Spectroscopic Study of Type Ia Supernovae from a Large, Homogeneous, Nearby Sample to Calibrate Distance Measurements

Saul Perlmutter, LBL

Greg Aldering, LBL

Peter Nugent, LBL

Gerson Goldhaber, UCB/LBL

Robert Knop, LBL

Abstract:

We propose to use the Lick 3-m with the Kast double spectrograph to spectroscopically screen ~ 60 nearby supernovae candidates, and study ~ 30 that are Type Ia supernovae, to be discovered as part of a large international campaign. The goals of this campaign are to determine the luminosity function, investigate known and new photometric and spectroscopic luminosity indicators, determine better lightcurve templates and spectral time series at all optical wavelengths (especially prior to maximim light), and calculate the rates, for nearby Type Ia supernovae. The search is scheduled for Feburary and March of 1999. After screening supernova candidates, detailed spectroscopy and photometry will be obtained for all that are bright Type Ia supernovae. The Lick 3-m will be used to obtain the crucial initial spectroscopic follow-up of candidates.

I. Scientific Justification

Introduction

The Supernova Cosmology Project (SCP) at Lawerence Berkeley National Lab, in cooperation with teams of astronomers and physicists from the UK, CTIO, ESO, the EROS microlensing search, and the QUEST quasar search, are undertaking a large CCD-based program to systematically discover and follow more than 30 nearby Type Ia supernovae (SNe Ia) during the upcoming semester. The goals of this survey are as diverse as the individuals involved, but the focus will be on determining those properties of Type Ia supernova affecting their use for cosmology. In particular, this program will determine

- the intrinsic luminosity function of SNe Ia
- relations between lightcurve shapes, spectral diagnostics, etc., and luminosity
- the $UBVRI$ lightcurve behavior, beginning well before maximum.
- spectral time series (needed in particular for determining K-corrections), also beginning well before maximum.

This survey will also lead to a better determination of the rates for all types of supernovae at the current epoch, as well as relations between the properties of supernovae and their host galaxies.

Cosmology with Type Ia Supernovae

For the past several years the Supernova Cosmology Project has exploited Type Ia supernovae as standard candles to probe the geometry of the universe. Several studies have now shown that Type Ia supernovae (SNe Ia) can be used as calibrated standard candles with an intrinsic dispersion in luminosity- and reddening-corrected peak magnitudes of $\sim$0.1 mag (Hamuy *et al* 1996a, Riess *et al* 1996). The SCP has used Keck, other ground-based, and HST data to demonstrate that SNe Ia observed over a large redshift range measure the cosmological parameters Ω_M and Ω_Λ far better than has ever been done before. (Perlmutter *et al* 1997, 1998a, 1998b). Presently the SCP has discovered over 65 SNe Ia in the redshift range $0.2 < z < 0.9$, with more on the way from upcoming observing runs at CFHT, Keck, and HST. Figure 1 shows the Hubble diagram using our 42 first high-z SNe discovered through March 1997 (Perlmutter *et al* 1998b), along with 18 SNe from the Calan-Tololo SNe survey (Hamuy *et al* 1996b). Figure 2 shows the constraints placed on Ω_M and Ω_Λ from the best fit to the Hubble diagram of Figure 1.

Type Ia Supernovae as Standard Candles

Various means have been used to determine the intrinsic (relative) luminosities of SNe Ia from their lightcurves. Based on early results from the Calan-Tololo survey, Phillips *et al* (1993) showed that the quantity Δm_{15}, which measures the brightness difference from maximum to 15 days after maximum, was correlated with intrinsic luminosity. Hamuy *et al* 1996a confirmed this correlation (with a slightly different slope) for all but the reddest SNe Ia from the Calan-Tololo survey. Riess *et al* 1996 used a different approach based on templates with different lightcurve shapes. The SCP has used a method, close in spirit to Δm_{15}, in which all SNe Ia lightcurves at each bandpass can be fitted by a template which is simply stretched in time about the date of maximum light. The amount of stretching, S, has been found to correlate with intrinsic luminosity for the 18 SNe Ia from the Calan-Tololo survey discovered within 5 days of maximum (for SNe Ia discovered later after maximum, the date of maximum is not well determined). This procedure is demonstrated in Figure 3.

The scatter remaining after this correction and reddening corrections are applied can be as small as $\sim$ 0.1 mag. However, the SCP has found some high-z SNe Ia which have S values that are smaller or larger than those of the Calan-Tololo SNe. In order to improve our stretch-based description of SNe Ia lightcurves, well-studied lightcurves of nearby SNe Ia are needed covering a wider range in S. These SNe Ia must be beyond $\sim$10000 km s$-$1) so that peculiar velocities do not affect the determination of their relative distances. Also lightcurves with much more data prior to maximum for various stretch SNe Ia are needed to make templates covering the range of lightcurve dates we now have for high-z SNe Ia.

The Need for a Better Nearby Sample

Roughly half of the the statistical uncertainty in the measurement of $\Omega_M - \Omega_\Lambda$ from the 42 SNe Ia shown in Figs 1 & 2 arises from the small number of nearby supernovae available. Thus, a better sample of nearby SNe Ia will immediately translate into better constraints on cosmology. Furthermore, the statistical uncertainties on combinations of Ω_M and Ω_Λ are now becoming sufficiently small that systematic uncertainties must be examined even more closely.

One of the largest potential sources of systematic uncertainty stems from our reliance on the low-redshift SNe Ia dataset from the Calan-Tololo SN survey (Hamuy *et al* 1993, 1996a, 1996b) to anchor the low-redshift portion of the Hubble diagram *and* to define the relation between intrinsic SN luminosity and lightcurve shape. The Calan-Tololo survey was conducted by blinking photographic plates so its selection function and biases (i.e. Malmquist bias) are difficult to quantify. This makes it difficult to assess whether or not the statistical properties of nearby and distant supernovae are the same. Trends amongst the Calan-Tololo SNe, such as the presence of smaller stretch SNe at higher redshift, surprising little extinction for most SNe, and a dependence between peak color and luminosity (unrelated to extinction; Tripp 1998), calls for some caution in generalizing conclusions based on the Calan-Tololo SNe Ia. The small number of other SNe Ia for which good data are available are

not suitable because they are either too nearby to be in the Hubble flow, have inadequate or heterogeneous photometric coverage, or are heavily reddened. Moreover, few well-observed SNe Ia have been discovered before maximum, meaning that the date of maximum, and pre-max portions of template lightcurves we use to fit the high-z SNe are not well determined.

Good U-band lightcurves for use as templates are especially hard to come by, yet we have rest-frame U-band data from HST for high-z SNe Ia in need of a U-band template. Without NICMOS, rest-frame $U-$band will be the only portion of the spectrum of high-z SNe accessible with HST so the need for a U-band template is urgent.

In order to make full use of the hard-won data on higher redshift supernovae, our understanding of the empirical properties of SNe Ia need to be verified and refined, and their selection biases quantified. This can best be accomplished through the systematic study of the large, homogeneous sample of nearby SNe Ia we expect to find in our survey. These SNe will be discovered using the same search methods that have proved so successful in finding distant SNe *on demand*. This will enable the statistical properties of the new nearby sample and existing and future distant samples to be compared directly. This dataset will also be extremely valuable for modeling SNe explosions.

The Large Nearby Supernova Survey

The basic outline of the survey is as follows: During dark time in January, February, and March 1999 we will use wide-field CCD mosaics at the INT 2.5-m, EROS 1-m, KPNO 0.9-m, and QUEST 1-m to search for supernovae. Each survey will cover 100–400 deg^2 each month, with January observations serving as references for discoveries in February and March. The survey is optimized to find SNe Ia at redshift $z \sim 0.1$ approximately 10 days before maximum. The survey will also find other types of SNe, as well as some SNe Ia already past maximum, which will be screened out based on spectra taken shortly after discovery. SNe Ia still on the rise (as determined from photometric follow-up and spectroscopic dating) will be imaged in UBVRIJHK every 3–5 days for approximately two months, using a network of queue and classically scheduled 1-m class telescopes for which observing time has already been committed. Spectra will also be obtained periodically ($\sim$ once per week) using a network of 2.5-m and larger telescopes (This may include UV spectra from STIS on HST). Using our rates for SNe Ia at $z \sim 0.3$ (Pain *et al* 1996) it is expected that the combined searches will contribute $\sim$ 30 SNe per month for two months, yielding $\sim$ 60 SNe, of which more than 30 are expected to be SNe Ia before maximum. Thus, unlike most on-going SNe searches, all of the searching and follow-up for this survey is concentrated into just a few months, allowing the telescope time for the entire program to be classically scheduled and allowing for homogeneous selection and follow-up.

The search and follow-up has been distributed intentionally among several telescopes in geographically diverse locations, in order to make the program robust against bad weather or instrument failures. This is an important feature given the large amount of time being committed to discover and follow these SNe. All the data will be searched electronically, allowing the discovery efficiencies from each telescope/detector combination to be determined

through computer simulations. The faintest SNe will have $B \sim 19$ at maximum light, hence the need for spectroscopic follow-up on large telescopes. Had we chosen to focus on discovering brighter SNe, the search efficiency would have plummeted due to deadtime (readout, re-positioning) between fields, as presently few of these CCD arrays is sufficiently well aligned to allow drift-scanning.

The well-sampled lightcurves resulting from this intensive follow-up campaign will allow a much better determination of lightcurve properties and how they are related to intrinsic luminosity. Very few nearby SNe have good data prior to maximum light, so these lightcurves will open new avenues of study of both the empirical and theoretical properties of SNe. Because most of the SCP high-z SNe have been discovered before maximum (typically by ~ 10 days), so these early, well-sampled lightcurves can be used to create superior templates for use with high-z SNe.

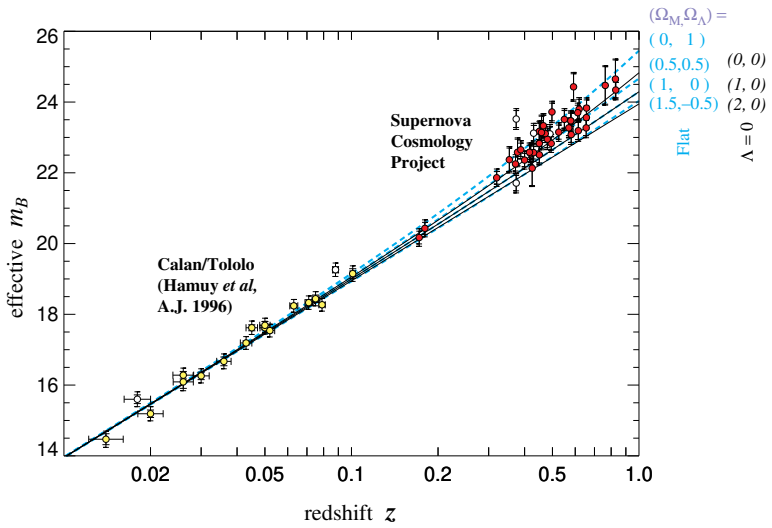

Figure 1: Hubble diagram based on the preliminary analysis of Perlmutter *et al* 1998b of 42 high-redshift Type Ia supernovae. The low-redshift SNe Ia are those from Hamuy *et al* 1996a which are suitable for analysis using the same methods as used for the high-redshift SNe Ia.

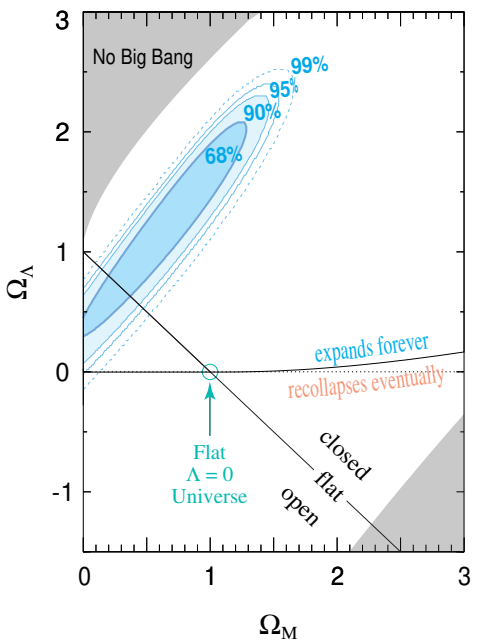

Figure 2: Contours showing the confidence region for Ω_M and Ω_Λ resulting from a preliminary analysis of over 42 SNe Ia, including 1997ap at $z = 0.83$ from Perlmutter *et al* 1998a. Shown are the 68%, 90%, and 99% confidence regions for an unconstrained fit for Ω_M and Ω_Λ. The grey region is excluded by the Big Bang, while the region $\Omega_M < 0$ is unphysical. Note that these contours are for 2 degrees of freedom; the confidence regions for e.g., Ω_Λ at a given Ω_M are different (smaller for a given confidence level). See Perlmutter 1997 and 1998b for further discussion and alternative plots.

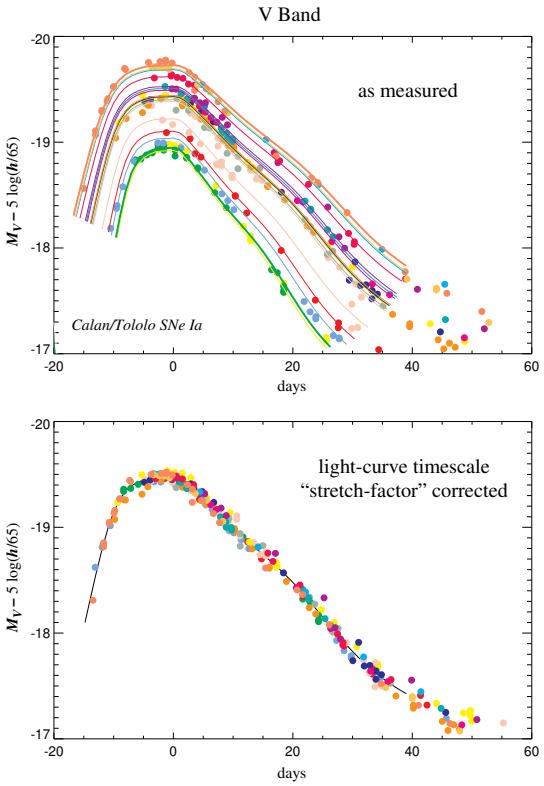

Figure 3: V-band lightcurves for nearby SNe Ia from Hamuy *et al* 1996b. The upper panel shows lightcurves for individual SNe Ia, with absolute magnitudes derived assuming pure Hubble flow and $H_o = 65$ km/s/Mpc. Template lightcurves from Leibundgut *et al* 1991 have been fit to the lightcurve for each SNe. Note that the brighter SNe have lightcurves which are broader and decline more slowly. Also notice that very few of these SNe have data well before maximum light. The lower panel shows the superposition of these data after using a linear correction for stretch, S, and scaling the time axis (with maximum at t = 0) by the same stretch-factor. We have found that the lightcurves for a given filter for most SNe Ia can be represented by a single stretched template. We have also found that this stretch factor is linearly proportional to the intrinsic luminosity (in magnitudes).

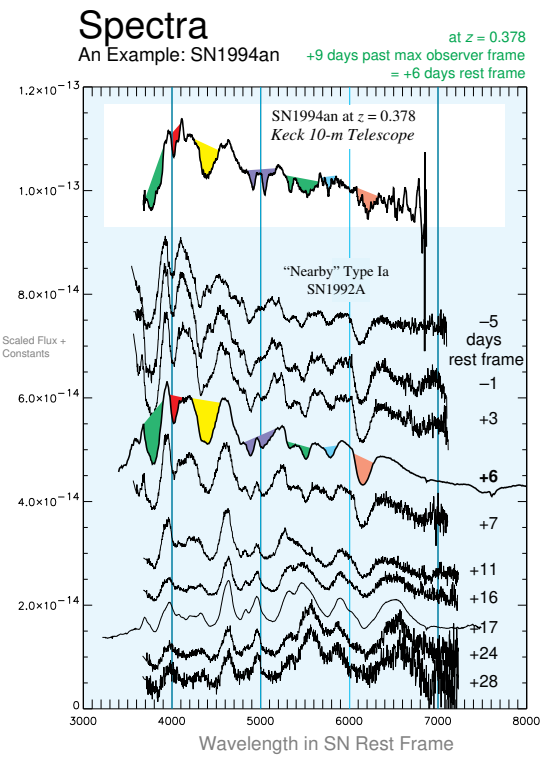

Figure 4: The evolution of the spectra of a Type Ia supernova as the explosion ages. This was constructed using spectra from different SNe Ia obtained at different epochs. The shaded regions highlight portions of the spectra which are seen to evolve with time. Some of these can also be used as luminosity indicators.

II. Lick Observations

Spectroscopic follow-up with the Lick 3-m plays a key role in this project. Shortly after our first discovery run during February dark time, we expect to have $\sim$ 60 SNe candidates for which spectroscopy is needed to confirm them as SNe, measure their redshifts, and determine their SNe types. For those that are SNe Ia, better S/N spectra will then be required to spectroscopically date them (cf. Figure 4 for an example of the change in SNe Ia features as the explosion ages) and to estimate their intrinsic luminosities using various line indices (e.g. from Si and Ca; see Nugent 1998 for more details). For some brighter SNe Ia, we may be able to measure Na I (5890,5896Å), and possibly K I 7699Å, absorption (expected to have $EW \sim 0.0$–0.5Å) and thereby constrain host galaxy extinction independent of SNe colors. The spectra will also be used to develop more accurate K-corrections (Kim *et al* 1996), which are needed to convert the observed photometry of high-z SNe Ia to standard passbands. Wide spectral coverage is especially important for this purpose, since high-z photometry often uses unusual bandpasses (e.g the 4000Å wide F110W filter on NICMOS). The Kast double spectrograph is particularly well suited for this program since it enables efficient coverage of most of the optical spectrum.

In order to screen $\sim$ 60 SNe candidates, and obtain more detailed spectra for $\sim$ 15 of them, we are requesting 5 nights on the Lick 3-m. Two nights in February will be used to screen and obtain initial follow-up spectra of new SNe candidates, and three nights in March will be used similary for new SNe discovered in March as well as for continued follow-up of SNe discovered in February. (If the timing of this request interfers with block scheduling, some screening observations could be shifted to follow-up in April). We estimate from past experience, along with the specific properties of the Kast double spectrograph + 3-m combination, that screening observations will require $\sim$ 15 minutes per SNe, and that follow-up quality spectra will require roughly 45 minutes per SNe. With the inclusion of 10% overhead this leads to our request for 5 nights on the 3-m in semester one of 1999. These observations are to be coordinated with many other observatories, so the optimal dates cannot be determined until we hear when the search runs have been scheduled. It is crucial to obtain this initial spectroscopic follow-up as soon as possible after discovery to determine the properties of SNe Ia before maximum, and to concentrate follow-up at Lick and other observatories on the most interesting SNe as soon as possible. We estimate that the best period will be several days after new moon in February and March.

III. Relation to and Review of On-going Keck Programs

This proposal is designed to obtain better "calibration" data on nearby Type Ia supernova which will allow a more accurate and robust treatment of the high-redshift data obtained as part of the supernova cosmology project we have been conducting for the past several years on Keck. Although both programs are important for utilizing SNe Ia for cosmology, they are independent projects which can proceed on their own.

During the last four semesters we have carried out two sets of "back-to-back" SNe searches

for SNe at high redshifts ($0.3 < z < 0.9$). The first set included one search at the end of semester 1996B and a second search at the start of semester 1997A. This strategy allowed us to obtain follow-up photometry of the 1996B discoveries "for free" while carrying out the 1997A search. The first search of the latest pair was at the end of semester 1997B, and the second search occurred in March, 1998. Keck spectra were obtained for all four completed sets of discoveries while the SNe were near maximum light. These search runs now produce ample SNe that we can select an appropriate subset of the best candidates for observation at Keck. We have now discovered ~ 65 SNe using this technique, with a redshift distribution between 0.2 and 0.86, peaking at $z \sim 0.6$.

The scientific results of these and previous SNe discovery, follow-up, and analysis campaigns have been quite extraordinary. The addition of one SN, SN1997ap discovered in March 1997, to our seven previously published SNe for the first time closed off the confidence regions in the Ω_M, Ω_Λ plane and provided the first unconstrained estimates for Ω_M and Ω_Λ separately (i.e., without the assumption of a flat universe). Keck spectroscopy and HST imaging of 1997ap also demonstrated that this distant SN Ia looked and behaved just like nearby SNe Ia. These results were reported by Perlmutter *et al* in the Jan 1, 1998 issue of Nature.

We have submitted a paper with results based on 42 SNe for which complete data is currently available. This analysis rules out the "standard" flat, $\Omega_M = 1, \Omega_\Lambda = 0$ cosmology, and indicates an answer to one of the most sought-after questions in cosmology — whether the universe will expand forever or eventually recollapse. Our data indicate that the universe will expand forever, quite possibly with the aid of a positive cosmological constant. These results represent a tremendous step forward for cosmology, and are largely dependent on Keck data.

References

Hamuy *et al* , 1993, AJ, 106, 2392.
Hamuy *et al* , 1996a, AJ, 112, 2391.
Hamuy *et al* , 1996b, AJ, 112, 2408.
Kim *et al* , 1996, PASP, 108, 190.
Pain, R., *et al* , 1996, ApJ, 473, 356.
Perlmutter *et al* , 1997, ApJ, 483, 565.
Perlmutter *et al* , 1998a, Nature.
Perlmutter *et al* , 1998b, ApJ, submitted (cf. www-supernova.lbl.gov).
Phillips *et al* , 1993, ApJ, 413, L105
Riess *et al* , 1996, ApJ, 473, 88.
Tripp, 1998, A&A, in press.