1 Scientific Justification

The Hubble diagram for Type Ia supernovae (SNe Ia), extended to redshifts well beyond $z = 0.25$ (Fig. 1), provides 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 are addressing in the current series of semesters' proposals: (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 $0.5 \lesssim z \lesssim 1.2$ 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 therefore are proposing comprehensive search-and-follow-up campaigns each semester for which a multi-telescope effort is possible. Keck's role is key for the higher redshift work, because only the Keck can obtain the spectra that identify the Type Ia supernovae and provide their redshifts even when the host galaxy redshift cannot be observed.

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). $\Omega_\Lambda = 0$ could be ruled out at well over 3σ, while 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 according to simulation. These data would provide 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 the highest redshift that we can confirm with spectroscopy, and these are our most time-consuming observations.

This proposed semester's work would take advantage of an unusual opportunity to concentrate in this highest redshift range: the Subaru Observatory is conducting an "Observatory Large Project" that will use the wide-field Suprime-Cam to observe four fields to great depths in B, R, i', z' with observations spread over 13 nights beginning in September 2002 and continuing into November. The observations will be structured such that the supernovae up to redshift $z \sim 1.4$ will be discovered on the rise in each of these fields, and lightcurve points obtained past maximum. Members of the team that built the Suprime-Cam have joined with the Supernova Cosmology Project to use Subaru for such high-redshift supernova work (leading to several discoveries and follow-up last spring). For this current Subaru campaign, Keck spectroscopy would be crucial, since the supernovae to be studied would all be at $z > 1$. The matching photometry (including J-band, approximating restframe B) will be obtained from the 13-night campaign itself and from additional proposed IR time on Suburu (and possibly from NICMOS if the cryocooler is successful) .

The current series of semesters' work will also study the Hubble diagram out to $z \sim 1$, providing 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 data set that will result from this series of observing campaigns will tighten these constraints by 40%, potentially ruling out several contending theories if the current w value holds.

(B) Refining and Testing a Cosmology Tool: SN 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. Several different refinements/tests are being addressed by the current series of campaigns, however this Semester 2002B proposal will concentrate on those that are only possible with a sample of the highest-redshift supernovae, since the Subaru Observatory Large Project provides an unusual opportunity to work in this redshift range.

Hubble diagram shape test. 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. Observations of SN 1997ff support a no-dust, no-evolution intrepretation, but are not sufficiently constraining (Riess *et al.* 2001).

Hubble diagram dispersion test. With a set of well-measured high-z SNe, it will be possible to check for the increased dispersion in absolute magnitude that would be expected from evolution or abnormal dust extinction. Over the past year, Prof. Gene Commins (a new faculty member of our collaboration) has been studying models of dust creation, composition, and distribution, with the goal of constraining its contribution to the statistical and systematic uncertainties in the supernova cosmology measurements.

Conclusion. This proposal focuses on the unusual science opportunities presented in Semester 2002B by the Subaru Observatory Large Program. We hope to make major strides in the highest-redshift range of our ongoing multi-semester campaign to build a well-measured SN Ia Hubble diagram extending to these 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. This fundamental science is only possible with Keck.

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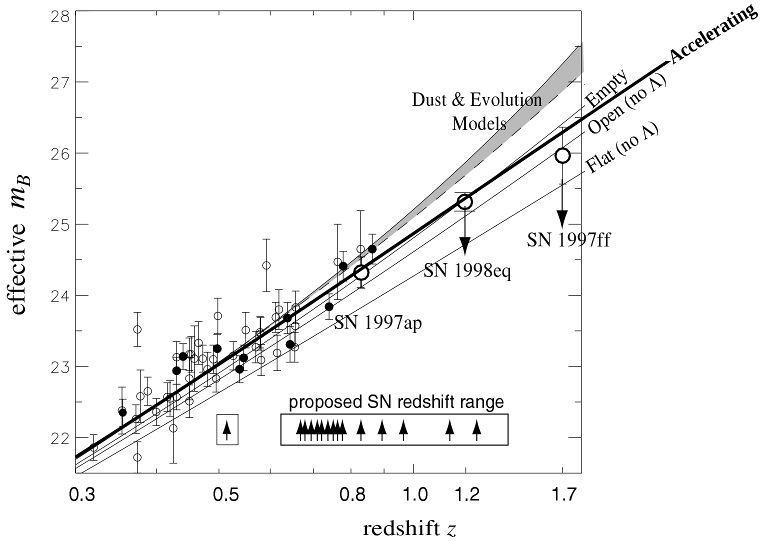

Figure 1: Open points show Hubble diagram for 42 high-z SNe (Perlmutter *et al.* 1999) along with comparable non-host-extinction-corrected points (filled circles) for our more recently discovered SNe with HST followup (Knop *et al.* 2000, 2001). current data. The "Open (no The magnitude difference between the best-fit "Accelerating (Λ)" world model $(\Omega_M, \Omega_\Lambda)$ =(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 SN evolution or grey dust hypotheses (the grey 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 $z = 1.2$ (Aldering *et al.* 1998) is suggestive (as is the serendipitous data for SN1997ff at $z = 1.7$, Riess *et al.* 2001), but more SNe at this redshift with better measurements are necessary.

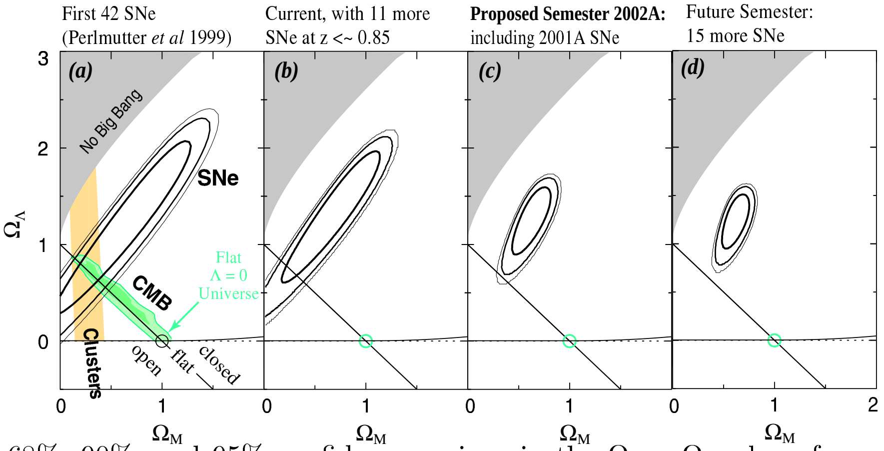

Figure 2: *(a)* 68%, 90%, and 95% confidence regions in the Ω_M—Ω_Λ plane from the 42 distant SNe Ia in Perlmutter *et al.* 1999, with the overlap of the recent combined CMB results (Jaffe *et al.* 2001) and the Ω_M measurements from galaxy clusters. *(b)* Results presented by Knop *et al.* (2000) for the confidence region after including our next 11 SNe Ia with HST followup. *(c)* Expected confidence region size after proposed semester 2002A (including the SNe from our 2001A Keck proposal). *(d)* After one more semester. 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)*.

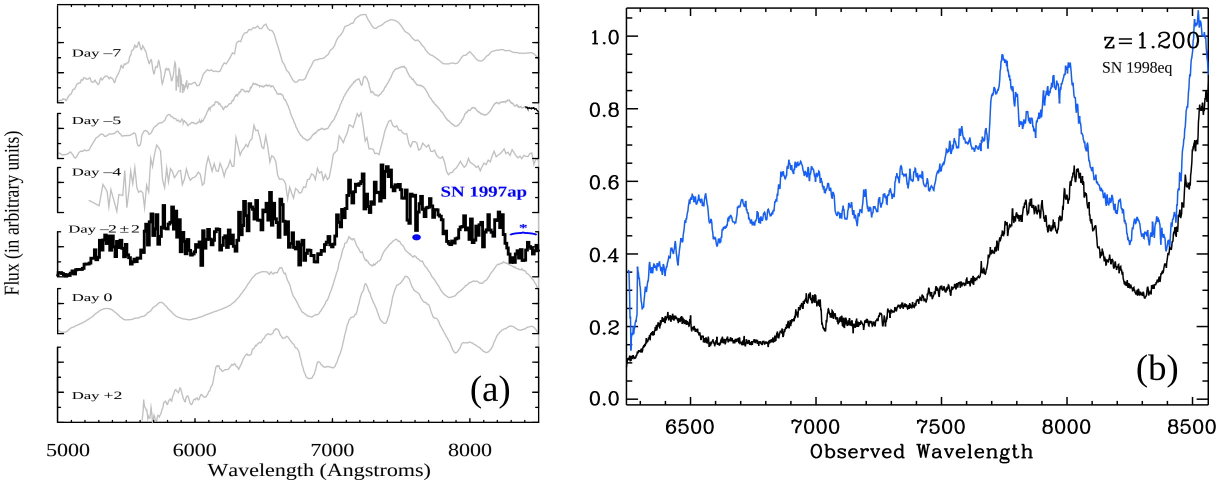

Figure 3: (a) Our Keck spectrum of SN1997ap (solid line) at $z = 0.83$ (Perlmutter *et al.*, 1998). Also shown are nearby SNe at different epochs, redshifted to match SN1997ap. The Fe lines in the (rest-frame) UV portion of the spectrum and the Ca II H&K trough around 3800 Å restframe are used for the spectral identification from ESI and LRIS of the highest-redshift SNe. (b) Spectrum of SN1998eq (upper line) at $z = 1.2$ from our 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.

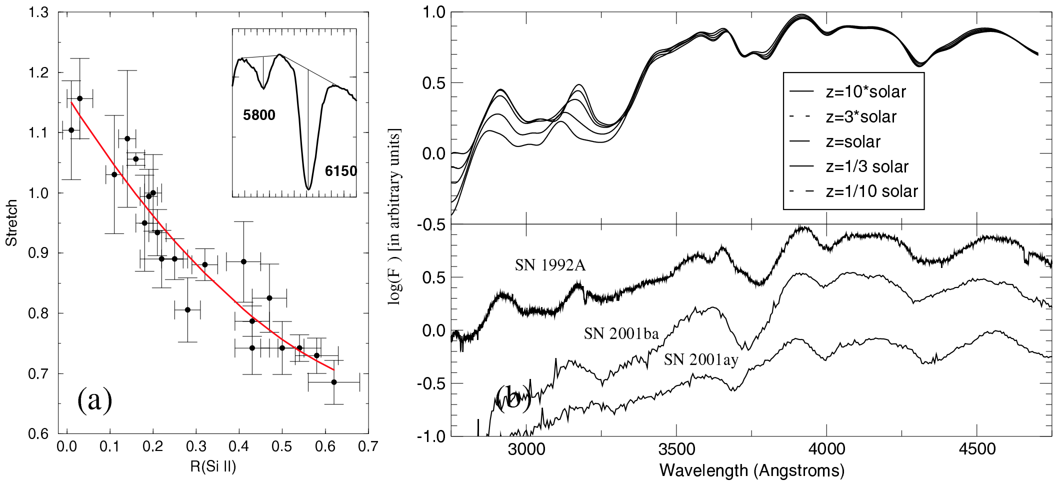

Figure 4: (a) The tight relationship between the spectroscopic ratio $\mathcal{R}$(SiII) and the lightcurve timescale stretch for well-observed low-redshift SNe Ia (see Nugent *et al.* 1995 for a similar $\mathcal{R}$(CaII) plot). The inset shows how this spectral ratio is measured. (b) *Top panel*: Maximum light spectrum synthesis models of W7 (a deflagration model by Nomoto *et al.* (1984) of a SN Ia) with varying metallicities in the outer C+O layer. *Bottom panel*: A plot of SNe 1992A, 2001ba and 2001ay which strongly confirms that the greatest differences among SNe Ia occur in the UV. We observed the spectra of the latter two with HST this past spring in an effort to increase our understanding of this metallicity effect.

2 Progress to Date

Significant samples of well-studied SNe Ia at the higher redshifts are the key ingredients to further progress on the measurement of cosmological parameters. 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. See Fig. 3b.) Since then we have successfully transferred the *searches* to smaller telescopes, such as CFHT and CTIO—and, most recently, Subaru (Doi *et al.* 2001) — 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 run, 2001A, identified 17 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 $z \sim 0.7$ (See Fig. 1). 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 WFPC2. 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 $\sim$ 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 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.* (2002, currently being refereed) 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.

3 Technical Justification

Feasibility: The Supernova Cosmology Project has repeatedly demonstrated our ability to *a)* discover large numbers of high–z SNe Ia ($\sim$ 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 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 $z = 1.20$. Last spring, our Type Ia supernova discoveries with Subaru demonstrated Suprime-Cam's unusual capability to find such supernovae to redshifts beyond our previous work with only a few hours of observations. With 13 nights to repeatedly observe four fields in 4 bands, the Subaru Observatory Large Project (and further proposed IR observations), this campaign will perform almost all of the above steps in a single program; Keck's role will be 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.)

Targets: All of the supernovae to be observed in this proposal will be discovered in the four fields ($\sim 1\Box^\circ$) to be chosen by the Subaru Observatory Large Project team. These fields will be observable from September through November, and will fill the nights. Note that the first of these observations will play the role of "reference images" to subtract off of the discovery images that follow several weeks later. Within these four fields, we expect approximately 8 SNe Ia at redshifts $z > 1$, which will be the targets of the Keck observations.

Exposures: *All our exposure times are based on experience with real Keck data for high-z SNe.* 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 estimating the number of candidates we will confirm, we include a $\sim$ 20% allowance for these interlopers. In semester 2002B, in coordination with the Subaru Observatory Large Program, we will confirm 5 SNe at $z \sim 1.2$ (for HST followup), requiring observation of 10 candidates with $m_I \sim 25$ (two of which are likely to be at $z \sim 0.85$ but early in their lightcurve, thus faint; two may be interlopers — SN II or AGN). The SNe will require 5 hrs exposures each to achieve useful signal-to-noise to identify SN Ia features, while the screening of the other candidates will require over 3 hrs exposures each. Including 15% overhead for calibration, target acquisition, focusing, MALIGN'ing, and readout, the total time requested is 44 hours, or 5 nights.

Note that although they are not the focus of this semester's primary work, any lower-redshift supernovae that are discovered in the screening will be scientifically useful: For example, 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 ∼2890 and 3165 Å have FWHM of ∼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 spectrum (either with ESI or LRIS) of over 3 hours will allow us to measure spectral features sufficiently well to execute these two tests. These measurements will be compared to our Cycle 9 (and awarded Cycle 11) 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 and (though not the focus of this semester's proposal) with higher statistics at the previous redshifts; this in turn requires more imaging time to find and follow the supernovae, and more spectroscopy time to confirm their types and redshifts. We are therefore now moving to larger "rolling campaigns," whenever possible, in which the supernova lightcurves are collected in repeated observations of the same wide-area fields, and the supernovae are discovered in the same repeated images. This semester's Subaru Observatory Large Project is an example of this approach for the highest redshifts. These are extremely difficult observations; we will need 5 dark nights to obtain redshifts and spectroscopy confirmation for 9 SN Ia candidates. We find that we can observe within 6 days of new moon, but we cannot specify exactly which dates will be requested until the Subaru Observatory schedules their Large Project dates.

It will therefore be crucial to 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 and do a second instrument set-up in the middle of the run.)

We have developed customized techniques for faint-object spectroscopy, to minimize both statistical and systematic sources of noise. These techniques including chopping, deweighting of OH lines (ESI only), detailed corrections for slit illumination and fringe patterns which shift due to flexure (even with ESI!), and closed-loop offsetting and atmospheric refraction drift-correction based on the comparison of guider frames with our deep SN images. The resulting spectra will be of quality similar to our recent Keck spectra of SN1997ap ($z = 0.83$) and SN1998eq ($z = 1.20$), shown in Fig. 3. If, as anticipated, an LBNL $2k \times 4k$ red-sensitive CCD becomes available we will obtain higher S/N and/or push to higher redshift.

Backup Programs

The 13 nights of observations used over the 10 week campaign for the Subaru Observatory Large Project will provide built-in redundancy, so they should have no difficulty supplying sufficient supernovae. However, if the weather is consistently marginal and the searching is not as deep as planned, the SNe at $z \sim 0.9$ that they should easily find would be observed; these still tighten the constraints on the measurements of Ω and Λ.

Supplementary Observations

The Subaru Observatory Large Program together with the proposed IR time will by itself provide most of the elements of the comprehensive observing program necessary to obtain a sufficient dataset to characterize the SN types and luminosities, and to obtain the necessary color and light curve shapes. The Keck will then add the crucial spectroscopy information.

Status of Previously Approved Keck Programs

Semester 2001A: In this first highly successful six-night run we used one night of LRIS + Keck I and five nights of ESI + Keck II to obtain specta of 17 SNe, including three SNe Ia at $z > 1$. Our strategy of observing for six nights in one semester paid off, as we were able to use the three poorer seeing (~ 1 arcsec) nights and one cirrusy night to confirm brighter targets, and use the two 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. This run also gave us extensive experience with ESI, enabling us to refine our reduction techniques to best exploit ESI's advantages (and compensate for small remaining problems).

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 were there parallel CTIO MOSAIC or Subaru SuprimeCam runs.

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) at the highest redshift that Type Ia SNe have yet been 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 the results presented in Knop *et al.* (2000, 2001). (See Figs. 1 and 2.)

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), which highlights the evidence for a cosmological constant. Eight additional papers based on our Keck work 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), (iii) the rate of Type Ia SNe at $0.35 < z < 0.85$ (Pain *et al.*, 2001), (iv) constraints on the spatial variation of the Hubble constant from our data (Kim *et al.*, 1997), (v)a study of the timescale stretch parameterization of type Ia supernova B-band light curves (Goldhaber *et al.*, 2001), (vi) the use of SN spectra for the determination of subtype and age of SNe Ia (Riess *et al.*, 1998), (vii) results on the $z = 0.83$ supernova 1997ap, and implications for cosmological measurements (Perlmutter *et al.*, 1998), and (viii) 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) an analysis constraining metallicity variations and evolution from our SN spectra, and (iii) 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. A number of papers on these topics have also appeared in conference proceedings.

Path to Science from Observations

As in the past, we will use spectral lines of the host galaxy to determine the redshift. These lines, whether seen in emission (e.g. OII 3727Å) or absorption (e.g. Ca II H & K), can 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 SN spectra are smoothed on a scale of $\sim$ 20Å (after removing any lines due to the host galaxy – and in the case of ESI – deweighting the spectral regions covered by OH lines) and compared with those of nearby SNe to ascertain the SN type.

The Keck redshifts will be used along with follow-up photometry from the Subaru Observatory Large Project 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 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 SN 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, accurate offseting is critical to take advantage of the narrow slit widths possible under the best seeing conditions. On our last ESI run we found that comparing guider image captures with our deep search images allowed for better offsets than standard offseting from a single bright star since the slit position relative to numerous field objects could be determined with high accuracy. Monitoring of the frames also allowed us to compensate for changes in atmospheric refraction as well as the very small flexure of the guider camera. Therefore, we will request that the night assistant continuously run the save-to-disk option for the guider. This can impact disk-space on the summit.

There are no technical concerns with the searches as we have developed, tested, used an extensive image analysis software suite 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 runs must be coordinated with the "rolling search" run to be scheduled for the Subaru Observatory Large Program, 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 and/or ESI on Keck each semester (or - more recently - combined pair of semesters) for the last five years. To reduce and analyze the spectra, our group has developed 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 three permanent staff scientists, one professor, a scientist/project coordinator, four postdocs and three graduate students. By 2002B the group will grow, with the addition of two new postdocs. The group uses the extensive computing facilities available at LBNL. In addition, collaborators in the US, 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.

Publications

(* = Keck data contributed to this publication.)

* The Type Ia Supernova Rate at Redshifts $0.35 < z < 0.85$, R. Pain *et al.* 2001, submitted to Astrophysical Journal.

* Timescale Stretch Parameterization of Type Ia Supernova B-Band Light Curves, G. Goldhaber, D. E. Groom, A. Kim, G. Aldering, P. Astier, A. Conley, S. E. Deustua, R. Ellis, S. Fabbro, A. S. Fruchter, A. Goobar, I. Hook, M. Irwin, M. Kim, R. A. Knop, C. Lidman, R. McMahon, P. E. Nugent, R. Pain, N. Panagia, C. R. Pennypacker, S. Perlmutter, P. Ruiz-Lapuente, B. Schaefer, N. A. Walton, T. York, 2001, Astrophysical Journal, 558, 359

* Latest Cosmological Results from Type Ia Supernovae, R. Knop, *et al.*, 2000, Bulletin of the American Astronomical Society, 197, 950

* The Rise Times of High- and Low-Redshift Type Ia Supernovae Are Consistent, G. Aldering, R. Knop, P. Nugent 2000, Astronomical Journal, 119, 2110.

* 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.

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* 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.

High Redshift SNe in the Hubble Deep Field, R. L. Gilliland, P. E. Nugent & M.M. Phillips, ApJ, vol. 521, p.30-49, 1999

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gia, H. J. M. Newberg, W. J. Couch, Astrophysical Journal, 517, 565 (1999).

* Snapshot Distances to SNe Ia – All in ’One’ Night’s Work”, A. Riess, P. Nugent, A. Filippenko, R. Kirshner and S. Perlmutter, Astrophysical Journal, September, 1998.

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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*Implications for the Hubble Constant from the First Seven Supernovae of $z > 0.35$, A. Kim *et al.*, Astrophysical Journal, 476, L63 (1997).

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*Observation of cosmological time dilation using type Ia supernovae as clocks. (The Supernova Cosmology Project: III.) G. Goldhaber, *et al.*, in Thermonuclear Supernovae, NATO ASI, eds. R. Canal, P. Ruiz-LaPuente, and J. Isern (1996).

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A Type Ia supernova at $z = 0.457$. S. Perlmutter, C. Pennypacker, G. Goldhaber, A. Goobar, J. Desai, A. Kim, M. Kim, R. Muller, H. Newberg, I. Small, R. McMahon, B. Boyle, D. Carter, M. Irwin, P. Bunclark, K. Glazebrook, and R. Ellis, Astrophysical Journal Letters, 440, L41 (1995).

Discovery of the most distant supernovae and the quest for Ω. G. Goldhaber, B. Boyle, P. Bunclark, D. Carter, R. Ellis, S. Gabi, A. Goobar, A. Kim, M. Kim, R. McMahon, R. Pain, C. Pennypacker, S. Perlmutter, I. Small, and R. Terlevich, Nuclear Physics B (Proc. Suppl.) 38, 435 (1995).

Publications In Preparation

New Limits on Cosmological Parameters Ω_M and Ω_Λ from HST Observations of Eleven Supernovae at Redshifts z=0.36-0.86, R. Knop, *et al.*, 2001, in preparation

Results from a Deep Supernova Search at Keck, G. Aldering, *et al.*, 2001, in preparation

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.

*Three High-Redshift Supernovae: Circular 7046, 5 November 1998, Supernova Cosmology Project.

*Supernova 1999ab, Circular 7109, Supernova Cosmology Project.

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

*Supernova 1999am, Circular 7122, Supernova Cosmology Project.

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*Supernovae 1999az, 1999ba, 1999bb, Circular 7131, Supernova Cosmology Project.

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

Supernova 2001ay in IC 4423, Circular 7612, P. Nugent, G. Aldering, I. Hook, S. Perlmutter, L. Wang

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This is a copy of the cover letter sent with the Semester 2001B proposal, requesting zero time to be allocated in 2001B as part of the year-long plan described in the current Semester 2002A proposal:

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