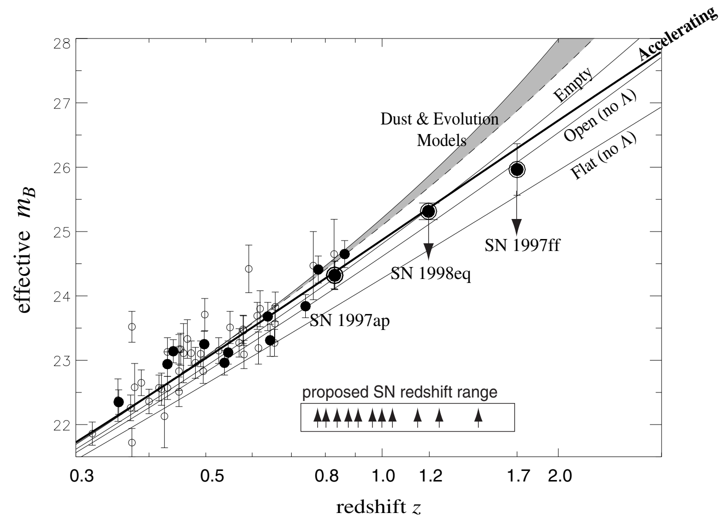

Figure 1: Open points show Hubble diagram for 42 high-z SNe (Perlmutter *et al.* 1999) along with comparable non-host-extinction-corrected points (filled circles) for our more recently discovered SNe with HST followup (Knop *et al.* 2000). The Einstein-de Sitter, "Flat (no Λ)" case $(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$ is strongly excluded by the current data. The "Open (no Λ)" case (0.28,0.00) indicates that some contribution from a cosmological constant is required for values of Ω_M favored by dynamical measurements. The magnitude difference between the best-fit "Accelerating (Λ)" world model (0.28, 0.72) and suitable ones with Ω_Λ=0 show redshift dependencies which would be very hard to mimic within the context of SNe evolution or gray dust hypotheses (the gray shaded region is an example model with uniform dust). By extending our survey beyond z=1, the *shape* of the Hubble diagram alone would become sufficient evidence to support a cosmological constant. The preliminary magnitude estimates of our highest redshift SN1998eq at $z = 1.2$ is suggestive (as is the serendipitous data for SN1997ff at $z = 1.7$), but more analysis and more SNe at this redshift (as proposed here) are necessary.

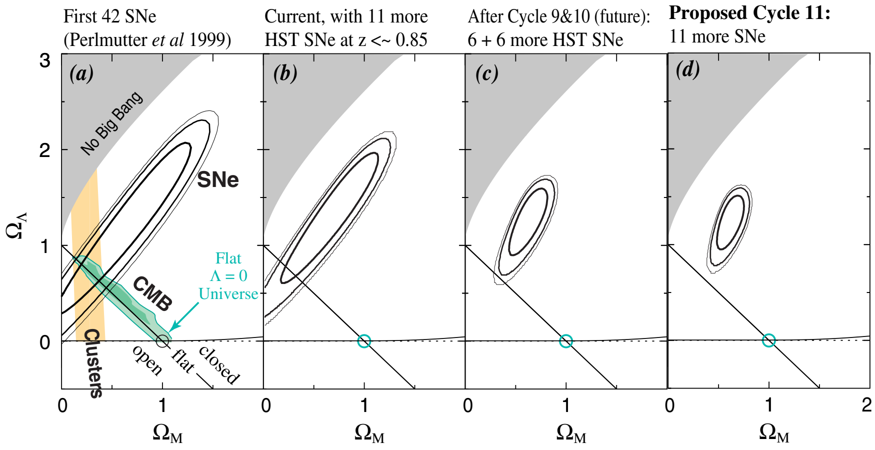

Figure 2: *(a)* 68%, 90%, and 95% confidence regions in the Ω_M—Ω_Λ plane from the 42 distant SNe Ia in Perlmutter *et al.* 1999 (including two observed with HST). These results indicate $\Omega_\Lambda > 0$, in agreement with the overlap of the recent combined CMB results (Jaffe *et al.* 2001) with the Ω_M measurements from galaxy clusters. *(b)* Results presented by Knop *et al.* (2000) for the confidence region after including our additional 11 SNe Ia which have lightcurves from WFPC and NICMOS. *(c)* Expected confidence region size after including six SNe 1a observed in Cycle 9 and an additional six (4 with $z \sim 0.85$ and 2 with $z \sim 1.2$) projected for Cycle 10, which is underway. *(d)* Now including the 11 HST SNe requested in this proposal. These simulations show that our proposed program can check the curvature of the universe found by the CMB program; we dramatize the point by showing a scenario in which the universe is *not* flat, e.g., using the central Ω_m,Ω_Λ value of panel *(a)*.

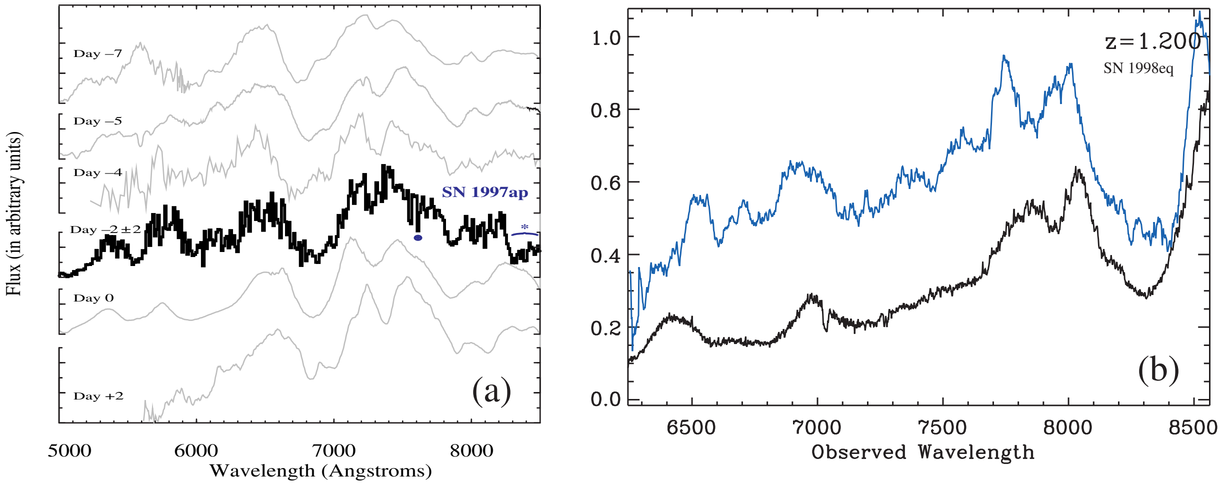

Figure 3: (a) Our Keck spectrum of SN1997ap (solid line) at $z = 0.83$ (Perlmutter *et al.*, 1998). Also shown are nearby SNe at different epochs, redshifted to match SN1997ap. The Fe lines in the (rest-frame) UV portion of the spectrum and the Ca II H&K trough around 3800 Å restframe are used for the spectral identification from LRIS of the highest-redshift SNe. (b) Spectrum of SN1998eq (upper line) at $z = 1.2$ from our recent Keck pilot study. Also shown (lower line) is the spectrum of the nearby Type Ia SN1992a at day 5 past maximum, redshifted to match SN1998eq. This demonstrates that we can obtain an identification of the supernova type, even at this very high redshift. The strong, narrow OII line from the host galaxy (which confirms the redshift) has been removed from the spectrum shown here.

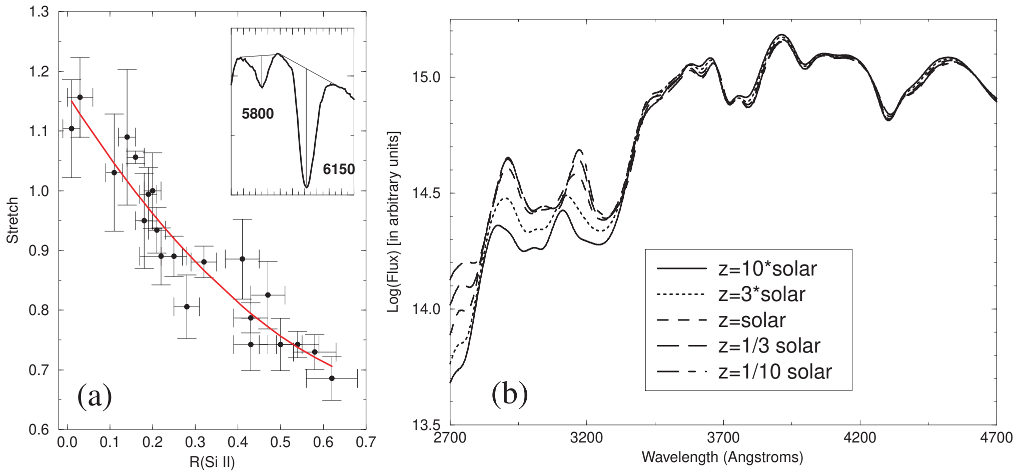

Figure 4: (a) The tight relationship between the spectroscopic ratio $\mathcal{R}$(SiII) and the lightcurve timescale stretch for well-observed low-redshift SNe Ia (see N95 for a similar $\mathcal{R}$(CaII) plot). The inset shows how this spectral ratio is measured. (b) Maximum light spectrum synthesis models of W7 (a deflegration SN Ia model by Nomoto *et al.*) with varying metallicities in the outer C+O layer. Note the change in both the strength of several restframe UV features and the wavelengths of their minima (which we propose to measure for one $z \sim 0.5$ SN Ia).

2 Progress to Date

Significant samples of well-studied SNe Ia at the higher redshifts are the key ingredients to further progress. We have now built up the foundations for this work, and have begun collecting the relevant supernovae. The foundation-work began in October 1998 with our very successful pilot study using Keck imaging and spectroscopy in order to demonstrate that SNe Ia up to $z = 1.2$ could be found and studied using existing facilities. SN 1998eq at $z = 1.200$ was the key discovery from this run, and we obtained its complete I-band and J-band light curves using HST (Aldering et al 1998, 2001). ($z = 1.2$ is still the highest-redshift for which there is spectroscopic confirmation of a Type Ia.) Since then we have successfully transferred the *searches* to smaller telescopes, such as CFHT and CTIO—and, most recently, Subaru— with wide-field imagers which give a larger $A \cdot \Omega$ product than LRIS. The Keck spectroscopy runs of 1999B, 2000A, and 2001A demonstrated that the resulting high-z SNe can be efficiently targeted and studied. The most recent, 2001A, run (the first to use the once-a-year large-batch mode proposed here for 2002A) identified 20 SNe, the largest number ever in a single run, including three confirmed beyond $z = 1$.

After the most recent supernovae (and those proposed here) fade and their lightcurves can be constructed, their data points will fill in the sparse/empty regions of the Hubble diagram beyond $z \sim 0.7$. The lower-redshift regions have now been much better measured with the data from the four semesters prior to fall 1998. Keck spectra were obtained for all four sets of discoveries while the SNe were near maximum light, and eleven of these SNe were observed by the HST with both NICMOS and WFPC. As shown in Figures 1 and 2b, the cosmological results from the eleven SNe (Knop et al. 2000, 2001)are in close agreement with results from the first supernova results (Perlmutter et al. 1999) that gave direct evidence for a cosmological constant. (A detailed discussion of the results from all previous Keck runs is presented later: We have now discovered ~ 100 SNe using these techniques, with a redshift distribution between 0.2 and 1.2, peaking at $z \sim 0.6$.)

Beyond these Hubble-diagram-cosmology presentations and publications, this year we have also been presenting and publishing results based on this project's Keck SN-redshift measurements on the study of SN Ia variations over time/redshift. Goldhaber et al. (2001) presented a statistically strong comparison of the SN Ia lightcurves over the span of redshifts extending to $z \sim 0.65$. Pain et al. (2001, submitted) studied the changing SN Ia rates over a comparable redshift range. Additional papers now in progress include a determination of the rates of SNe Ia at even higher redshifts, $z > 1$, and an analysis constraining metallicity variations and evolution from our SNe Ia spectra. NB: The previous papers from this program are discussed below.

Progress on Publications

Our most recent cosmology paper, (Perlmutter *et al.*, 1999), details the results from our first 42 SNe and highlights the evidence for a cosmological constant. Seven additional recent papers based on our results describe (i) the first measurements of cosmological parameters based on the first seven SN discoveries (Perlmutter *et al.*, 1997); (ii) a measurement of the rate of Type Ia SNe at $z \sim 0.4$ (Pain *et al.*, 1996, 2000), (iii) constraints on spatial variation of the Hubble constant from our data (Kim *et al.*, 1997), (iv) a study of cosmological time dilation of SN light curves (in final stages of preparation), (v) the use of SNe spectra for the determination of subtype and age of SNe Ia (Riess *et al.*, 1998), (vi) results on the $z = 0.83$ supernova 1997ap, and implications for cosmological measurements (Perlmutter *et al.*, 1998), (vii) the consistency of rise times measured for low and high-z supernovae (Aldering *et al.*, 2000).

Research is in progress which will result in additional papers. These include (i) a determination of the rates of SNe Ia at $z > 1$, (ii) a more accurate determination of the cosmological parameters from HST and Keck observations of 11 SNe Ia at $z < 0.86$, and (iii) an analysis constraining metallicity variations and evolution from our SNe Ia spectra. (iv) new limits on the cosmological parameters and possible systematics (grey dust or evolution) from SN 1998eq at $z = 1.20$. All these papers use the results from Keck spectroscopy obtained as part of our supernova cosmology program. Papers on many of these topics have also appeared in conference proceedings.

3 Technical Justification

Feasibility: The Supernova Cosmology Project has repeatedly demonstrated our ability to *a)* discover large numbers of high–z SNe Ia (> 20 per observing run) while they are still on the rise, *b)* obtain spectroscopic follow-up within a few days of discovery to confirm the SN type and redshift, *c)* acquire ground-based and HST light curve photometry, and *d)* analyze the data to obtain peak magnitudes and measure Ω_M and Ω_Λ. We have demonstrated this capability out to $z = 1.20$. A large battery of other telescopes (100 HST orbits, VLT, CTIO 4m, CFHT, WIYN, ESO 3.6m, Gemini, Subaru, and WHT will be focused on the 2002A campaign, ensuring the successful discovery and follow-up of the supernovae to be observed at Keck. Keck's role is to measure the redshifts and tell-tale SN Ia features of the highest redshift SNe Ia — a role only it can perform. (For instance, at 7500 Å, the effective aperture of Keck+LRIS is 1.6× that of VLT+FORS.) These are the SNe for which the 76 HST orbits were awarded; they can only be confirmed with Keck. (Even for $z < 1$ Keck is the only telescope fast enough to observe the targeted 18 SN candidates in the necessarily short window between the time of discovery and the start of photometric follow-up.)

Targets: We will obtain reference images just after new moon using the CFHT12k, CTIO MOSAIC, and Subaru SuprimeCam cameras. Just before the next new moon, we will observe the same fields again, and examine the tens of thousands of high-z galaxies to find those showing the new light of a SN that was not there on the previous observation. HST requires positions to within 1° three weeks prior to scheduled observations of transient objects, therefore, the searches will concentrate in two fields — a 1□° field reaching $m_I = 25.2$ with $S/N = 7$ (in the subtraction), and a 2□° field reaching $m_I = 24.2$ with $S/N = 7$ (in the subtraction). These fields must have little extinction and few stars, and be observable from both hemispheres. The final selection of fields depends on the dates scheduled for searching. Within these two fields we expect 4 SNe Ia with $z > 1$, 6 with $0.75 < z < 1$, and 15 with $z < 0.75$.

Exposures: All our exposure times are based on experience with real Keck data for high-z SNe. In semester 2002A we intend to carry out the following program:

- Confirm 2 SNe at $z \sim 1.2$ (for HST followup), requiring observation of 3 candidates with $m_I \sim 25$ for 4 hrs each (one of which is likely to be at $z \sim 0.85$ but early in its lightcurve, thus faint)

- Confirm 3 SNe at $z \sim 0.85$ (for HST followup), requiring observation of 4 more candidates with $m_I \sim 24$ for 2 hrs each (2 at $z \sim 0.85$ and 2 at lower redshift)

- Confirm 10 SNe at $z < 0.75$ (for ground-based photometric follow up with VLT, Subaru, WIYN, etc.) requiring observation of 8 more candidates for ~ 1.3 hours on average.
- Obtain one very detailed spectrum of a SN at $z \sim 0.5$ (to study the spectral lines that can indicate metallicity and evolutionary differences), requiring 4 hours.

Although our observing technique and candidate weighting scheme select against SNe II and AGN's, some of these pass through to our list of candidates, and so when confirming candidates a $\sim$ 20% allowance is needed to account for these interlopers. Thus, we will need to observe 18 candidates to confirm the 15 SNe above. Including 12% overhead for calibration, target acquisition, focusing, MALIGN'ing, and readout, the total time requested is 49 hours, or 6 nights.

We have developed customized techniques for faint-object spectroscopy, to minimize both statistical and systematic sources of noise. These techniques including chopping using a pivot star as reference and detailed corrections for slit illumination and fringe patterns which shift due to flexure. The resulting spectra will be of similar quality to our recent Keck spectra of SN1997ap ($z = 0.83$) and SN1998eq ($z = 1.20$), shown in Fig. 3.

For a $z \sim 0.5$ SN Ia, Keck can provide an excellent quality spectrum near maximum light which provides two important cross-checks — one for metallicity and the other for evolution. The positions of the iron-peak blends (Co and Fe of varying ionizations) at restframe $\sim$2890 and 3165 Å have FWHM of $\sim$100 Å and shift by 60 Å when going from 0.1 solar to 10 times solar metallicity (see Fig. 4b). Measurement of this shift is relatively insensitive to host-galaxy spectral contamination or reddening. The spectral ratios $\mathcal{R}$(CaII) (see Fig. 4a) and $\mathcal{R}$(SiII) measured to 17% and 6% respectively would allow a better than 3σ detection of evolutionary effects which could sufficiently alter the SN brightness to make the current datasets consistent with a flat, $\Omega_M = 1$ universe. Here host-galaxy spectral contamination is a serious issue and we would thus select a SN Ia with little host contamination. Scaling from our observations of 1997ap ($z = 0.83$, and no visible host), we find that a 4 hr spectrum (either with LRIS blue+red or ESI) will allow us to measure spectral features sufficiently well to execute these two tests. These measurements will be compared to our 2002A HST UV observations of nearby SNe Ia.

Telescope Time Requested. The science is now requiring us to study SNe Ia at higher redshifts than in previous work, in turn requiring more imaging time to find and follow the supernovae, and more spectroscopy time to confirm their types and redshifts. This is clearly science that will not work with too little telescope time scheduled once a semester. *Based on just Poisson statistics alone, for such a small sample, the expectation value of wasted HST orbits would be twice as large if this program were divided into two semesters; the comparison is even worse if typical observing conditions are factored in.* Therefore, for the 2000B through 2002A observing semesters we have been requesting sufficient telescope time scheduled once a year — 6 nights in semester 2002A. In accordance with this plan, we did not request time for semester 2001B (see our previous "proposal," requesting zero nights, and the explanatory letter to the TAC submitted with it, appended to the end of this propsal).

In total, we are asking for 6 dark nights to obtain redshifts and spectroscopy confirmation for 18 SNe Ia candidates. We find that we can observe within 6 days of new moon, and we will schedule discovery of the SNe just before new moon. **Please consult with us prior to scheduling specific dates.**

Instrumentation. In 2001A, we used both LRIS and ESI for this program. We found that ESI is superior for the purpose, primarily because the high resolution of ESI separates out the night skylines, allowing them to be excised from the data before smoothing to identify SNe and galaxy features. For 2002A, we therefore request the ESI spectrograph. (LRIS could still be used as a backup choice, but with the real-time observing and analysis software that we are now using, there is a significant efficiency gain if we use only ESI and do not have to re-tune the software in the middle of the run.)

Backup Programs

The CFHT12k, CTIO MOSAIC, and Subaru SuprimeCam searches supply built-in redundancy, so they should have no difficulty supplying sufficient supernovae. However, if for some reason they do not go as deep as planned, the SNe at $z \sim 0.9$ they should easily find would be observed; these still tighten the constraints on the measurements of Ω and Λ. On the other hand, should conditions at Keck preclude spectroscopy of SNe Ia at the highest redshift, we would pursue lower redshift SNe Ia since we must supply targets to HST.

Supplementary Observations

A comprehensive observing program is necessary to obtain a sufficient dataset to characterize the SN types and luminosities, and to obtain the necessary color, spectra, and light curve shapes. When targeting the highest accessible redshifts, as this program does, a large campaign is the only sensible approach since no single telescope is able to provide guaranteed coverage of the light curves given the vagaries of weather and instrument scheduling. The campaign requires tight coordination between the search, spectroscopy, and follow-up taking place at several observatories. We have already obtained 100 orbits at the HST in Cycle 10 which are dedicated to the follow-up of SNe discovered in semester 2002A. The goal is to schedule the photometric follow-up telescopes to trace out the ~ 40 days over the peak of the light curves (in the I-band) for all the SNe discovered. The start of the HST and ground-based photometric follow-up program is triggered by spectral confirmation at Keck.

Status of Previously Approved Keck Programs

Semester 2001A: In this first highly successful six-night run we used LRIS + Keck I and ESI + Keck II to obtain specta of 17 SNe, including three SNe Ia at $z > 1$. Our strategy of observing for five nights in one semester paid off, as we were able to use the poor seeing nights to confirm brighter targets, and use the better seeing nights to study SNe at $z > 1$. The Keck spectra allowed us to classify the SNe, obtain redshifts, and select the highest redshift targets for HST. In addition, the spectra are being compared to low redshift SNe Ia to test for the effects of evolution in the high-z sample.

Semester 2000A: The highlight of this two-night run at Keck was spectroscopy of a supernova candidate (from our CFHT search) that turned out to be a Type Ia SN at $z = 0.54$ at a very early phase in its light curve (only ~ 6 days after explosion). This early discovery allowed us to begin an intensive monitoring campaign to study the supernova in great detail, including near-IR imaging with ISAAC on the VLT. This data set will allow a detailed comparison with nearby Type Ia supernovae to check for signs of evolution or extinction by dust. These results have encouraged us to pursue detailed spectroscopy of another $z \sim 0.5$ SN Ia.

Semester 1999B: Three nights were awarded for the second week of October, 1999. The

time was used for spectroscopy of candidate SNe that were discovered in a search at CFHT earlier that month. Out of the 10 candidates discovered, we were able to observe 6 of them, and two of those were found to have $z \sim 0.9$. The data are now being analyzed. Note that the CFHT search was not as extensive in area or in depth as is being proposed for this run, nor was there a parallel CTIO MOSAIC run.
Semester 1999A: One night was awarded, and was not usable.
Semester 1998B: Three nights were awarded for a pilot study to find very high-z SNe. Two nights were used for imaging and one for spectroscopy, resulting in three Type Ia SNe with $z = 1.2$, 0.84 and 0.11. The SN with $z = 1.200$ (1998eq) is (still) the most distant Type Ia SN yet confirmed (see Fig. 3b and IAUC 7046). The discovery of this supernova demonstrates that it is feasible to find and obtain spectra for Type Ia events even for redshifts $z > 1$. The two highest redshift SNe from this run, both of which were discovered close to maximum light, were observed in I-band and J-band with HST WFPC2 and NICMOS.
Semesters 1997B and 1998A: In December 1997 and March 1998 we carried out searches using the BTC on the CTIO 4-m. The resulting SN candidates were observed spectroscopically with Keck on approximately 4 usable nights (over the two semesters). A total of 36 candidates were observed and 26 were confirmed as Type Ia, with mean redshifts of approximately 0.6–0.7. These were followed-up from the ground with CTIO-4m, WIYN, ESO 3.6m, WHT and INT telescopes, and 11 of these were also followed photometrically with HST using WFPC2 and NICMOS. The corresponding final reference images have been obtained for these SNe and final photometry is now being carried out to determine accurate light curves.
Earlier Semesters: Final host galaxy images have been obtained for nearly all the SNe discovered prior to the above semesters. These SNe have been analyzed and formed the basis of the analysis presented in Perlmutter *et al.* (1999) and other papers (see section on publications).

Path to Science from Observations

As in the past, we will use spectral lines of the host galaxy to determine the redshift. These *add* lines, whether seen in emission (e.g. OII 3727Å) or absorption (e.g. Ca II H & K), can *ESI* be identified even when the SN and galaxy light are blended, because the galaxy lines are much narrower than the SN lines. (In cases where there is no significant light from the host, redshifts will come from the supernova spectrum itself.) The SNe spectra are smoothed or re-binned on a scale of ~ 20Å (after removing any lines due to the host galaxy) and compared with those of nearby SNe to ascertain the SN type.

The Keck redshifts will be used along with follow-up photometry from HST, VLT, Subaru, WIYN, NTT, etc. to plot the Keck SNe Ia on the Hubble diagram. This requires that the light curve time of maximum, peak flux, and width, be measured. The light curve width is strongly correlated with the intrinsic supernova brightness, and is used to standardize the SNe Ia. K-corrections — which we have developed using the spectra of low-z SNe Ia — must also be applied, followed by correction for dust extinction from the host galaxy and the Galaxy. The extinction correction requires a knowledge of the unreddened intrinsic SN colors, which we have determined from low-z SNe Ia in elliptical galaxies and do not result in overcorrection for extinction (as is the case for some other treatments in the literature). Once the SNe Ia have been standardized, we can solve for the confidence intervals for the cosmological parameters. We have extensive software to undertake such light curve fitting, corrections, and parameter fitting.

The spectra will also be used to directly test the hypothesis that distant SNe are spectroscopically similar to nearby SNe, as was done for SN 1997ap (See Fig. 3 and also Perlmutter *et al.* (1998)). In most cases, the host galaxy light significantly contaminates the SN spectrum, and therefore a template spectrum of the host galaxy at the supernova site will eventually be obtained for at least one or two of these cases. This will be subtracted from the original (SN + galaxy) spectrum. (We are also examining the use of cataloged galaxy spectra for this purpose.) With these final reduced SNe spectra, we will measure key spectral features, such as the locations of the UV iron-peak lines, and the luminosity indicators, $\mathcal{R}$(CaII) and $\mathcal{R}$(SiII), for spectra with sufficient S/N (such as the $z \sim 0.5$ SN Ia we will target). The effect on our fits in the $\Omega - \Lambda$ plane due to any spectroscopically peculiar SNe Ia can be tested and used to set better limits on systematic uncertainties which could be caused by unrecognized spectroscopically peculiar SNe Ia. For our $z \sim 0.5$ SN Ia, stronger tests, including comparison of the UV spectral features with our Cycle 9 (and requested Cycle 11) HST UV spectra of nearby SNe Ia (from a separate program), and detailed $\mathcal{R}$(CaII) and $\mathcal{R}$(SiII) measurements will be possible.

Technical Concerns

Since the targets are faint, we calculate for each candidate accurate offsets from nearby stars. *add* A major advantage of the Keck telescope is the depth reached by the finder monitors. We*ESI* have developed, tested, used extensively image analysis software which makes it possible to compare the images of all 100,000 galaxies in the fields searched to their images on the earlier nights within 24 hours, to find the SNe before maximum light, and to identify the precise coordinates for follow-up spectroscopy and additional photometry.

The Keck SN candidate spectroscopy run must be coordinated with the search runs scheduled at CFHT and CTIO, so *please contact us before scheduling any nights allocated to us at Keck!*

Experience and Publications

Our group has extensive experience with faint object spectroscopy on telescopes around the world and has had successful runs using LRIS on Keck each semester for the last five years (except Semester 2000B). To reduce and analyze the spectra, our group has developed a few techniques that are specific to high-z supernova work.

Our group has also developed extensive techniques for the photometry of high-z SNe against the bright background of their host galaxies. A list of relevant publications appears at the end of this document.

Resources and Publication Timescale

The LBNL group consists of four staff scientists/professors, three postdocs and three graduate students. By 2002A the group will grow, with the addition of 3 new postdocs. The group uses the extensive computing facilities available at LBNL. In addition, collaborators in Sweden, France, Chile and the U.K. are actively participating in the project. Publication of the results will occur somewhat more than a year after discovery of the SNe; it is necessary to wait for the SNe to fade before template images of the host galaxies, and the derivation of accurate light curves, can be obtained. If there is insignificant host light, we can occasionally publish sooner: SN1997ap was discovered in March 1997, and a paper describing the data and results from that supernova was published by *Nature* in January, 1998. The results from the first 42 SNe (data obtained from Spring 1995 to Spring 1998, including final follow-up photometry on the Spring 1997 SNe) was published in *ApJ* in Fall 1999.

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(* = Keck data contributed to this publication.)

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* The acceleration of the Universe: measurement of cosmological parameters from type Ia supernovae, A. Goobar, S. Perlmutter, G. Aldering, G. Goldhaber, R.A. Knop, P. Nugent, P. G. Castro, S. Deustua, S. Fabbro, D. E. Groom, I. M. Hook, A. G. Kim, M. Y. Kim, J. C. Lee, N. J. Nunes, R. Pain, C. R. Pennypacker, R. Quimby, C. Lidman, R. S. Ellis, M. Irwin, R. G. McMahon, P. Ruiz-Lapuente, N. Walton, B. Schaefer, B. J. Boyle, A. V. Filippenko, T. Matheson, A. S. Fruchter, N. Panagia, H. J. M. Newberg, W. J. Couch, 2000, Physica Scripta, T85, 47.

* Constraining Dark Energy with SNe Ia and Large-scale Structure, S. Perlmutter, M. S. Turner, & M. White 1999, Phys. Rev. Lett., 83, 670.

* The Cosmic Triangle: Revealing the State of the Universe, N. Bahcall, J. P. Ostriker, S. Perlmutter, P. J. Steinhardt 1999, Science, 284, 1481.

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Gravity: From the Hubble Length to the Planck Length, G. Goldhaber, XXVI SLAC Summer Institute, August, 1998

* Discovery of a Supernova Explosion at Half the Age of the Universe and its Cosmological Implications, S. Perlmutter, G. Aldering, M. Della Valle, S. Deustua, R. S. Ellis, S. Fabbro, A. Fruchter, G. Goldhaber, A. Goobar, D. E. Groom, I. M. Hook, A. G. Kim, M. Y. Kim, R.A. Knop, C. Lidman, R. G. McMahon, P. Nugent, R. Pain, N. Panagia, C. R. Pennypacker, P. Ruiz-Lapuente, B. Schaefer and N. Walton, Nature, 391, 51 (1998).

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Publications In Preparation

* Type Ia Supernova Lightcurves: Composite B Lightcurve, Turn-on Behavior, and $1 +$

z Lightcurve Broadening, G. Goldhaber, D. Groom, & S. Perlmutter *et al.* 1999, to be submitted to Astrophysical Journal.

* The Type Ia Supernova Rate at Redshifts $0.35 < z < 0.85$, R. Pain *et al.* 1999, to be submitted to Astrophysical Journal.

Supernova Discoveries In IAU Circulars

More than 100 discoveries of supernovae, reported in International Astronomical Union Telegrams and Circulars, including:

Supernovae 1994F, 1994G, 1994H, Circular 5956, 24 March 1994, S. Perlmutter, *et al.*

Supernovae 1993al, 1994al, 1994am, 1994an, Circular 6263, 18 November 1995, S. Perlmutter, *et al.* (The Supernova Cosmology Project).

*Eleven High-Redshift Supernovae: 1995aq through 1995az, and 1995ba, Circular 6270, 6 December 1995, S. Perlmutter, *et al.* (The Supernova Cosmology Project).

*Fourteen High-Redshift Supernovae: Circular 6540, 17 January 1997, Supernova Cosmology Project.

*Sixteen High-Redshift Supernovae: Circular 6596, 20 March 1997, Supernova Cosmology Project.

*Nine High-Redshift Supernovae: Circular 6621, 9 April 1997, Supernova Cosmology Project.

*Seventeen High-Redshift Supernovae: Circular 6804, 6 January 1997, Supernova Cosmology Project.

*Twenty High-Redshift Supernovae: Circular 6881, 22 April 1998, Supernova Cosmology Project.

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*Supernovae 1999ae, 1999af, 1999ag, 1999ah, 1999ak, 1999al, Circular 7177, Supernova Cosmology Project.

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Supernova 2000ca, Circular 7413, G. Aldering & A. Conley

Supernova 2000cc, Circular 7414, G. Aldering & A. Conley

Supernova 2000cb, Circular 7410, G. Aldering & A. Conley

This is a copy of the cover letter sent with the Semester 2000B proposal, requesting zero time to be allocated in 2000B as part of the year-long plan described in the current Semester 2002A proposal:

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