NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: April 1, 2002 **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)***:**
Type Ia supernovae (SNe Ia) have provided direct evidence for an accelerating universe and for the existence of a "dark energy" driving that expansion. During the next few years SNe Ia observations will begin to address the properties of this dark energy. We propose to use GMOS and NIRI on Gemini to observe supernovae at two redshift ranges: $0.4 < z < 0.7$ and $z \sim 1.0$. These measurements will determine the equation of state of the dark energy, and will also allow us to set more stringent systematic limits on the current supernova data. With GMOS, we will obtain spectra of 30 supernovae at $z < 0.7$ discovered as part of the Tololo Rolling Supernova Search (TRSS), and of another two SNe at $z \sim 1$. These spectra will confirm the identity of candidates as SNe Ia and will measure redshifts. In addition, following our success with a SN Ia at z=1.06 during semester 2001A, we will obtain J-band photometry with NIRI of two SNe at $z \sim 1$. These will be used in tandem with HST and Subaru z-band measurements to provide rest-frame B-V colours, which are necessary for measuring any extinction by dust.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	GEM-NQ	GMOSN	4.5	dark	Sep - Nov	Sep - Dec
2	GEM-NQ	NIRI6	3.5	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 redshifts 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 possibility of a low-density open universe.

Further measurements of high-redshift supernovae 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 can be done today. Figure 1 shows the improvements in the cosmological parameters with these proposed observations, and what we expect to be able to achieve in five years. Indeed, in the example shown (where the simulated value of w is -0.8), we will be able 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 to obtain spectra of supernovae at $0.4 < z < 0.7$ 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 redshifts 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 $z \gtrsim 1$. These will be discovered by Subaru during the "Subaru Big Project" which includes 14 nights with SuprimeCam. Supernovae at these highest redshifts 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 $1\mu m$.

References

Aldering, G., Knop, R., and Nugent, P., 2000, AJ, 119, 2110 (AKN 2000)
Aldering, G., & Pain, R., 2001, in "Dark Energy Resource Book," ed. E. Linder
Domìnguez, Höflich, & Straniero, 2001, ApJ, 557, 279
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Perlmutter, S., *et al.*, 1997, ApJ, 483, 565
Perlmutter, S., *et al.*, 1998, Nature, 391, 51
Perlmutter, S., *et al.*, 1999, ApJ, 517, 565
Riess, A., *et al.*, 1998, AJ, 116, 1009

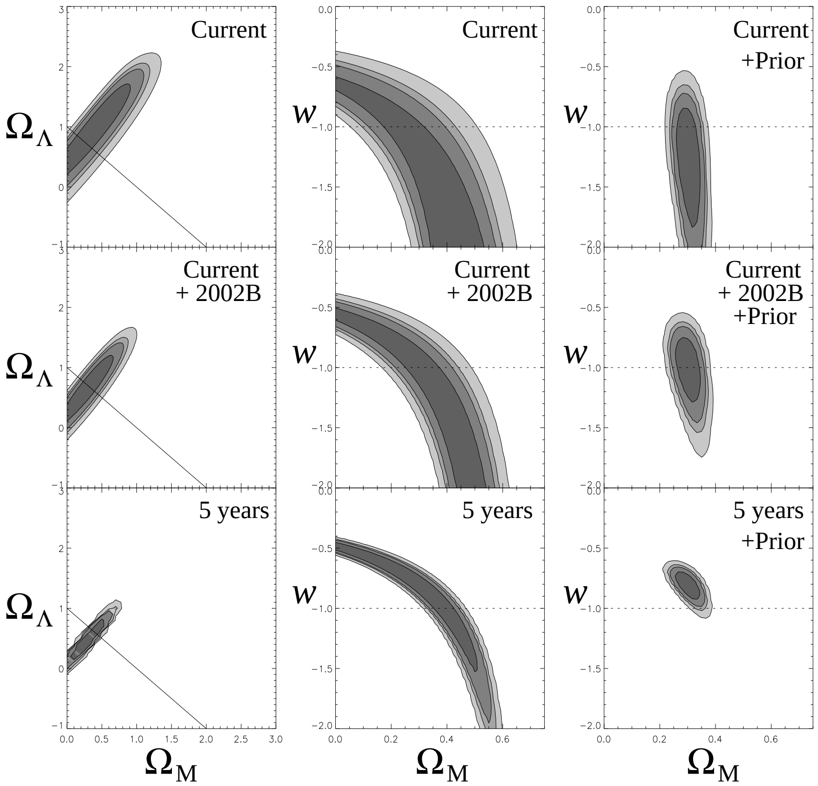

Figure 1: Simulated 68%, 90%, 95%, and 99% confidence limits on cosmological parameters from supernovae observed with this program. On the left are confidence limits in the Ω_M/Ω_L plane; other plots show confidence limits on Ω_M and the equation of state parameter w for the dark energy in a flat universe. On the right is included a 0.3 ± 0.04 prior on Ω_M, which simulates what will likely be available from independent measurements in five years. The top plots show the SCP's current best limits, including those from Perlmutter (1999) and from 10 supernovae discovered at CTIO and followed with WFPC-2 (Knop *et al.* 2002). The middle plots add 65 SNe from the TRSS 2002B (including ~ 30 observed spectroscopically with this program) plus four SNe at $z \sim 1.05$ (including those in hand and those to be observed with this program). The bottom plots show the potential situation in 5 years: 330 SNe at $z < 0.7$ from TRSS, plus 12 SNe at $z \sim 1.05$, plus 300 supernovae produced by the Supernova Factory (Aldering & Pain 2001).

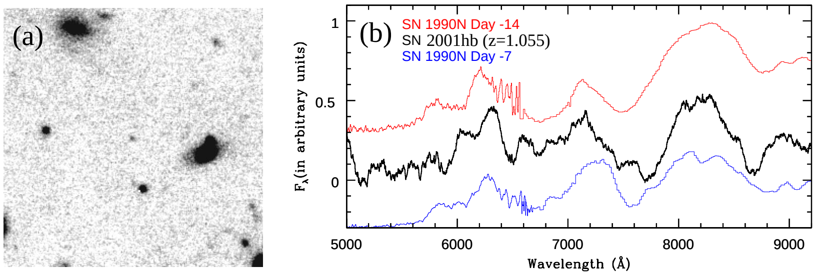

Figure 2: (a) $30'' \times 30''$ section of our NIRI image centered on SN2001hb at $z = 1.06$, discovered with CTIO/MOSAIC during semester 2001A. The combined NIRI image of $\sim$ 12 hours data reaches a signal to noise of about 14. (b) Spectrum of SN2001hb obtained in 2 hrs with ESI on Keck, smoothed to 155A, 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)*

We propose to use GMOS for spectroscopy, and NIRI for infrared imaging, to obtain spectra and lightcurves of supernovae in two regimes: $0.4 < z < 0.7$ and $z \gtrsim 1$.

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 $z < 0.7$. We propose to use GMOS on Gemini to complete the identification and measurement of redshifts of supernovae out to $z \sim 0.7$ which are too dim for the KPNO 4m and MMT time proposed as a part of TRSS. During the first semester of TRSS, this will amount to ~ 30 supernovae at $0.4 < z < 0.7$, where SNe Ia have peak I-band magnitudes between 22 and 23. Host galaxy photometric redshifts and points on the rise of the supernova lightcurve 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 0.5 hr will be sufficient for a single object; with overheads, this totals 35 hours of exposure time.

These observations will provide us with the redshifts and SN type confirmations necessary for the more distant SNe of TRSS, allowing the survey to achieve its goals both for measuring the cosmological parameters and for setting limits on systematic errors. For example, that survey will address evolution by measuring the rise-time of high-redshift supernovae to ~ 0.7 days (AKN2000)– which will require spectroscopic redshift measurements 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 have the rare opportunity to take advantage of a large, deep imaging survey on Subaru: the "Subaru Big Project," a campaign which will obtain multi-filter images of the Subaru/XMM deep field using 14 nights with SuprimeCam. This project will obtain ~ 8 faint ($I \sim 24.5$) candidates, of which ~ 6 should be $z > 1$ SNe Ia. Three confirmed $z > 1$ SNe Ia will be sent to HST for z'-band observation. We request time with GMOS on Gemini to obtain redshifts and type confirmations for two of these very faint candidates, requiring ~ 7 hours of on-source integration time. Photometric redshifts available for many of the host galaxies will help to select probable SNe Ia in the target redshift range.

NIRI OBSERVATIONS: For the supernovae discovered at $z \gtrsim 1$ by the Subaru Big Project, the rest-frame V-band light is shifted out beyond 1μm; observations in the J-band filter are necessary in order to measure a rest-frame B-V color and correct for host galaxy extinction. Spectra of these candidates will be obtained with GMOS (above) and with the Keck 10m telescope; z-band followup (corresponding to the rest-frame B-band) will be performed with ACS on HST and/or SuprimeCam on Subaru. We propose to use NIRI on Gemini to measure 2 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 magnitudes to a S/N~ 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. Figure 2 shows observations from Spring 2001 of SN2001hb at $z = 1.055$ (discovered at CTIO with MOSAIC), including a NIRI image and a Keck 10m spectrum comparable to what we can achieve with GMOS.

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.*

Supernovae at $z < 0.8$ will be discovered by the proposed TRSS survey using the Mosaic camera on CTIO; supernovae at higher redshifts will be discovered as a part of the Subaru Big Project with SuprimeCam on Subaru. In addition to GMOS, we will use ESI on the Keck 10m telescope to obtain spectroscopy of faint candidates. ACS on HST will be used to obtain z-band lightcurves of supernovae at $z \gtrsim 1$.

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 several years we have discovered and studied >100 SNe at redshifts $z = 0.03$–1.20, both photometrically and spectroscopically. Most of these supernovae were discovered at CTIO; a set of ~ 20 were discovered in 1999, including several with the KPNO 0.9m telescope. Eighteen of the high-redshift SNe have been observed with HST. The cosmological results from these discoveries , including the discovery of the universe's expansion and "dark energy," 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.

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: The search campaign was a striking success; more than 17 SNe Ia were discovered at $0.3 < z < 1.1$, as reported in IAUC 7763 and 7764. These supernovae were discovered with CTIO/MOSAIC and with CFHT/12x8k; follow-up of supernovae at $z \lesssim 0.8$ was performed with WIYN/MIMO. J-band observations of SN 2001hb at $z = 1.055$ (discovered with CTIO/MOSAIC) and SN2001gn at $z = 1.12$ were performed with Gemini/NIRI (as part of a test program for NIRI SV). Final analysis of these supernovae is in progress, and awaits final reference images to be obtained during 2002a.

UV Observations of Nearby Type Ia Supernovae: During 2001a, the program "UV Observations of Nearby Type Ia Supernovae" was successfully carried out at several ground-based facilities (including the photometry from CTIO 0.9m, the CTIO 1.5m, and YALO, as well as spectroscopy from the KPNO 2.1m and the KPNO 4m). These observations were aimed at better understanding the UV nature of SNe Ia, for purposes of measuring evolutionary/metallicity effects and calibrating high-redshift SNe Ia previously observed with HST.

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).*

GMOS Spectroscopy: We aim to obtain spectra of 30 SNe Ia candidates at $0.4 < z < 0.7$ discovered with the TRSS to confirm the SN type and obtain a redshift. The design of the TRSS will give us both preliminary photometric redshifts of host galaxies and points on the rise of the supernovae lightcurve. This will produce a large gain in the efficiency of the spectroscopic observations, as we will be able to ensure that the candidates observed are within a few days of maximum light. At the target redshift range, supernovae peak at I band magnitudes of 22-23. A typical exposure time of 1800s per object is sufficient for a screening observation to confirm supernova type and measure a precise redshift. Including 25% overhead and 30 min. to acquire each object, this totals 35 hours of Gemini time.

The TRSS will proceed over a period of four months (September through December), with supernovae being discovered and coming to maximum light throughout the period. GMOS spectroscopy of the target objects will be spread over several nights around dark time during each of the first three months of TRSS.

In addition, we aim to obtain spectra of two faint ($I \sim 24.5$) candidates expected to be at $z \gtrsim 1$, discovered with the Subaru Big Project. These will require on-source exposures of 3.5 hours each; adding 25% overhead and 30 minutes of acquisition for each object totals 10.3 hours. Figure 2 shows a smoothed Keck 10m spectrum of SN2001hb, a supernova at $z = 1.055$, at a quality similar to what we expect to be able to achieve with GMOS.

In total, we request 45.3 hours of GMOS spectroscopy observations. All observations will use a $0.75''$ slit, the R400_G5305 grating, and the OG515 order sorting filter.

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 GMOS time be divided between the U.S. and U.K. allocations in approximately the proportion of partner shares, i.e. 30.2 hours (US) and 15.1 hours (UK).

Summary: We will use Gemini/GMOS for the spectroscopic confirmation and redshift measurements of 32 SNe, including ~ 30 at $0.4 < z < 0.7$ and two at a redshift $z \sim 1$.

IMPORTANT NOTE: Because these observations are coordinated with supernova discoveries at other telescopes, please contact the PI of the program before scheduling any of the observations.

Instrument Resources

Filters: OG515_G0306
Dispersers: R400_G5305
Focal Plane Units: Longslit 0.75 arcsec

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	SNz <0.7 x 30	2:00:00	0:00:00.	J2000	22.5	900	PPO	50	50	any	50	30 SNe, 30 min each
1002	SNz 1	2:00:00	0:00:00	J2000	24.5	210	PPO	50	50	any	50	
1003	SNz 1	2:00:00	0:00:00	J2000	24.5	210	PPO	50	50	any	50	

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 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. (Lightcurve widths and peak rest-frame B magnitudes will be determined to S/N > 20 from HST 850LP and/or Subaru Z-band, as mentioned above).

In the J-band, SNe Ia in the redshift range of interest are predicted to have peak magnitudes 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 $z = 1.06$ SN2001hb (Fig. 2). Two supernovae will require 87,600s = 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).

IMPORTANT NOTE: Because these observations are coordinated with supernova discoveries at other telescopes, please contact the PI of the program before scheduling any of the observations.

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	80	80	50	
2002	SN2	2:00:00	0:00:00	J2000	23.8	43800	Pp	50	80	80	50	