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

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Abstract:

We propose to use the Lick 1-m to obtain $UBVRI$ photometric lightcurves for $\sim$ 30 nearby 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 1-m will be used to obtain well sampled $UBVRI$ lightcurves needed to determine peak brightness and lightcurve width (a luminosity indicator).

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 strongly 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 ~ 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.

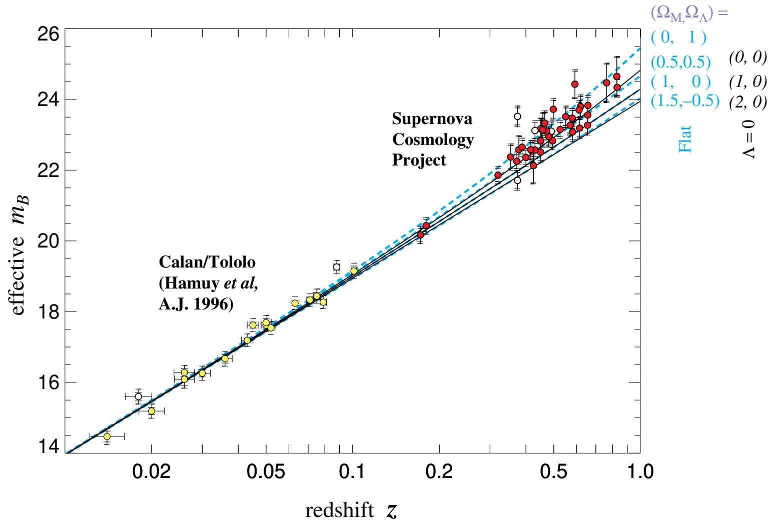

Figure 1: Hubble diagram based on the preliminary analysis of Perlmutter *et al* 1998b of 42 high-redshift Type Ia supernovae. The low-redshift SNe Ia are those from Hamuy *et al* 1996a which are suitable for analysis using the same methods as used for the high-redshift SNe Ia.

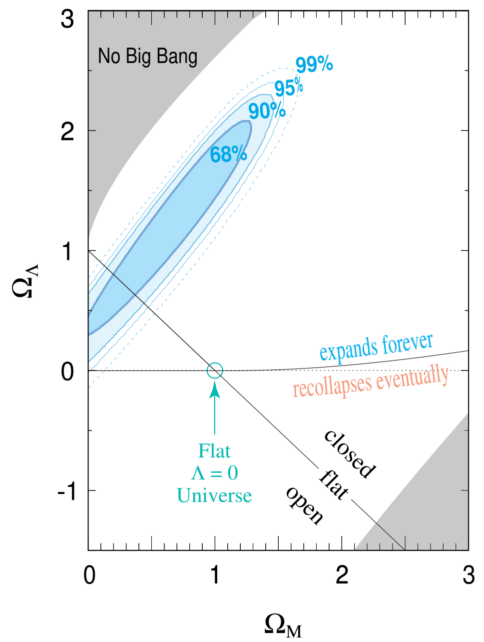

Figure 2: Contours showing the confidence region for Ω_M and Ω_Λ resulting from a preliminary analysis of over 42 SNe Ia, including 1997ap at $z = 0.83$ from Perlmutter *et al* 1998a. Shown are the 68%, 90%, and 99% confidence regions for an unconstrained fit for Ω_M and Ω_Λ. The grey region is excluded 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.

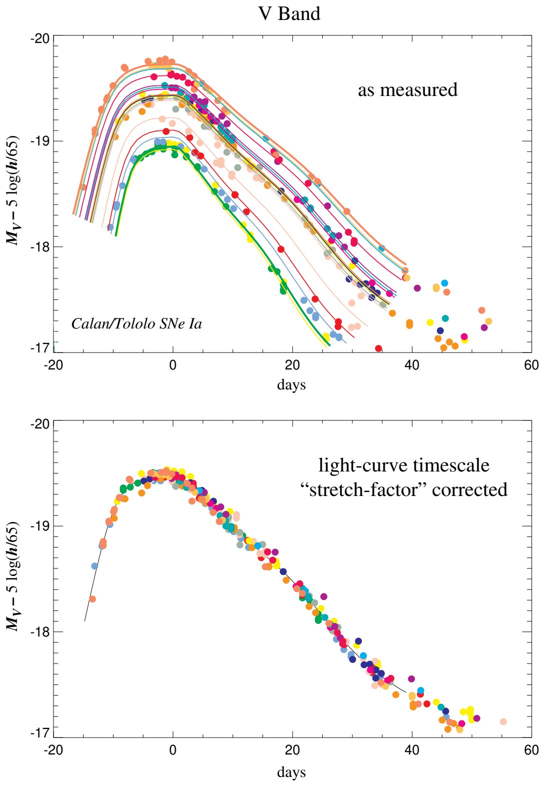

Figure 3: V-band lightcurves for nearby SNe Ia from Hamuy *et al* 1996b. The upper panel shows lightcurves for individual SNe Ia, with absolute magnitudes derived assuming pure Hubble flow and $H_o = 65$ km/s/Mpc. Template lightcurves from Leibundgut *et al* 1991 have been fit to the lightcurve for each 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).

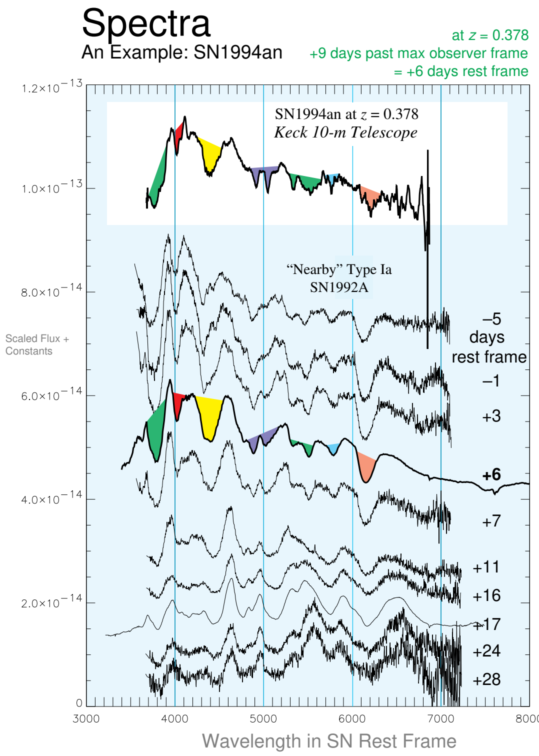

Figure 4: The evolution of the spectra of a Type Ia supernova as the explosion ages. This was constructed using spectra from different SNe Ia obtained at different epochs. The shaded regions highlight portions of the spectra which are seen to evolve with time. Some of these can also be used as luminosity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

II. Lick Observations

The specific goal of the Nickel observations is to contribute to a photometric time series sampled every 3–5 days for these $\sim$ 30 Type Ia supernovae during the period -10 to $+30$ days from maximum. During this period the targets will range in brightness from $B \sim 19$ to $B \sim 21$. Non-photometric conditions can be used, since the photometry can be scaled from other stars in the field which have been previously calibrated. Observations will be obtained in $UBVRI$ with emphasis on UBV. Few other telescopes have CCD's with good, flat U response, so Nickel U photometry using Dewar #2 will be more efficient and result in a smaller color term than with other telescopes with which lightcurves will be obtained. Furthermore, the queue-scheduled YALO telescope on CTIO, which will provide many of our lightcurve observations, does not even have a Johnson U filter.

In order to obtain well sampled lightcurves for $\sim$ 30 SNe Ia we are requesting roughly 2 nights per week from Feb 13 through the end of March (the end of the current proposal period) on the Lick 1-m. When possible we would like to have the two nights spaced by a few days to allow denser sampling of the lightcurves when clear, or increase our chances of obtaining weekly lightcurve points if the weather is bad. Similar allocations of time have been requested at comparable facilities located throughout the world, so some weather insurance is already built-in. Dates in this sequence within 3 days of full moon would be skipped. A sample schedule would be Feb 13, Feb 17, Feb 21, Feb 25, Mar 5, Mar 9, Mar 13, Mar 17, Mar 21, and Mar 25.

Note that Lick 3-m time for spectroscopic follow-up of these same SNe is pending.

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