NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: September 30, 2000 **Category:** Cosmology

Cosmology with High-Redshift Type Ia Supernovae

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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.

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 (for which we will use several different tests). The WIYN-SYN telescope will allow us to photometrically follow-up a selection of these supernovae to measure 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 ($z \gtrsim 1$) supernova whose rest-frame V-band will have been redshifted to our J-band.

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	4	dark	Apr - Jun	Apr - Jun
3	GEM-NQ	NIRI6	3.5	bright	May - Jun	May - Jun
4						
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.

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, both by tests and improvements of the supernova measurements and by independent, cross-cutting cosmological measurements. In particular the recent balloon-based CMB measurements [Jaf00] strongly indicate that the geometry of the universe is flat, reinforcing evidence for an accelerating universe by eliminating the possibility of a low-density open universe (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 2001A to discover and study 15 SNe Ia, with the most distant to be followed with Gemini and 76 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 2001A, $\Omega_\Lambda = 0$ could be ruled out at better than 3σ. For a flat universe, Ω_M and Ω_Λ could be constrained to $\sim 7\%$. The resulting estimate of Ω_M, for *any* Ω_Λ, is still accurate to ± 0.2 in this simulation and would be 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 quite small compared to the statistical error. Remaining sources of systematic uncertainty which are unlikely, but possible, are SN Ia evolution and abnormal dust extinction. For this proposal, we have identified a series of refinements and tests that will "sharpen" this cosmological measurement tool by addressing these two issues: 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. Spectral tests for metallicity dependence will also be used (see Fig. 3). Restframe B-I colors from MOSAIC, WIYN, and VLT (J-band) will test for abnormal extinction.

Conclusion. By concentrating our year's effort on one large campaign (*and not requesting time on the alternate semesters*), 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.

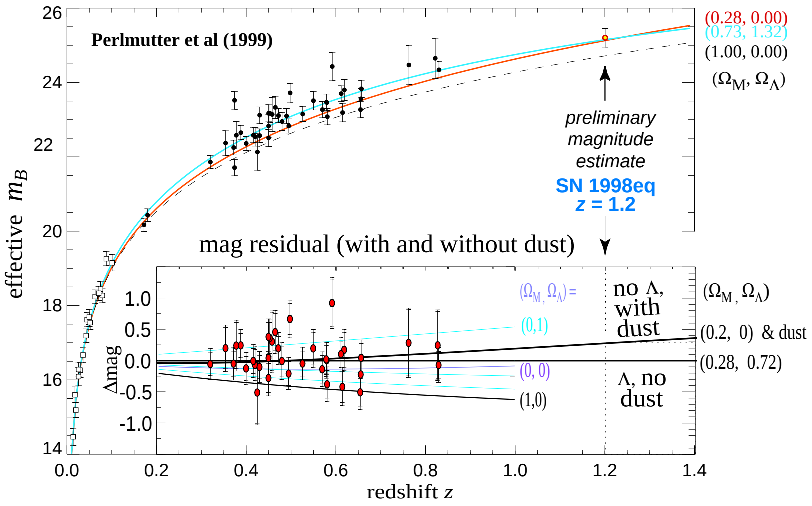

Figure 1: Hubble diagram for 42 high-z SNe (Perlmutter *et al.* 1999). The best-fit world model with $(\Omega_M, \Omega_\Lambda) = (0.73, 1.32)$ is drawn through the data (grey line). The Einstein-de Sitter case (1.0, 0.0) is strongly excluded by the current data (dashed line). The poor fit to the case $(\Omega_M, \Omega_\Lambda) = (0.28, 0.00)$ 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 world model and suitable ones with $\Omega_\Lambda = 0$ show redshift dependencies which would be very hard to mimic with SN evolution or grey dust (see inset panel). By extending our survey to $z \gtrsim 1$, the *shape* of the curve alone would become sufficient evidence to support a cosmological constant. The preliminary magnitude estimate of our highest redshift SN 1998eq at $z = 1.2$ is suggestive, but more analysis and more SNe at this redshift are necessary.

References

[Agu99] Aguirre, A. 1999, ApJ, 525, 593

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

[Jaf00] Jaffe, A. *et al.* 2000 astro-ph/000733, submitted to Phys. Rev. Lett.

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

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

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

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

[Pai00] Pain, R. *et al.* 2000, to be published.

[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.

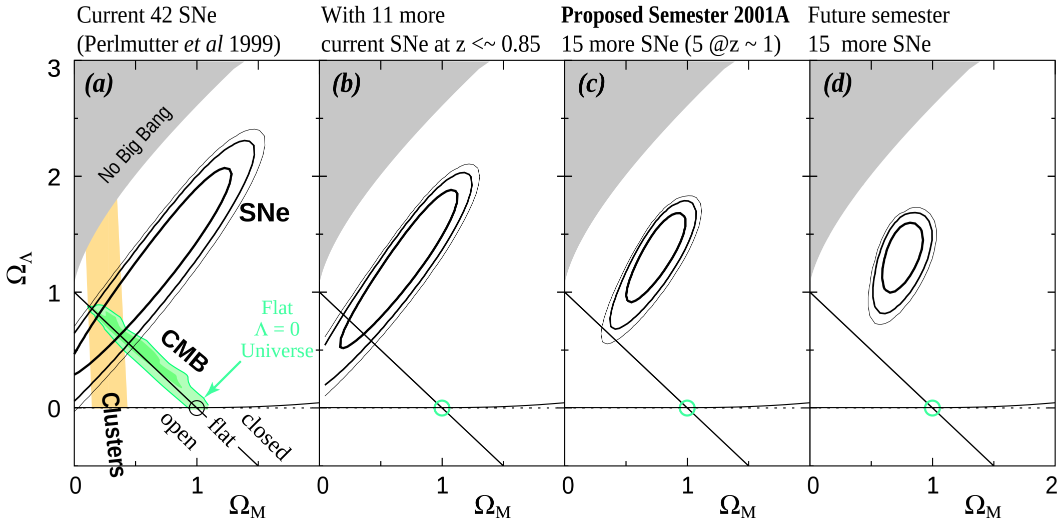

Figure 2: (a) 68%, 90%, and 99% confidence regions in the $\Omega_M - \Omega_\Lambda$ plane from the 42 distant SNe Ia in Perlmutter *et al.* 1999. These results indicate $\Omega_\Lambda > 0$, in agreement with the overlap of the recent combined CMB results (Jaffe *et al.* 2000) with the Ω_M measurements from galaxy clusters. (b) Expected confidence region after including our additional 11 $z < 0.85$ SNe Ia currently under analysis. (c) Confidence region expected from the observations requested in this proposal, including two at $z \sim 1.2$. (d) Future confidence region after another similar 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).

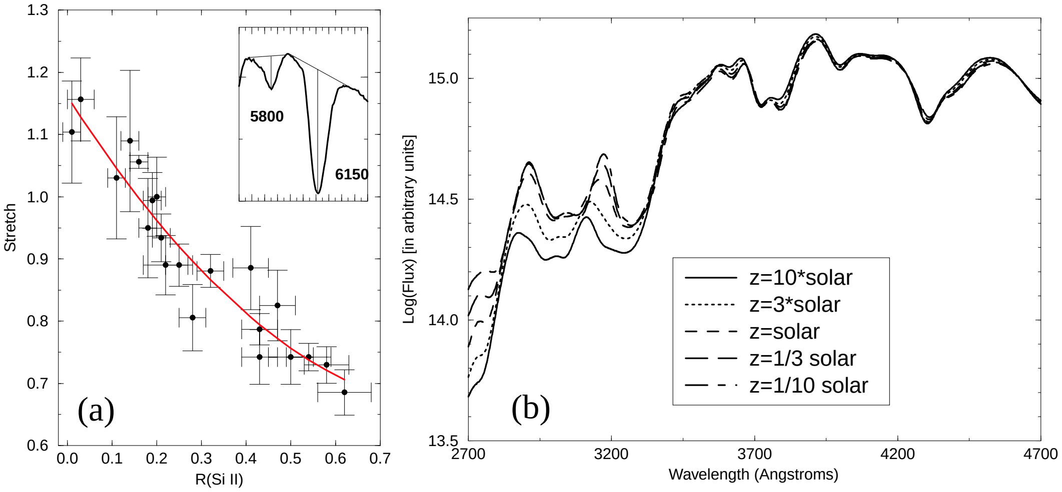

Figure 3: (a) The tight relationship between the spectroscopic ratio $\mathcal{R}$(SiII) and the lightcurve timescale stretch for well-observed low-redshift SNe Ia (see [Nug95] for a similar $\mathcal{R}$(CaII) plot). The inset shows how this spectral ratio is measured. (b) Maximum light spectrum synthesis 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 as part of this campaign).

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. List all telescopes on which you have applied for or been granted time for observations related to this project. For each, indicate the nature of the observations, and describe the importance of the observations proposed here in the context of the entire program. (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 in the likely event that systematics are small. 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 with an upper envelope set by the number of SNe Ia which can be discovered and spectroscopically confirmed as a function of redshift, but decreased 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 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 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), NTT (optical), and VLT (optical + NIR).

The basic product of the observations will be 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 (described under CTIO 4-m technical description). A successful search is required to feed all of the scheduled follow-up (including HST). **Thus the search we propose with the CTIO 4-m MOSAIC is the most critical aspect of this proposal**. The next most critical aspect is NIR photometry of $z \sim 1.2$ SNe Ia that the advent of Gemini makes possible (see Gemini technical description). Without these observations our highest-z HST-observed SNe Ia cannot be corrected for host-galaxy extinction. Finally, high-quality optical lightcurve follow-up for the lowest-z SNe Ia benefits greatly from a queue-scheduled telescope such as WIYN-SYN (see WIYN-SYN technical description).

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the Principal Investigator 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.*

Demonstrated Successes.

Over the past few years we have discovered and studied >80 SNe ($\sim$ 70 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. Thirteen 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, and additional papers are in preparation.

$\boxed{\star}$ 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 and are currently being reduced. 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. The balance of the imaging data is being reduced.

$\boxed{\star}$ 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. Final analysis of the SNe lightcurves for which final reference images were obtained is now underway. The photometry will be combined with HST photometry to provide significant new constraints on the cosmological parameters.

$\boxed{\star}$ 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 photometry is being reduced, using the final references which 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 being 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.

$\boxed{\star}$ 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 final analysis of the SNe lightcurves is underway.

$\boxed{\star}$ CTIO 4-m Mar 98/Apr 98, Keck Apr 98: On 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. Now that final reference images have been obtained (in Apr 99) the final analysis of these SNe is underway.

Why CTIO? *(For CTIO proposals only.) Explain why access to the southern hemisphere is needed to achieve your scientific goals.*

The supernovae discovery phase of our Spring 2001 campaign requires a 4-m class telescope with a wide-field camera at a site with good seeing. In our experience, due to the excellent seeing, good weather and superb staff support, the CTIO 4-m has proven to be the most successful telescope by far in this most important discovery stage.

The spectroscopic follow-up requires a 10-m class telescope, while the photometry requires a 4-m class or space-based telescope. We are submitting complementary proposals to or already have been awarded time at the CFHT, NTT, VLT, HST and Keck telescopes.

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 succesfully works as follows: We will obtain reference images just after new moon using the MOSAIC camera on the CTIO 4-m telescope and at the 12x8k camera on the CFHT telescope. Just before the next new moon, we will 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 those at the highest redshifts (e.g. SN1998eq at $z = 1.2$).

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 avoid regions of high galactic extinction. The final selection of fields depends on the dates scheduled for searching.

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 $7\ \sigma$ 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 $7\ \sigma$. 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, Pai00], 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 detection inefficiencies (e.g. due to SNe buried within galaxy cores). 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-SYN, NTT, 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 two closely timed epochs: Only SNe Ia discovered at or before maximum produce useful light curves. Therefore the two 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 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 (2nd epoch) images must be completed several days prior to new moon so that confirming spectroscopy at Keck and VLT and follow-up photometry from HST, Gemini, WIYN-SYN, NTT and VLT can commence by new moon.

Search scheduling: Our preference is for a reference run near new moon in April (April 24-26) and a search run near 3rd quarter in May (May 16-18). Alternatively a similar timing for a March reference (March 26-28) and an April search (17-19) could be suitable. 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 product 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. (We have tested this use of laptops during previous runs.) This may be unnecessary if the Internet upgrades in progress are completed on time.

Rationale for a concentrated annual search: 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, we are requesting sufficient telescope time scheduled once a year — 6 CTIO 4-m nights in semester 2001A.

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:
Grating/grism:
Order:
Cross disperser:

Slit:
Multislit:
λ_{start}:
λ_{end}:

Fiber cable:
Corrector:
Collimator:
Atmos. disp. corr.:

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 will be used to obtain restframe B-band and V-band lightcurves for the discovered SNe Ia in the redshift range $z = 0.35$–0.65. 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 SNe 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 colors 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 negligible contributor).

In the search (see CTIO 4-m technical section), we expect to find 5–10 SNe Ia in the redshift range $z = 0.35$–0.65. 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 for the remaining epochs of the lightcurve to be followed with WIYN-SYN.

Observer-Frame Day	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	25	15	7200	4200	11,400
32	New/3rd	24.1	23.0	16	12	7200	4200	11,400

The table indicates that the total WIYN-SYN time needed to observe a single $z \sim 0.5$ SNe Ia is roughly 10 hours spread over 4 epochs. Thus our total WIYN-SYN request to follow 4 such SNe Ia is 40 hours, or 4 night equivalents. Note that the target table attached to this section is a representation of an amortized average time for each observation.

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.

Instrument Configuration

Filters:
Grating/grism:
Order:
Cross disperser:

Slit:
Multislit:
λ_{start}:
λ_{end}:

Fiber cable:
Corrector:
Collimator:
Atmos. disp. corr.:

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

Target Table for Run 2: WIYN-SYN/MIMO

Obj ID	Object	α	δ	Epoch	Mag.	Filter	Exp. time	# of exp.	Lunar days	Sky	Seeing	Comment
SN1	Supernovae 1	13:00:00	0:00:00	2000	23	R	2700	4	7	phot	0.8	Obs. over weeks
SN1	Supernovae 1	13:00:00	0:00:00	2000	22.5	I	5400	4	7	phot	0.8	Obs. over weeks
SN2	Supernovae 2	13:00:00	0:00:00	2000	23	R	2700	4	7	phot	0.8	Obs. over weeks
SN2	Supernovae 2	13:00:00	0:00:00	2000	22.5	I	5400	4	7	phot	0.8	Obs. over weeks
SN3	Supernovae 3	13:00:00	0:00:00	2000	23	R	2700	4	7	phot	0.8	Obs. over weeks
SN3	Supernovae 3	13:00:00	0:00:00	2000	22.5	I	5400	4	7	phot	0.8	Obs. over weeks
SN4	Supernovae 4	13:00:00	0:00:00	2000	23	R	2700	4	7	phot	0.8	Obs. over weeks
SN4	Supernovae 4	13:00:00	0:00:00	2000	22.5	I	5400	4	7	phot	0.8	Obs. over weeks
L1	PG1323	13:25:45	-08:50:00	2000	13	R	10	1	7	phot	1.0	SN1-4
L1	PG1323	13:25:45	-08:50:50	2000	13	I	10	1	7	phot	1.0	SN1-4
L2	SA104	12:43:55	-00:34:00	2000	12	R	5	1	7	phot	1.0	SN1-4
L2	SA104	12:43:55	-00:34:00	2000	12	I	5	1	7	phot	1.0	SN1-4

Observing Run Details for Run 3: 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. Two SNe Ia will therefore require 87,600 seconds = 24.3 hours on target.

We request photometric conditions (median sky transparency or better).

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 35 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 hours (US) and 12 hours (UK).

Targets: The search procedure will detect SNe Ia to $I = 25.2$. We have developed extensive software to find and accurately identify these supernova candidates within days of the observations. We will determine redshifts for around 15 of the faint (likely high-redshift) candidates using Keck and from this will select 2 $z > 1$ SNe Ia for detailed follow up.

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 those at the highest redshifts (e.g. SN1998eq at $z = 1.2$).

Instrument Resources

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

Target Table for Run 3: GEM-NQ/NIRI6

Obj ID	Object	α	δ	Epoch	Mag.	Obs. time	WFS stars	IQ %	SB %	WV %	CC %	Comment
1001	Supernovae 1	13:00:00	0:00:00	J2000	23.8	1000	p	50	any	80	50	Object TBD
1002	Supernovae 2	13:00:00	0:00:00	J2000	23.8	1000	p	50	any	80	50	Object TBD

NOAO observing proposal LaTeX macros v2.3.