NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: March 27, 2002 **Category:** Cosmology

Cosmology with High-Redshift Type Ia Supernovae

PI: Robert Knop **Status:** P **Affil.:** Vanderbilt University
Physics and Astronomy, VU Station B 351807, Nashville, TN 37204-1807 USA
Email: r.knop@vanderbilt.edu Phone: (615)322-6165 FAX: ________

CoI: Isobel Hook **Status:** P **Affil.:** University of Oxford
CoI: Saul Perlmutter **Status:** P **Affil.:** Lawrence Berkeley National Laboratory
CoI: Greg Aldering **Status:** P **Affil.:** Lawrence Berkeley National Laboratory
CoI: Eric Smith **Status:** T **Affil.:** Vanderbilt University
CoI: Ariel Goobar **Status:** P **Affil.:** University of Stockholm, Sweden
CoI: Christopher Lidman **Status:** P **Affil.:** European Southern Observatory

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

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	GEM-NQ	GMOSN	4	dark	Sep - Nov	Sep - Dec
2	GEM-NQ	NIRI6	4	bright	Sep - Nov	Sep - Dec
3						
4						
5						
6						

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

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) 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 (SCP) developed an approach to this measurement (Perlmutter *et al.* 1997, 1998, 1999) that resulted in a determination, based on 42 SNe with redshfits between 0.18 and 0.83, of $\Omega_M \sim 0.3$ for a flat universe (Perlmutter *et al.* 1999; see also Riess *et al.* 1998); balloon-based CMB measurements have strengthened the evidence for an accelerating universe by indicating that the geometry of the universe is flat, ruling out the possibiliby of a low-density open universe.

Further measurements of high-redshift supernova hold promise for two things. First, over the next few years it will be possible to begin to address the properties of the "dark energy" which is driving the expansion of the universe, by measuring w, the equation of state (p/ρ); a value of $w = -1$ would indicate vacuum energy, or a cosmological constant. In a few years, sufficient supernova data at a range of redshifts together with independent constraints on Ω_M from, e.g. large scale structure, it will be possible to measure w to approximately five times better accuracy than may be done today. For example, if the dark energy has a true value of $w = -0.8$, within five years we could have sufficient supernova data to rule out vacuum energy.

Second, more and better measurements of supernovae will allow us to minimize the effects of systematic errors on the results. For example, the effects of host galaxy dust extinction may be addressed with high-quality color measurements of a large quantity of supernovae. The effects of grey dust are addressed by obtaining measurements of supernovae at intermediate $(z < 1)$ and high $(z > 1)$ redshifts, thereby looking into the epochs of both acceleration and deceleration.

This Proposal: This proposal will measure supernovae at two redshift regimes. First, we will use GMOS on Gemini obtain spectra of supernovae at $0.5 < z < 0.8$ produced by the Tololo Rolling Supernova Search (TRSS) for High-Redshift Supernova (proposed as a NOAO survey project by Knop *et al.*, proposal ID# N0021), which will be relying on this proposed time in order to confirm the identification as a SN Ia and measure the redshfits of the higher-z supernovae discovered as a part of the survey. The possible improvements on the cosmology due to this five-year survey (implicitly including redshifts obtained by this proposal) are shown in Figure 1. This proposed Gemini spectroscopy of SNe at $0.4 < z < 0.7$ will allow the TRSS to achieve its goals both in measuring w and setting limits on the effects of supernova evolution and host galaxy extinction.

In addition, with Gemini we propose to perform infrared photometric observations of supernovae at $z \gtrsim 1$, which will be discovered both by the CRSS by Subaru during the "Subaru Big Project" which includes 14 nights with SuprimeCam. Supernovae at these highest redshfits are the most challenging to follow; however, they have a large scientific impact. They provide the greatest leverage in decoupling measurements of Ω_M and Ω_Λ, thereby shortening the long axis of the confidence ellipse which results from measurements of supernovae at $z < 1$ (see Figure 1). Second, they are at a high enough redshift that observing them allows us to look back to the era of deceleration. Observations of supernovae at $z > 1$ together with intermediate redshifts of $z < 1$ provide a complete picture which can clearly distinguish an accelerating cosmological expansion from systematic effects. These most distant supernovae require measurements in the infrared, since rest-frame B- and V-band, where supernovae are best understood as standard candles, are redshifted out beyond wavelengths of $1\mu m$.

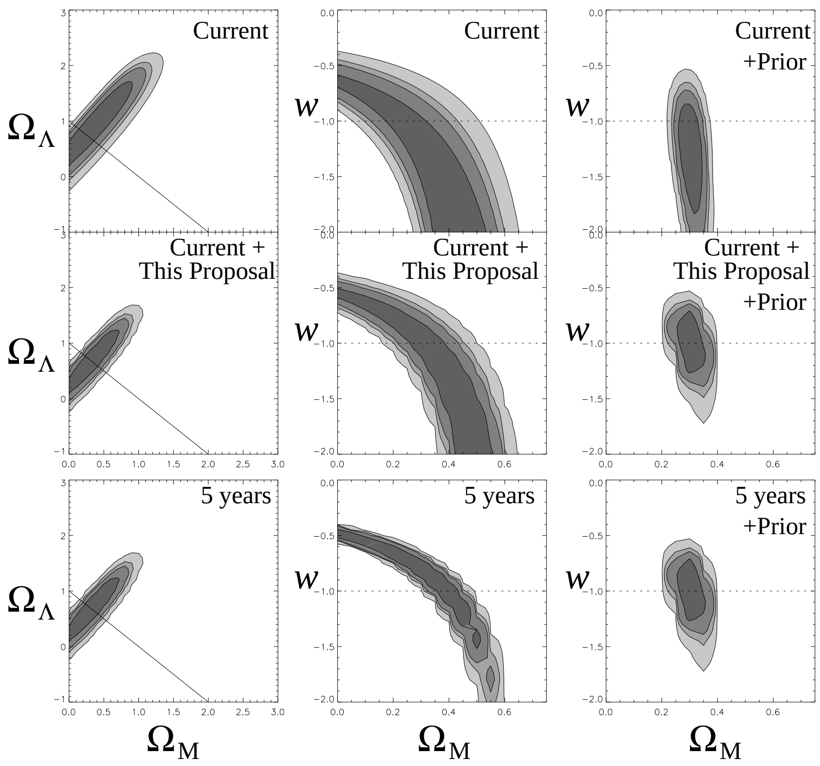

Figure 1: Simulated 68%, 90%, 95%, and 99% confidence limits on cosmological parameters from supernovae observed with this program. On the left are confidence limits in the Ω_M/Ω_L plane; other plots show confidence limits on Ω_M and the equation of state paramter w for the dark energy in a flat universe. On the right is included a 0.3 ± 0.04 prior on Ω_M, which simulates what will likely be availabel from independent measurements in five years. The top plots show the SCP's current best limits, including the results from 10 supernovae followed with WFPC-2. The middle plots add 65 SNe from the SNRSS (including ~ 30 observed spectroscopically with this program), three SNe at $z \sim 0.85$, and three SNe at $z \sim 1.05$. The bottom plots show the potential situation in 5 years: 330 SNe at $z < 0.7$ from CTRSS, plus 15 SNe at $z \sim 0.85$, plus 15 SNe at $z \sim 1.05$, plus 300 supernovae produced by the Supernova Factory.

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)*

We propose to use GMOS for spectroscopy, and NIRI for infrared imaging, to obtain spectra and lightcurves of supernovae in three redshift regimes: $0.4 < z < 0.7$, $0.8 < z < 1$, and $z > 1$.

GMOS OBSERVATIONS

The proposed TRSS would proceed over four months one semester each year for five years, using the Mosaic camera to simultaneously find and obtain high-quality lightcurves of > 300 supernovae at $z < 0.8$. We propose to use GMOS on Gemini to complete the identification and measurement of redshifs of supernovae out to $z \sim 0.7$ which are too dim for the KPNO 4m and MMT time proposed as a part of that survey. During the first semester of the survey, this will amount to 25–35 supernovae at $z < 0.7$. Supernovae at the targeted redshifts have I-band magnitudes between 22 and 23.5. Photometric redshifts and points on the rise of the lightcruve will allow us to both improve the odds that a given candidate will be a SN Ia, and to ensure that we are observing near maximum. An observation of < 1 hr will be sufficient for a single object, and thus we request 3 nights (27 hours) of observing time for this set of supernovae.

These observations will provide us with the redshifts and necessary for the higher-redshift supernoave of TRSS, allowing it to achieve both its measurements on the cosmological parameters and its limits on systematic errors. For example, that survey will address evolution by measuring the rise-time of high-redshift supernovae to ~ 0.7 days (AKN2001)– which will require a spectroscopic redshift measurement to take into account the effects of time dilation. According to the models of Domínguez *et al* 2001 this will allow us to constrain evolution in the mean peak SN brightness between low- and high-redshift to within 0.07 mag. (Photometric redshifts will help us screen candidates to make our use of GMOS more efficient, but are not precise enough for a $\sim 3\%$ measurement of a supernova lightcurve rise time.) Likewise, the R-I colors produced by the survey will allow a measurement of a shift in the mean extinction between high- and low-redshift supernovae as low as 0.015 mag.

In addition, we propose to obtain spectra of 3–4 candidates at $0.8 < z < 1$, produced by the TRSS and/or the Subaru Big Project, which will use 14 nights during 2002B with the SuprimeCam wide-field imager on the 8m Subaru telescope. These spectra will require an additional night (9 hours) of time with GMOS. Building up observations of these higher-redshift supernovae will allow us to shorten the long axis of the confidence region on the Ω_M/Ω_Λ plane; the middle plot on Figure 1 includes the results of three $z \sim 0.85$ supernovae observed with this program as well as three $z \sim 1.05$ supernovae observed with NIRI.

NIRI OBSERVATIONS

With the Subaru Big Project, we will discover of a number of supernovae at $z > 1$. At these redshifts, the rest-frame V-band light has shifted out beyond 1μm, so observations in the J-band filter are necessary in order to measure a rest-frame B-V color and correct for host galaxy extinction. The spectra of these highest redshift supernovae will be obtained with the Keck 10m telescope; z-band followup (corresponding to the rest-frame B-band) will be perfored with ACS on HST and/or SuprimeCam on Subaru. We propose to use NIRI on Gemini to measure ~ 3 SNe Ia in the J-band at $z > 1$. These supernovae will peak at magnitude 23.8. The uncertainty in rest-frame B-V will be dominated by this J-band measurement. We will measure the J-band magnitude to a S/N of 14 (thereby giving us S/N 10 in the final measurement once a host galaxy reference image is subtracted), requiring ~ 24 hours of on-target exposure time.

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.*

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. Please include original proposal semesters and ID numbers when available.*

Demonstrated Successes: Over the past few years we have discovered and studied >100 SNe ($\sim$ 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). Additional papers are in preparation (including topics such as new limits on cosmological parameters, properties of host galaxies, high redshift SN spectra, etc.) and 10 presentations were made at the January 2002 Meeting of the AAS with preliminary results for these papers.

Spring 2002a SNe Ia Search: Six nights have been scheduled for the CTIO-4m/Mosaic for a "two-epoch" search. In addition, confirmation and follow-up time has been scheduled for Gemini-N/GMOS (35 hours), Gemini-N/NIRI (35 hours), and WIYN (5 nights).

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 (reported in IAUC 7763 and 7764), 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. Final analysis awaits acquisition of final reference images 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 last 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 $\sim$ 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.

Previous 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 (shown in Figure 2) on the cosmological parameters, which agree well with the previous results.

$\boxed{\star}$ 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, 2002) 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, 2002).

Observing Run Details for Run 1: 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).*

[NEED TO UPDATE. BELOW IS 2002A] 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.

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 $z > 1$

Instrument Resources

Filters:
Dispersers:
Focal Plane Units:

R.A. range of principal targets (hours): 1 to 3

Dec. range of principal targets (degrees): -5 to +5

Target Table for Run 1: GEM-NQ/GMOSN

Obj ID	Object	α	δ	Epoch	Mag.	Obs. time	WFS stars	IQ %	SB %	WV %	CC %	Comment
1001	SN1	2:00:00	0:00:00.	J2000	24.2	3200	PPO	50	80	any	50	Obs. over weeks

Observing Run Details for Run 2: 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): 1 to 3

Dec. range of principal targets (degrees): -5 to 5

Target Table for Run 2: GEM-NQ/NIRI6

Obj ID	Object	α	δ	Epoch	Mag.	Obs. time	WFS stars	IQ %	SB %	WV %	CC %	Comment
2001	SN1	2:00:00	0:00:00	J2000	23.8	43800	Pp	50	any	80	50	
2002	SN2	2:00:00	0:00:00	J2000	23.8	43800	Pp	50	any	80	50	

NOAO observing proposal LaTeX macros v2.6.