NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: September 30, 2001 **Category:** Cosmology

Cosmology with High-Redshift Type Ia Supernovae

PI: Saul Perlmutter **Status:** P **Affil.:** Lawrence Berkeley National Lab
Institute for Nuclear and Particle Astrophysics, One Cyclotron Road, MS 50/232, Berkeley, CA 94720 USA
Email: saul@lbl.gov Phone: 510-486-5203 FAX: 510-486-5401

CoI: Greg Aldering **Status:** P **Affil.:** Lawrence Berkeley National Lab
CoI: Robert Knop **Status:** P **Affil.:** Vanderbilt University
CoI: Isobel Hook **Status:** P **Affil.:** University of Oxford
CoI: Gerson Goldhaber **Status:** P **Affil.:** University of California at Berkeley
CoI: Peter Nugent **Status:** P **Affil.:** Lawrence Berkeley National Lab
CoI: Nicolas Regnault **Status:** P **Affil.:** Lawrence Berkeley National Lab

Daniel Kasen
Alex Conley
Michael Wood-Vase
Pierre Astier
Reynald Pain
Ariel Goobar

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)***:**

The current Type Ia supernova Hubble diagram and CMB observations argue for a flat universe with some form of “dark energy” accelerating its expansion. Studies of distant supernovae can probe the expansion history of the universe through our current dark-energy-dominated era back to a matter-dominated era, making them one of the best current methods to study the amount and nature of such dark energy. With this program of SN studies we have an 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. The CTIO 4-m telescope will reach back in time to find supernovae when the universe was still matter-dominated, extending our understanding of the expansion of the universe and possible evolution of supernovae over time. The Gemini GMOS will provide spectroscopic confirmation of a selection of these SNe and, together with the WIYN telescope, will allow us to obtain photometric follow-up – and hence a measurement of the brightness of these standard candles as a function of redshift. The Gemini NIRI will allow us to obtain crucial data for the very highest-redshift ($z > 1$) supernova whose rest-frame V-band will have been redshifted to our J-band. The CTIO search triggers all of the confirmation and follow-up work requested here as well as that which we have requested at other facilities.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	CT-4m	MOSAIC	6	dark	Mar - May	Mar - May
2	WIYN-SYN	MIMO	6.35	dark	Apr - May	Apr - May
3	GEM-NQ	GMOSN	3.5*	grey	Apr - Jul	Apr - Jul
4	GEM-NQ	NIRI6	3.5*	bright	May - Jul	May - Jul
5						
6						

Scheduling constraints and non-usable dates *(up to four lines).*

The success of this project relies on coordinated observations between numerous observatories. *It is crucial that we be contacted prior to scheduling to insure that the search is properly timed.*
(*)The Gemini runs in this proposal are jointly submitted to the UK. We request that the time be divided as follows: US(46.8 hrs), UK(23.3 hrs).

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

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. We developed an approach to this measurement 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 [Per99, see also Rie98]. This evidence has been increasingly strengthened, in particular by the recent balloon-based CMB measurements [Jaf01] which strongly indicate that the geometry of the universe is flat (Fig. 2a). There are now two important directions to pursue in this proposal:

(1) Extending and Filling a SN Ia Hubble Diagram to $z \sim 1.2$. Significant improvements are being made in the systematic uncertainties of SN measurements, so it is now useful to reduce the statistical uncertainty with an additional ∼100 SNe Ia. This is a key task, and we are therefore proposing a concerted effort in 2002A to discover and study 15 SNe Ia, with the most distant to be followed with Gemini and 100 HST-awarded orbits. Only HST can provide accurate optical photometry at these higher redshifts, and the wide-field MOSAIC is crucial to discover these SNe.

The Hubble diagram to $z \sim 1.2$ can address several important scientific questions. First, it allows a determination of the curvature of the universe and decoupled measurements of Ω_M and Ω_Λ: SNe Ia beyond $z \sim 0.85$ can dramatically shorten the major-axis of the current Ω_M–Ω_Λ error ellipse (cf. [Goo95] and Fig. 2). After our proposed observations in 2002A, $\Omega_\Lambda = 0$ could be ruled out at better than 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 according to simulation. These data would provide a first check on the CMB measurements that indicate a flat geometry. Second, the Hubble diagram out to $z \sim 1$ provides a way to constrain the physics of the "dark energy" that apparently is accelerating the universe's expansion—by measuring its equation-of-state ratio, $w \equiv p/\rho$. Current constraints on w are consistent with a wide range of dark energy theories, including a Cosmological Constant ($w = -1$) [Per99, Gar98]; the proposed data set, together with data now being analyzed, can tighten these constraints by 40%, potentially ruling out several contending theories.

(2) Refining and Testing SNe Ia as a Cosmology Tool. We have shown [Per97, Per99] that possible systematics in the measurement of Ω_M, Ω_Λ due to K-corrections, Malmquist bias, etc. are small compared to the statistical error. Remaining possible sources of systematic uncertainty are SN Ia evolution and abnormal dust extinction. We propose observations that will "sharpen" this cosmological measurement tool by addressing these two issues as follows: 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. Comparing HST measurements of SNe Ia at $z \sim 0.85$ (HST) and HST and Gemini measurements at $z > 1$ will provide a direct test for such possible systematics. Observations of SN 1999ff support a no-dust, no-evolution interpretation, but are not sufficiently constraining [Rie01]. Spectral tests for metallicity dependence will also be used. Restframe B-I colors from MOSAIC, WIYN, Gemini NIRI (J-band) and VLT (J-band) will test for abnormal extinction.

Conclusion. By concentrating our year's effort on one large campaign (*that is, we intentionally requested zero nights in 2001B in order to focus on 2002A),* we can most effectively pursue the goal of a well-measured SN Ia Hubble diagram at the highest redshifts and directly study the cosmological parameters, curvature, and dark energy. These SNe also refine our evolution/dust checks on systematics. Having pioneered these techniques, we see this large CTIO 4-m-led campaign as the crucial next step. This fundamental science is only possible with the use of the NOAO facilities requested here.

References

[Ald98] Aldering, G. 1998, IAU Circular 7046.

[Ald00] Aldering, G. 2000, AIP Conf. Proc. "Cosmic Explosions"

[Jaf01] Jaffe, A. H. *et al.*, 2001, Phys. Rev. Lett. 86, 3475

[Gar98] Garnavitch, P. *et al.* 1998, ApJ, 509, 74.

[Goo95] Goobar, A. and Perlmutter, S. 1995 ApJ, 450, 14.

[Kno00] Knop, R. *et al.* 2000, B.A.A.S., 197, 950

[Kno01] Knop, R. *et al.* 2001, in preparation

[Nug95] Nugent, P. *et al.* 1995 ApJ, 455, 147.

[Pai96] Pain, R. *et al.* 1996, ApJ, 473, 356.

[Pai01] Pain, R. *et al.* 2001, Submitted to ApJ.

[Per97] Perlmutter *et al.* 1997 ApJ, 483, 565.

[Per99] Perlmutter *et al.* 1999 ApJ, 517, 565.

[Rie98] Riess, A. *et al.* 1998 AJ, 116, 1009.

[Rie01] Riess, A. *et al.* 2001 ApJ, in press.

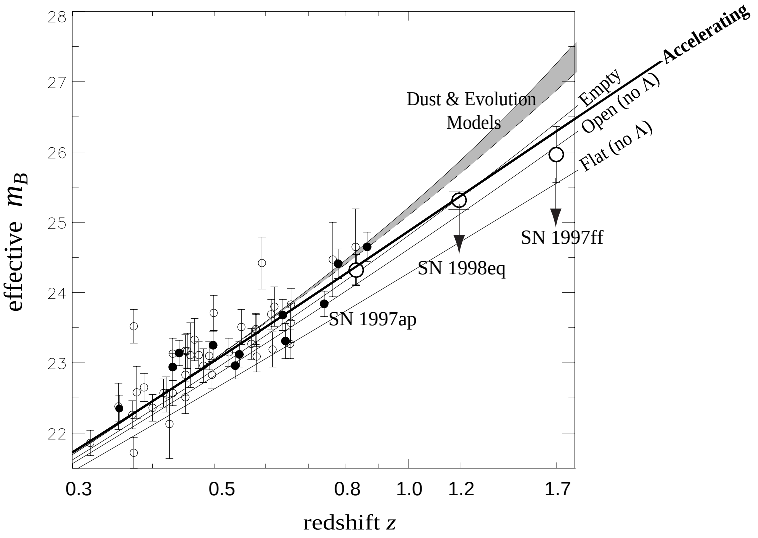

Figure 1: Open points show Hubble diagram for 42 high-z SNe (Perlmutter *et al.* 1999) along with comparable non-host-extinction-corrected points for our more recently discovered SNe with HST followup (Knop *et al.* 2000, 2001). The magnitude difference between the best-fit "Accelerating Λ" world model $(\Omega_M, \Omega_\Lambda) = (0.28, 0.72)$ and suitable ones with $\Omega_\Lambda = 0$ show redshift dependencies which would be very hard to mimic within the context of SNe evolution or gray dust hypotheses (the gray shaped 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 estimate 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, and better (planned, not serendipitous) measurements, as proposed here are necessary.

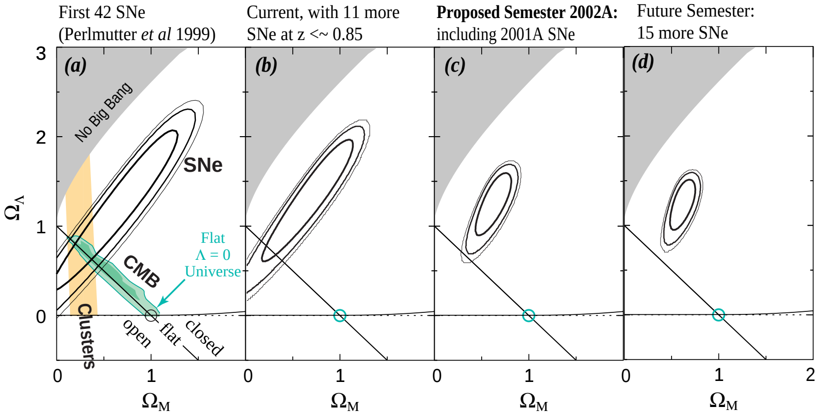

Figure 2: (a) 68%, 90%, and 99% confidence regions in the $\Omega_M - \Omega_\Lambda$ plane from the 42 distant SNe Ia in Perlmutter *et al.* 1999. with the overlap of the recent combined CMB results (Jaffe *et al.* 2001) and the Ω_M measurements from galaxy clusters. (b) Results presented by Knop *et al.* (2000) for the confidence region, after including our next 11 SNe Ia with HST followup. (c) Expected confidence region after proposed semester 2002A (including SNe from this proposal). (d) After one more semester. The 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).

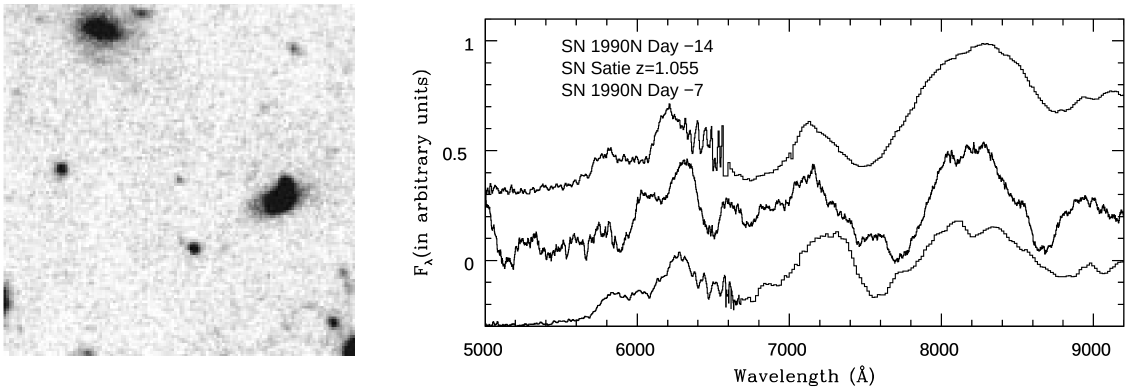

Figure 3: (a) 30" × 30" section of our NIRI image centered on "Satie", a supernova at $z = 1.06$ discovered in our search during semester 2001A. The combined (12 hr) NIRI image reaches S/N $\sim$ 14; a final reference image with NIRI is needed to subtract host galaxy light. (b) Spectrum of "Satie" obtained in 2 hrs with ESI on Keck, smoothed to 155 $\AA$, and compared to the nearby template SN1990N.

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

The program described under Scientific Justification requires the detection and follow-up of 15 SNe Ia out to a redshift of 1.2. Our program has the dual aim of testing for the presence of hypothesized systematics while further constraining the amount and nature of the dark energy. Our discovery of SN 1998eq [Ald98] demonstrated that wide-area detectors on large telescopes at excellent sites now enable the discovery of SNe Ia out to $z \sim 1.2$. For a search out to this redshift, ~ 15 good SNe Ia can be harvested during the large campaign proposed here. Thus, we have optimized the redshift distribution of these proposed SNe Ia assuming an upper envelope set by the number of SNe Ia which can be discovered and spectroscopically confirmed as a function of redshift, but modulated to account for Poisson fluctuations, uncertainties in the SN Ia rate, and using $z = 1.2$ as an upper limit. We have further emphasized redshifts where cross-filter K-corrections are small. Given these constraints, our calculations, (see Fig. 2c) show that two $z \sim 1.2$ SNe Ia along with three $z \sim 0.85$ SNe Ia and ten $z < 0.85$ SNe Ia make the greatest improvement over our current results (Figs. 2a & 2b), and also can be efficiently discovered together. Photometry of these SNe Ia, along with spectroscopy and restframe B-I colors of one or more $z \sim 0.5$ SNe Ia also allow questions of SN Ia evolution and abnormal dust to be directly addressed.

The experiment consists of three observational components: a search during which the SN candidates are found, spectroscopic confirmation, classification and redshift determination of the SN candidates, and optical and NIR follow-up to obtain the SN Ia lightcurves. The SN Ia discoveries require deep wide-field imaging on the CTIO 4-m with MOSAIC. The spectroscopic confirmation will be obtained using Gemini, Keck, and VLT. The photometric follow-up at $z \sim 1.2$ will be undertaken by HST (optical) and Gemini (NIR), follow-up at $z \sim 0.85$ by HST (optical) and VLT (NIR), and that at $z \leq 0.85$ by a combination of WIYN (optical), Gemini (optical + NIR), NTT (optical), and VLT (optical + NIR).

The goal is to obtain a complete lightcurve in restframe B (for SNe at $z < 1$) or U (for SNe at $z > 1$) and a B-V color at maximum for all SNe Ia. The lightcurve width is essential for standardizing the SNe, as SNe with wider lightcurves are intrinsically more luminous than those with narrower lightcurves. Additional restframe B- and V-band magnitudes at peak are necessary for SNe at $z > 1$ because of the susceptibility of the absolute U magnitude to intrinsic variations and host galaxy dust extinction. These measurements are fundamental to the construction of the SN Ia Hubble diagram. For one or more $z \sim 0.5$ SNe Ia with early discovery, high S/N spectroscopy will be used to determine the SN Ia metallicity using restframe UV features (for which comparison low-z spectra are being obtained with 24 HST orbits) and line ratio luminosity indicators $\mathcal{R}$(SiII) [Nug95] (see Fig. 3). For these same SNe Ia, restframe B-I color (using Z- and J-band observations from VLT) will be used to determine the full host-galaxy extinction law (rather than assuming it from B-V measurements)

These observations are very demanding, starting with the search (see CTIO 4-m technical description). A successful search is required to feed all of the scheduled follow-up (including 100 awarded HST orbits). **Thus the search we propose with the CTIO 4-m MOSAIC is the most critical aspect of this proposal**. Next is NIR photometry of $z \sim 1.2$ SNe Ia that the advent of Gemini makes possible. Without these observations our highest-z HST-observed SNe Ia cannot be corrected for host-galaxy extinction. GMOS spectroscopy provides the crucial data needed to identify type Ia SNe and hunt for clues of evolution. Finally, the high-quality optical lightcurve follow-up for the medium-z SNe Ia is obtained using WIYN and Gemini.

Use of Other Facilities *Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program.*

To insure as best as possible that we will be able to feed the scheduled follow-up, we will complement the CTIO-4.0 m run with a search using the 12x8k camera at the CFHT telescope. In addition, for the very highest SNe, we will also be searching with the SuprimeCam on Subaru.

To insure that we will be able to obtain the spectroscopic confirmation of our candidates, this time-consuming observing work will also be carried out using 8-m – 10-m class telescopes such as VLT and Keck in addition to Gemini. The photometric follow-up of the most distant SNe Ia ($z > 0.85$) requires the use of HST (optical) and Gemini (NIR). The photometric follow-up of the SNe Ia in the redshift range $z = 0.35$–0.85 will be undertaken on ground based 4.0-m and 8.0-m telescopes. Therefore, we are submitting complementary proposals to —or have been awarded time at— the TNG, CFHT, NTT, VLT, Subaru, HST and Keck telescopes. All of the follow-up observation fails if the SNe are not found and if those at high redshift cannot be calibrated with NIR photometry – so the role of NOAO as proposed here is absolutely crucial to the success of the coordinated program.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. If you wish to identify this proposal as a resubmission, include the old proposal ID number and semester.*

Demonstrated Successes: Over the past few years we have discovered and studied >100 SNe (~ 80 at CTIO) at redshifts $z = 0.03$–1.20. We have followed each of these SNe with photometry over the light curve (beginning before or at maximum light in almost every case) and spectroscopy near peak for most. Almost all of our SNe are Type Ia since SNe Ia are typically 2 magnitudes brighter than the other types. Eighteen SNe Ia have been observed by the HST. Nineteen others formed the core of the Spring 1999 Nearby Campaign (a campaign to study low-redshift, $z < 0.1$, SNe Ia). The results have been published in Perlmutter *et al.*, 1997, Perlmutter *et al.*, 1998, and Perlmutter *et al.*, 1999, Knop *et al.*, 2000, Goldhaber *et al.*, 2001, Pain *et al.* (submitted), and additional papers are in preparation.

Spring 2001a SNe Ia Search: We were awarded 3 nights in March 2001 and 3 nights in April 2001 at CTIO-4.0m/Mosaic for the Spring 2001 SNe Ia search, as well as 2 nights at WIYN/MIMO and 35 hours at Gemini/NIRI for the follow-up. The search campaign was a striking success, as more than 17 SNe Ia have been discovered in the redshift range $z = 0.35$–1.1, and HST follow-up photometry was triggered for five of the highest redshift SNe. Although half of the WIYN time was lost due to bad weather conditions, this telescope allowed us to gather good 3rd epoch points for the SNe Ia detected in the redshift range $z = 0.35$–0.55. Observations of the most distant SNe Ia —$z \sim 1.055$ detected with CTIO/MOSAIC and $z \sim 1.12$ detected at CFHT/12x8k— have been carried out at Gemini/NIRI. Because of cancellation of the queue this program was not carried out in queue mode. However it was used as a test program for NIRI SV (broadband imaging mode with the f/6 camera). About 12 hours of useful data were obtained in this way, approximately half of our original request (when overheads are taken into account). The data quality is good, and the images are currently being reduced (see figure 3). Final analysis awaits acquisition of final reference images (proposed here) of the SN's underlying host galaxy.

UV Observations of Nearby Type Ia Supernovae: The program "UV Observations of Nearby Type Ia Supernovae" was successfully carried out this past spring at several ground-based facilities and HST. The spectra of Hubble-flow SNe Ia observed from HST and from the ground were taken at weekly intervals over a range in time starting slightly before maximum light and extending to +30 days. These observations were aimed at accomplishing the following three goals: (1) Calibration of the rest frame UV light curves of SNe Ia and an assessment of their potential use as distance indicators through UV light curve shape analyses. (2) Improvement in our understanding of the physics of SNe Ia, metallicity/evolutionary effects and correlations between peak brightness and UV spectral features. (3) Calibration of the SNe Ia previously observed by HST at high-redshift.

$\boxed{\star}$ CTIO 0.9-m Apr/May 01 We were awarded 2 nights on the CTIO 0.9-m for the photometric screening of the nearby supernova candidates and initial UBVRI photometry. Both nights were good and the data is currently being analyzed.

$\boxed{\star}$ CTIO 1.5m Apr/May 01 We were awarded 3 nights on the CTIO 1.5-m for follow-up photometric observations of the supernovae, particularly concentrating on U-band photometry. All of the nights were good and the data is currently being reduced.

$\boxed{\star}$ YALO Apr/May 01 We were awarded ~ 20 hrs on the YALO 1.0-m for the BVI photometric follow-up of the 2 HST observed supernova candidates. The light curves from these observations are almost completely reduced.

$\boxed{\star}$ KPNO 2.1-m Apr/May 01 We were awarded 6 nights on the KPNO 2.1-m for both spectroscopic screening of supernova candidates and spectroscopic follow-up of our HST supernova. All nights were good and we issued reports of supernova discovered/classified in IAUC's: 7612, 7614, 7618, 7640.

$\boxed{\star}$ KPNO 4.0-m Apr/May 01 We were awarded 1 night on the KPNO 4.0-m which was used for late-time spectroscopic follow-up of the HST observed supernovae. The red observations have been reduced.

Detection and Observation of Nearby Type Ia Supernovae: To control the systematic errors affecting the $(\Omega_m, \Omega_\Lambda)$ measurements it is necessary to gather as much information as possible on the intrinsic properties of SNe Ia. In particular, measuring the intrinsic colors of SNe Ia with good precision allows for the correction for absorption by dust. Also studying the spectral evolution of SNe Ia helps to constrain theoretical models of these objects. Such studies are only possible on nearby SNe Ia, $z < 0.15$. In Spring 1999, we undertook a large nearby supernova search in collaboration with other groups. More than 50 SNe were discovered, among which 19 were SNe Ia in the nearby Hubble flow discovered near maximum (Aldering 2000). Papers are near submission on the overluminous SN Ia SN1999aw and on the hypernova SN1999as; analysis of the balance of the dataset is underway. CTIO and KPNO instruments played a key role in the photometric and spectroscopic follow-up of these events, as follows:

$\boxed{\star}$ CTIO 4-m Mar/Apr 00 We were awarded four nights for final reference spectra of SNe from the very successful Spring 1999 Nearby Campaign. Substantial time was lost over the four nights due to technical problems at the telescope. Final reference spectra (i.e. after the SN has faded) and improved host-galaxy redshifts were obtained for 10 SNe. Additionally, three SNe were confirmed in IAUCs.

$\boxed{\star}$ CTIO 1.5-m Feb/Apr 00 We were awarded six nights for final *UBVRI* photometry reference points for SNe from the Spring 1999 Nearby Campaign. We obtained final references (i.e. after the SN has faded) for 15 SNe.

$\boxed{\star}$ KPNO 4-m Apr 99 We were awarded two nights at the KPNO 4-m to obtain spectral time series for SNe Ia discovered as part of the Nearby Campaign. On the first of these nights we successfully obtained spectra for 14 SNe Ia from the total sample of 19 SNe Ia which had intensive follow-up. The second of these nights was unusable due to strong winds.

$\boxed{\star}$ KPNO 2.1-m Apr 99 We were awarded four nights to obtain *UBVRI* photometry of Nearby Campaign SNe Ia. Half of this time was lost due to clouds or strong winds.

$\boxed{\star}$ CTIO 1.5-m Mar/Apr 99 We were awarded seven nights to obtain *UBVRI* photometry of Nearby Campaign SNe Ia. Most of this time was usable, and the resulting photometry was reduced after the final references were taken in Spring 2000.

$\boxed{\star}$ CTIO 0.9-m Mar/Apr 99 We were awarded four Director's Discretionary nights during bright time to obtain *UBVRI* photometry of the brighter Nearby Campaign SNe Ia. Most of this time was usable, and the photometry is now reduced.

$\boxed{\star}$ CTIO 4-m Mar 99 We were awarded four nights to screen and obtain spectral time series for nearby supernova discovered as part of the Spring 1999 Nearby Campaign. With the CTIO 4-m we screened the bulk of the 40 SNe discovered in this Campaign, and obtained over half of the spectral time-series data for the Campaign. The discoveries from CTIO were reported in IAUC's 7128 (SN1999as), 7130 (SN1999aw, SN1999ax, SN1999ay), 7131 (SN1999az, SN1999ba, SN1999bb), 7134 (SN1999be, SN1999bf), and 7136 (SN1999bi, SN1999bj, SN1999bk, SN1999bl, SN1999bm, SN1999bo, SN1999bp). Along with the other SNe discovered in the Campaign, this is the largest number of spectroscopically confirmed SNe ever discovered in such a short period of time.

Detection and Observation of High-z type Ia Supernovae:

$\boxed{\star}$ CTIO 4-m Apr 99: We were awarded two nights for final photometric followup at the CTIO 4-m to provide high quality reference images in both R and $I-$ for most of the high-z SNe discovered in the previous two semesters. Both nights were clear, but half of the first night was lost to computer problems. Analysis of the SNe lightcurves for which final reference images were obtained has been presented in Knop *et al.* (2000). The photometry has been combined with HST photometry to obtain new constraints on the cosmological parameters, which agree well with the previous results, as shown in Figure 2b from Knop *et al.*, (2000).

$\boxed{\star}$ CTIO 4-m Dec 98/Jan 99: We were awarded five nights of final photometric followup at the CTIO 4-m to provide high quality reference images in both R and $I-$ for most of the high-z SNe discovered in the previous two semesters. All but one of these nights was clear, and the resulting data went into the Knop *et al.*, (2000) analysis.

$\boxed{\star}$ CTIO 4-m Mar 98/Apr 98, Keck Apr 98: On this our third run with the BTC we were able to discover > 20 high-z SN candidates at CTIO, 13 of which were spectroscopically confirmed including 8 SNe Ia observed with multi-color photometry with HST. Using the final reference images from the following year's observing runs (above two items), the photometry analysis of these SNe was completed, combining both ground-based and HST data (Knop *et al.* 2000).

Observing Run Details for Run 1: CT-4m/MOSAIC

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

Search Technique: The search technique we have developed and used so successfully works as follows: We obtain reference images just after new moon using the MOSAIC camera on the CTIO 4-m telescope, and with SuprimeCam on the Subaru telescope. Just before the next new moon, we observe the same fields again, and examine the tens of thousands of high redshift galaxies ($z \sim 0.3$–1.5) to find those showing the new light of a SN that was not there on the previous observation.

We have regularly demonstrated our ability to find and follow distant supernovae in this way over the last several years (See International Astronomical Union Telegrams and Circulars by the Supernova Cosmology Project in which we have reported more than 100 discoveries of supernovae), including spectroscopically confirmed SNe Ia at the highest redshifts (e.g. SN1998eq at $z = 1.2$, as well as the $z = 1.055$ and $z = 1.12$ SNe Ia detected in Spring 2001 on the CTIO-4.0 m and CFHT).

We have developed extensive software to find and accurately identify these supernova candidates within days of the observations. As in our 2001A run where we discovered 17 SNe, we will determine redshifts for around 15 of the faint (likely high-redshift) candidates and from this will select 2 $z > 1$ SNe Ia for detailed follow up.

The targets will be found in search fields with declination near 0° so that they can be observed by telescopes in both hemispheres. We will also take care to select regions of low Galactic extinction. The final selection of fields depends on the dates scheduled for searching.

Note that we will guarantee the discoveries for all the follow-up by providing complementary searches at other telescopes with different weather (see above.)

Imaging depth: Our deepest imaging must reach SNe Ia at $z = 1.2$, having $I = 24.5$ at maximum. To allow for discovery 0.4 mag below maximum (pre-max) and a dispersion of 0.3 mag, we aim at detecting $I = 25.2$ on the subtraction. Based on our previous successful search experience to this depth and guidance from the NOAO exposure time calculator, we estimate that MOSAIC under good conditions (i.e lunar phase 0–7 days, airmass 1.0–1.5, seeing $1.1''$) can detect $I = 25.2$ point sources at $> 7\ \sigma$ *after subtraction* with 5.4 hours of integration. Note that a 7 σ threshold is necessary to suppress spurious candidates given the 10^7 independent samples present in such large images, and the great expense of spurious candidates targeted for spectroscopic follow-up at the faintest targeted magnitudes.

For the shallow search ($0.35 < z < 0.8$), we aim to detect ~ 10 SNe Ia, including at least one ~ 10 rest-frame days before maximum at 7 σ. This requires images reaching $R = 24.2$. This depth can be achieved in less than 10 minutes. Split exposures are needed to veto cosmic rays and asteroids.

Areal coverage: Using our rate determinations [Pai96, Pai01], we have conducted Monte-Carlo simulations to estimate the number of pre-max SNe detectable with a search to $I = 25.2$ with an optimal 3-week spacing between epochs. The rate is based on actual observations (conducted the same way as proposed here), so it already includes any detection inefficiencies. These simulations showed that we should detect ~ 8 SNe Ia/$\square^\circ$ before maximum with $0.8 < z < 1.2$ (median z=1). In order to guarantee discovery of 5 SNe Ia with $0.8 < z < 1.2$ to be followed with HST, three MOSAIC pointings (1.14 $\square^\circ$) are required.

Note that HST requires target coordinates to within 1° three weeks *prior to discovery* of our SNe Ia.

Since the SN Ia locations are not known yet, all of our deep search fields must be located within a single 1° radius on the sky. The result is that the deep field can be observed for at most 6 hrs per night. These crucial deep observations comprise the bulk of our observing time request.

For the shallow search, 10 pre-max SNe Ia to be followed with WIYN, NTT, Gemini and VLT are desired. Our simulations indicate that 20 pointings reaching $R = 24.2$ are required to meet this target. For many of these objects, the S/N will be good enough for the photometry on the detection image to contribute significantly to the light curve, especially because early discovery helps constrain measurement of the lightcurve width. As in previous searches in this redshift range, we will search in R- and I-bands, making it possible to have early photometry points in both these bands.

The need for closely timed epochs: Only SNe Ia discovered at or before maximum produce useful light curves. Therefore two successive imaging epochs must be separated by 3–4 weeks since the time from explosion to 7 rest-frame days before peak is 3 weeks at $z = 0.5$ and 4 weeks at $z = 1.0$. Since each faint SN-candidate requires ~ 4 hrs on Keck, Gemini or VLT, spectroscopy of post-max SNe Ia is an expensive waste of large-aperture telescope time. Larger epoch spacings can result in up to 60% of candidates being post-max. For this reason the basic proposed timing of the observations is crucial, and we cannot simply use pre-existing deep imaging as references (e.g. from DeepLens) for this search. The discovery images must be completed several days prior to new moon so that confirming spectroscopy at Keck, Gemini and VLT and follow-up photometry from HST, Gemini, WIYN, NTT and VLT can commence by new moon.

Search scheduling: At this time, our preference is for a reference run near new moon in April (April 13-15) and a search run near 3rd quarter in May (May 6-8). Alternatively a similar timing for a March reference (March 14-16) and an April search (6-8) could be preferable —depending on timing of the HST servicing mission. Depending on the HST and Keck availability, it is also possible to split the discovery observations over two epochs. The timing of the search dictates the scheduling at all follow-up telescopes (including HST). Therefore, *it is essential that we be contacted prior to scheduling as coordination amongst the participating telescopes is vital.* The exact target fields are to be determined based on the time of year the CTIO observations are scheduled.

Image analysis resources: In our past searches, the data rate–bandwidth ratio has allowed us to ship our search data to LBNL over the Internet for reduction and analysis within hours of data taking. The larger search data set which MOSAIC will produce, combined with the remoteness of CTIO, may require that image co-addition take place at CTIO and that co-added images then be sent via the Internet to LBNL for searching. We will take the necessary UNIX-compatible laptops to the search run for this purpose. Note that we have a proven success at reducing data at the telescope in this way, and sending it up to LBNL for further processing.

Rationale for a concentrated annual search: The science is now requiring us to study SNe Ia at higher redshifts, 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 at the higher redshifts, 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; In accordance with this plan, we did not request time for semester 2001B.

Reference Images for the SNe Ia Discovered During the 2001 Run: Note that the deep images taken during the next run will serve a double purpose, as they will also be used as final

I-band reference images needed for the photometric follow-up of last Spring's 2001A run. This will allow us to save a large amount of observation time on other telescopes like WIYN. Note also that for the search run, we will build deeper images by combining the first period reference images with observations of the same fields taken at CTIO-4.0m during the previous runs.

Summary of the observing time request: The deep search requires three pointings of 5.4 hrs exposure (plus 0.4 hrs of overhead) in I-band at two epochs. The deep search region is visible for only 6 hrs per night (see above), so 3 nights (3×5.8 hrs/6 hrs visibility per night = 3 nights) at each epoch. The balance of each night will be necessary to conduct the shallow search, which requires twenty pointings of 10 minutes in R-band and 10 minutes in I-band at two epochs. *3 nights per epoch for two epochs brings our total request to 6 nights.* The MOSAIC time requested here is absolutely essential to the success of this international, multi-telescope campaign.

Instrument Configuration

Filters: R, I	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 10 to 11

Dec. range of principal targets (degrees): +7 to +8

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

Observing Run Details for Run 2: WIYN-SYN/MIMO

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

The WIYN-SYN telescope, in combination with the Gemini/GMOS instrument —see proposal below— will be used to obtain restframe B-band and V-band lightcurves for the discovered SNe Ia in the redshift range $z = 0.35$–0.55. It will also be used to obtain final R and I band reference images for $z = 0.35$–0.55 SNe Ia discovered during the Spring 2001 run.

SNe Ia Photometric Followup: At these redshifts restframe B-band is observer-frame R-band, while restframe V-band is observer-frame I-band. A full restframe B-band lightcurve over maximum is required to obtain the peak brightness and the lightcurve width for each SN Ia. The lightcurve width is essential for standardizing the SNe Ia, as SNe Ia with wider lightcurves are intrinsically over-luminous while those with narrower lightcurves are intrinsically under-luminous. Restframe V-band measurements near peak are required to measure the SNe Ia color needed to correct for host-galaxy extinction. The ratio of total-to-selective extinction is 4.2 for B-V, thus peak magnitudes accurate to 0.04 mag are required to keep the extinction correction error below 0.25 mag. (Note that the intrinsic dispersion of extinction-corrected lightcurve-width standardized SNe Ia is only 0.12 mag and is thus a relatively minor contributor).

In the search (see CTIO 4-m technical section), we expect to find 5–10 SNe Ia in the redshift range $z = 0.35$–0.55. We will select the 4 best of these —discovered well before maximum— to follow with WIYN-SYN. The CTIO 4-m search will provide a pre-maximum photometry point.

The following table gives representative exposure times for a $z \sim 0.5$ SNe Ia observed at 4 epochs. We see that the time needed to observe a single $z \sim 0.5$ SN Ia at maximum in the R and I bands is about 5.2 hours. Therefore, we request 20.8 hours, or 2.6 equivalent nights at WIYN-SYN/MIMO to observe 4 SNe Ia at 3 different epochs. Adding 15 min per visit plus 25% of elapsed time, to take into account the overheads, our total request is 30.75 hours, or 3.85 equivalent nights. Obtaining 4th epoch points for such distant SNe Ia is beyond the capability of WIYN and will be carried out with the complementary work described above in "Use of Other Facilities".

Day Observer-Frame	Moon	R-mag	I-mag	S/N [R]	S/N [I]	Exp. R [s]	Exp. I [s]	Total [s]
0	New	22.4	22.2	25	25	1200	4200	5400
8	3rd	22.6	22.2	25	25	1800	4200	6000
22	1st	23.4	22.7	15	—	7200	—	7200
32	New/3rd	24.1	23.0	15	—	7200	—	—

Reference Images: We also need to collect deep photometry reference images for the SNe Ia detected during our highly successful Spring 2001 run and observed with ground-based telescopes, including WIYN/MIMO. The target table lists the exposure times needed in the R and I bands for each SNIa. The total exposure time needed for taking reference exposures is 13.9 hours, or 1.75 equivalent nights. If we add 0.15 min per visit, plus 25% of elapsed time to take into account the overheads, our total request is 20h, or 2.5 nights.

Summary: In our experience, the WIYN-SYN telescope has allowed us to obtain high quality photometry observations for SNe Ia at a redshift up to $z = 0.55$. It will be used to follow-up 4 SNe Ia in the redshift range $z = 0.35$–0.55. WIYN-SYN/MIMO will also be used to gather R and I reference images of the SNe Ia discovered during the Spring 2001 run, and followed-up with ground instruments. For these two projects, we request a total amount of 50.78 hours, or 6.35 equivalent nights on WIYN-SYN/MIMO.

We note that the reference observations could be carried out in classical mode. In that case, we would want the time to be scheduled near the time of discovery of the new SNe.

We have a great deal of experience working with the WIYN queue observers, promptly providing updated targets and exposure times for the newly discovered SNe Ia. In our past SNe Ia search follow-up the queue capability of WIYN has been an essential ingredient, allowing lightcurve coverage not possible with conventional scheduling.

Finally, we note that we provided NOAO with the red-sensitive LBNL CCDs and are eager to observe with one if it becomes available at WIYN. Indeed, it would be the ideal detector since it was developed at LBNL specifically for this high-redshift supernova work.

Instrument Configuration

Filters: R, I	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 10 to 14

Dec. range of principal targets (degrees): -10 to +10

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

Target Table for Run 2: WIYN/MIMO

Obj ID	Object	α	δ	Epoch	Mag.	Filter	Exp. time	# of exp.	Lunar days	Sky	Seeing	Comment
SN1	Supernova 1	10:30:00	+07:00:00.0	2000	23.2	R	5200	6	0	phot	0.8	Obs. over weeks
SN1	Supernova	10:30:00	+07:00:00.0	2000	22.8	I	11700	13	0	phot	0.8	Obs. over weeks
SN2	Supernova	10:30:00	+07:00:00.0	2000	23.2	R	5200	6	0	phot	0.8	Obs. over weeks
SN2	Supernova	10:30:00	+07:00:00.0	2000	22.8	I	11700	13	0	phot	0.8	Obs. over weeks
SN3	Supernova	10:30:00	+07:00:00.0	2000	23.2	R	5200	6	0	phot	0.8	Obs. over weeks
SN3	Supernova	10:30:00	+07:00:00.0	2000	22.8	I	11700	13	0	phot	0.8	Obs. over weeks
SN4	Supernova	10:30:00	+07:00:00.0	2000	23.2	R	5200	6	0	phot	0.8	Obs. over weeks
SN4	Supernova	10:30:00	+07:00:00.0	2000	22.8	I	11700	13	0	phot	0.8	Obs. over weeks
SN5	Supernova	10:30:00	+07:00:00.0	2000	23.2	R	5200	6	0	phot	0.8	Obs. over weeks
SN5	Supernova	10:30:00	+07:00:00.0	2000	22.8	I	11700	13	0	phot	0.8	Obs. over weeks
L1	PG1323	13:25:45	-08:50:00	2000	13	R	10	1	0	phot	1.0	SN1-5
L1	PG1323	13:25:45	-08:50:00	2000	13	I	10	1	0	phot	1.0	SN1-5
L2	SA104	12:43:55	-00:34:00	2000	13	R	5	1	0	phot	1.0	SN1-5
L2	SA104	12:43:55	-00:34:00	2000	13	I	5	1	0	phot	1.0	SN1-5
SN	Holst	15:43:45.8	+07:57:50	2000	21.9	R	300	1	0	phot	0.8	Reference
SN	Holst	15:43:45.8	+07:57:50	2000	21.9	I	1200	1	0	phot	0.8	Reference
SN	Strauss	09:44:31.5	+08:02:03	2000	21.9	R	300	1	0	phot	0.8	Reference
SN	Strauss	09:44:31.5	+08:02:03	2000	21.9	I	1200	1	0	phot	0.8	Reference
SN	Bizet	14:01:51.2	+05:05:38	2000	23.1	R	1800	1	0	phot	0.8	Reference
SN	Bruch	14:02:00.9	+05:00:59	2000	23.1	R	1800	1	0	phot	0.8	Reference
SN	Massenet	13:57:04.5	+04:31:00	2000	23.1	R	1800	1	0	phot	0.8	Reference
SN	Vivaldi	15:45:35.9	+08:16:51	2000	23.1	R	1800	1	0	phot	0.8	Reference
SN	Salieri	14:01.51.4	+04:53:12	2000	24.1	R	13800	1	0	phot	0.8	Reference

Observing Run Details for Run 3: GEM-NQ/GMOSN

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

(a) GMOS Spectroscopy: We aim to obtain spectra of 5 SNe Ia candidates to confirm the SN type and obtain a redshift. Typical exposure times of 3600s each are sufficient for an initial screening of 5 candidates in the magnitude range 23–25. More exposure time would then be spent on two candidates that appear to be likely $z > 1$ type Ia supernovae —either from those screened by GMOS or from elsewhere. These will require additional exposure times of 3 hours each. Note that the final spectra can be smoothed heavily to reveal the supernova features (Fig. 3).

The total on-source time requested is 11 hours. Following the GMOS web page guidelines, we add 30 minutes per new target, plus 25% of elapsed time to take into account the overheads. Here, we assume that obtaining the I-band flats to reduce the effects of fringing is included in the 25% overhead. We therefore require 17.2 hours for the GMOS spectroscopy observations.

(b) GMOS Imaging: GMOS will also be used to obtain lightcurves for two SNe Ia discovered in the redshift range $z \sim 0.7$–0.85 —higher redshift SNe Ia require HST for optical observations.

Exposure Times and Overheads: We intend to obtain 5 i' points —rest frame B— and 1 z point —rest frame V— around maximum, with a S/N ratio of 20. The table below presents representative exposure times for a $z \sim 0.8$ SNIa observed at GMOS. It shows that obtaining a lightcurve takes about 6.75 hours per supernova. The corresponding time for a $z = 0.75$ SN Ia is 5.3 hours. Therefore, the total on-source time requested is 12 hours. Adding 25% of elapsed time, plus 15 minutes per visit to take into account the overheads, we therefore request 18 hours on GMOS. We also assume that the z and i images at peak can be obtained with the spectroscopy, removing the acquisition overhead for these. The target table summarizes the photometric observations we plan to carry out at GMOS.

Day Observer Frame	I-Mag	Z-Mag	S/N [I]	S/N [Z]	Exp. I[s]	Exp. Z[s]	Total
0	23.1	23.1	20	20	480	2820	3300
10	23.3	—	20	—	660	—	660
20	23.7	—	20	—	1380	—	1380
30	24.3	—	20	—	4140	—	4140
40	25.0	—	20	—	14880	—	14880

Division of time between TACS: This proposal is being submitted on behalf of the Supernova Cosmology Project, and we are also applying for Gemini time for this program via the U.K. TAC —see proposal by Hook *et al. Cosmology with High-Redshift Type Ia Supernovae.* We request that the time be divided between the U.S. and U.K. allocations in approximately the proportion of partner shares, i.e. 23.5 hours (US) and 11.7 hours (UK).

Summary: We will use Gemini/GMOS for the spectroscopic confirmation of 5 SNe, including 2 at a redshift $z > 1$, and the follow-up of two SNe Ia discovered in the redshift range $z = 0.7$–0.8. We request 35.2 hours (US+UK) in May and June for this purpose.

Instrument Resources

Filters: i_G0302, z_G0304, OG515_G0306
Dispersers: R400_G5305
Focal Plane Units:

R.A. range of principal targets (hours): 10 to 14

Dec. range of principal targets (degrees): -10 to +10

Target Table for Run 3: GEM-NQ/GMOSN

Obj ID	Object	α	δ	Epoch	Mag.	Obs. time	WFS stars	IQ %	SB %	WV %	CC %	Comment
2001	SN1	10:30:00	+07:00:00.0	J2000	24.2	3200	PPO	50	80	any	50	Obs. over weeks
2003	SN2	10:30:00	+07:00:00.0	J2000	24.2	3200	PPO	50	80	any	50	Obs. over weeks
2011	PG1323	13:25:45	-08:50:00	J2000	13	5	PPO	50	80	any	50	SN 1–2
2012	PG1323	13:25:45	-08:50:00	J2000	13	5	PPO	50	80	any	50	SN 1–2
2013	SA104	12:43:55	-00:34:00	J2000	13	5	PPO	50	80	any	50	SN 1–2
2014	SA104	12:43:55	-00:34:00	J2000	13	5	PPO	50	80	any	50	SN 1–2

Observing Run Details for Run 4: GEM-NQ/NIRI6

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

Exposure times: For the two SNe Ia at $z > 1$, we need to determine the rest-frame B-V color with S/N ratio of 10. (Cosmological models at these higher redshifts are easier to differentiate than at lower redshifts.) The noise will be dominated by the J-band (rest-frame V) measurement, and since this measurement will involve subtracting a final J-band reference frame (to be obtained in a future semester) from the at-peak J-band data requested here, the current J-band data must reach a S/N of 14. (Restframe B will be determined to S/N > 20 from HST 850LP and/or VLT Z-band, as mentioned above).

In the J-band, SNe Ia in the redshift range of interest are predicted to have peak magnitude of $J = 23.8$. To estimate the required exposure time we have used the NIRI ITC with the following assumptions: median image quality (using the PWFS but not the OIWFS since we are using the f/6 camera), median sky transparency, 80%-ile water vapor and sky background, and airmass < 1.2. This gives an exposure time of 43800 seconds, in good agreement with the results from the observations taken in semester 2001a on the $z = 1.06$ SN "Satie" (Fig. 3). Observing one new supernova and the reference image for Satie will therefore require 87,600 seconds = 24.3 hours on target.

Overheads: Following the guidelines on the NIRI web page of 15 minutes per new target plus 25% of elapsed time used for off-setting etc., the total overheads would be 8.6 hours. We include an additional 2 hours to obtain photometric calibration for the two SN fields. Suitable standards will be chosen once the target positions are known. At this stage we include photometric calibration time as an overhead on top of the target exposure time. The total request is therefore 34.9 hours.

Division of time between TACs: This proposal is being submitted on behalf of the Supernova Cosmology Project, and we are also applying for Gemini time for this program via the U.K. TAC (see proposal by Hook *et al.* "Cosmology with High-Redshift Type Ia Supernovae"). We request that the time be divided between the U.S. and U.K. allocations in approximately the proportion of partner shares, i.e. 23.3 hours (US) and 11.6 hours (UK).

Instrument Resources

Filters: BB: J (1.25 um)
Dispersers:
Focal Plane Units:

R.A. range of principal targets (hours): 10 to 11

Dec. range of principal targets (degrees): +7 to +8

Target Table for Run 4: GEM-NQ/NIRI6

Obj ID	Object	α	δ	Epoch	Mag.	Obs. time	WFS stars	IQ %	SB %	WV %	CC %	Comment
3001	SN1	10:30:00	+07:00:00	J2000	23.8	43800	PP	50	any	80	50	
3002	Satie	13:57:12	+04:20:27	J2000	23.8	43800	pp	50	any	80	50	Reference

---

NOAO observing proposal LaTeX macros v2.5.