The Carnegie Supernova Project

Wendy L. Freedman (for the Carnegie Supernova Project) 1

Carnegie Observatories, 813 Santa Barbara St., Pasadena, CA 91101, USA

Abstract. The Carnegie Supernova Project (CSP) is aimed at providing an independent measure of change in the the Hubble expansion as a function of redshift, and setting constraints dark energy contribution to the total energy content of the universe. Using type Ia supernovae (SNIa), the CSP differs from other projects to date in its goal of providing an I-band restframe Hubble diagram. The CSP is focused on testing for and reducing systematic uncertainties, obtaining a sample of multiwavelength observations of approximately 200 supernovae over the redshift range $0 < z < 0.6$. The $UBVRIYJK_s$ data for low-redshift supernova are intended to provide a database for the determination of the Hubble constant, accurate K- and S-corrections, comparison with theoretical models of supernovae, and for comparison with the $RIYJ$ data of high-redshift supernovae. The goal is to measure the evolution of the expansion rate, to characterize the acceleration of the Universe, and constrain the equation of state, $w$, to a precision and accuracy of $10\%$. Type II SNae as independent distance indicators. Following an ongoing, initial test period, the project will begin during the fall of 2004. Here an overview of the project is given, and some preliminary results from the pilot program are presented.

1. Introduction

The evidence for an accelerating universe, with its implication for the existence of a repulsive dark energy, is of profound significance for particle physics and cosmology. Yet the explanation for the dark energy remains a complete mystery. There are at least two major challenges to a theoretical understanding of the dark energy: 1) the small magnitude of the dark energy component relative to its expected value based on standard particle physics – a discrepancy with the observed value of 55 orders of magnitude or more, and 2) it appears that we are living at an epoch when coincidentally the dynamics of the expansion are only now becoming dominated by the dark energy. Given these immense challenges and the current lack of a physical understanding of dark energy, further empirical characterization of the evolution of the expansion rate of the Universe is clearly needed.

In general relativity, the expansion of the Universe, described in terms of the scale factor, $a(t)$ can be written:

$$\ddot{a}/a = -4\pi G \sum_i (\rho_i + 3P_i)$$

where $\rho$ is the energy density and $P$ is the pressure of the various components (matter, radiation, dark energy) of the Universe. Both energy and pressure
govern the dynamics of the universe. This equation allows for the possibility of both negative as well as positive pressure, with a negative pressure acting as an effective repulsive gravity. Any component of the mass-energy density can be parameterized by its ratio of pressure to energy density, \( w = \frac{P}{\rho} \).

In a universe with dark energy, the expansion rate of the Universe is given by:

\[
H^2(z) = \frac{H_0^2}{[\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^3(1+w)]}
\]

where \( \Omega_m \) and \( \Omega_\Lambda \) represent the matter and dark energy densities. For ordinary matter \( w = 0 \), for radiation \( w = 1/3 \), and for the cosmological constant (dark energy) \( w = -1 \).

There are two main observational approaches that currently provide evidence for dark energy. First are measurements of the Hubble diagram using type Ia supernovae (SNIa), for which the best fit yields a model with \( \Omega_m \sim 0.3 \), and \( \Omega_\Lambda \sim 0.7 \) (Riess et al. 1998; 2004; Tonry et al. 2003; Perlmutter et al. 1999; Knop et al. 2003). Second are measurements of the angular power spectrum of the cosmic microwave background (CMB), which provide an independent check on, and a consistent set of cosmological parameters as the SNIa (Spergel et al. 2003, Page et al. 2003). The Wilkinson Microwave Anisotropy Probe (WMAP) results, combined with measurements of large-scale structure, yield results consistent with the type Ia supernova measurements, with a matter density of about one third, and the remaining two-thirds contribution from a dark energy component.

There are multiple advantages of using SNIa for measurements of \( \Omega_\Lambda \). First, SNIa are luminous and can observed over a wide redshift range. They offer a means of directly providing measurements of a change in the expansion rate over time, and hence for an acceleration of the Universe. (The CMB measurements provide constraints on the energy density of an additional component such as dark energy, but not on the acceleration of the Universe.) Second, the dispersion in the SNIa Hubble diagram (~0.14 mag) is small enough that the shape of the Hubble diagram can be used to separate \( \Omega_m \) and \( \Omega_\Lambda \), independently of the nearby, local calibration sample. Third, potential effects due to evolution, chemical composition dependence, dust properties, and gravitational lensing, can be empirically tested, calibrated, and corrected.

However, as ongoing and future supernova surveys yield larger sample sizes, the statistical uncertainties will decrease further, and systematics will dominate the total uncertainty. An increasing challenge for “precision measurements” in cosmology, is understanding and minimizing small systematic uncertainties, essential for characterizing the nature of the dark energy.

2. The Carnegie Supernova Project (CSP)

The Carnegie Supernova Project (CSP) makes use of the unique resources available to us at the Las Campanas Observatory (LCO): the 1-m Swope, 2.5-m duPont, and two 6.5-m Magellan telescopes, instrumented with CCDs and IR cameras and CCD spectrographs. At low redshift, the goal is to provide well-
observed lightcurves from the near-ultraviolet to the near-IR ($UBVRIYJHK_s$)$^2$. An immediate result of this effort will be a fundamental dataset on the photometric and spectroscopic systematics of both type Ia and II SN events.

The primary aim of the CSP is to establish a rest-frame I-band Hubble diagram, while at the same time assembling an extensive database for low redshift supernovae, useful for a variety of supernova studies. For the Hubble diagram, the I band represents the best compromise wavelength to work at; shorter rest-frame passbands (UBV) have the advantage that they can be followed out to higher redshifts, but they suffer larger systematic uncertainties. The I passband offers important advantages for minimizing potential systematic effects such as reddening and metallicity; however, the objects cannot be observed to as great distances. Hence, optical and near-infrared observations remain quite complementary (see Figure 1). However, by a redshift of 0.5, the differences amongst various cosmological models are quite significant (that is, testing for a dark energy component does not require observations to high redshifts). The I-band restframe data will thus provide both a critical test of the current shorter-wavelength restframe data, as well as an independent measure of the dark energy component.

Observations of low-redshift supernovae ($z<0.2$) are being carried out using the 1-meter Swope and 2.5-meter Dupont telescopes. The high-redshift ($z>0.2$) observations are being carried out at the Baade 6.5-meter telescope, using the Persson Auxilliary Near-Infrared Camera (PANIC).

We itemize here the many parts to and goals of the CSP:

1) To provide a reference data set with high signal-to-noise, uniformly-calibrated photometry of type Ia supernovae, for comparison with high-redshift supernovae for cosmology studies.

2) To provide bolometric light curves for comparison with theoretical models for supernovae.

3) To obtain an independent measure of the Hubble constant based on infrared photometry.

4) To characterize in detail the nature of supernova light curves over a range of wavelengths.

5) To investigate whether the light curves or spectra of type Ia supernovae differ with age of the progenitor.

6) To search for possible metallicity effects.

7) To study the connection of gamma-ray bursts and supernovae (in collaboration with Berger et al.)

8) To study nearby velocity flows – deviations from the smooth Hubble expansion.

9) To improve the determination of photometric K-corrections

10) To improve S-corrections (spectral corrections).

11) To obtain independent estimates of the Hubble constant using type II supernovae.

12) To search for independent evidence of acceleration using type II supernovae.

---

$^2$The Y-band is centered at 1µm; Hillenbrand et al. 2002.
2.1. Low Redshift

For the nearby sample, the goal is to obtain $UBVRIYJHK_s$ photometry and optical spectroscopy for 125 low-redshift type Ia supernovae and 100 type II supernovae. Photometric observations with a precision of $\sim0.03$ mag will be obtained every 2-4 nights so that large gaps in the light curves, common in supernova studies to date, can be minimized. The observations are being carried out from the time of discovery through 50 days past maximum for SNIa, and through the extended plateau phase for SNII. An additional goal is to obtain optical spectroscopy every 5-7 days from discovery through 40 days past maximum.

The photometry obtained for many of the CSP supernovae will provide a unique resource for improving the precision of these objects as distance indicators, and for computing bolometric light curves for comparison with theoretical models. This nearby sample will serve as a reference for the rest-frame $I$ and $Y$ light curves of the sample of 120 high-redshift SNIa that we have begun to
obtain. Furthermore, the infrared photometry will be extremely valuable for independent determinations of the Hubble constant as described below. It will also be very useful for studying the nearby peculiar flows of galaxies out to \( \sim 10,000 \) km/s.

**Near-Infrared Distances to Nearby Supernovae:** Near-infrared observations offer the promise of improving the precision of SNIa as cosmological standard candles for the determination of \( H_0 \). Meikle (2000) and Elias et al. (1985) have noted the advantages of infrared photometry of supernovae, but the recent availability of large-format infrared arrays now allows the full potential of infrared observations to be exploited. Nearby supernova distances can be calibrated, using the local Cepheid distance scale to yield a value of \( H_0 \) at cosmologically interesting distances.

Well-known advantages of infrared photometry are reduced sensitivity to both reddening and metallicity. In addition, the \( JHK \) data for type Ia supernovae show peak absolute magnitudes in the near infrared that are nearly constant, independent of decline rate (Meikle 2000; Krisciunas et al. 2004). The correlation between absolute magnitude and decline rate is steepest in the \( B \) band, and becomes essentially flat at \( H \) (see Figure 2).

We are also obtaining photometric and spectroscopic data on Type II supernovae for an independent check on both the local distance scale, and measurements of dark energy. Infrared measurements for SNII are critical for reducing the systematic effects of reddening and metallicity. Since SNII have young, massive progenitors, they are found typically in regions with average higher extinctions than the lines of sight to SNIa.

### 2.2. High Redshift

To date, very few rest-frame \( I \)-band measurements have been obtained for supernovae at high redshift. At \( z \sim 0.25 \) this wavelength is redshifted out of the reach of CCDs (thus requiring large-format infrared arrays), while, in addition, the objects are faint (requiring large telescopes). Using the 6.5-meter Baade telescope, our goal over the course of the next five years is to observe a sample of \( \sim 120 \) SNIa between \( z = 0.2-0.6 \), obtaining \( YJ \) for each of the candidates, and \( RI \) photometry for a subset of the sample. These data will provide rest-frame \( BVI \) photometry for each supernova, yielding two colors, allowing accurate reddening corrections to be determined. We are obtaining 5-6 observations in \( Y \) and \( J \) covering the SN maximum and thereby allowing a firm measure of the peak magnitude. Because optical photometry is being obtained by the Legacy and ESSENCE programs (see Section 3) for these supernovae, our observations will afford a unique opportunity to ascertain the level at which different photometric calibrations, K-corrections, and reddening corrections impact the results.

HST NICMOS observations are available for a few high-redshift supernovae (Riess et al. 2004), but due to practical limitations, the bulk of measurements at high \( z \) are UV/optical restframe. Ultimately observations from a future space mission (e.g., the Joint Dark Energy Mission) may routinely obtain long-wavelength data for the high-redshift supernovae (\( 0.7 < z < 1.7 \)). However, the telescopes/instruments at Las Campanas offer a means to make significant progress today from \( 0 < z < 0.7 \), and the CSP will provide a means of eliminating reddening as a potential remaining source of systematic error for this
In late 2003 and early 2004, we obtained YJ photometry coverage for eight supernovae with I-band magnitudes ranging from 21.3 to 24.0 mag, and redshifts fairly uniformly distributed from 0.2 to 0.84.

redshift range, while providing a fiducial I-band comparison for future studies at higher redshifts. If we live in a universe where \( w = -1 \), then this redshift range is the one where the cosmological effects of dark energy are manifest. At higher redshifts, matter will dominate the expansion.

In late 2003 and early 2004, we obtained YJ photometry coverage for eight supernovae with I-band magnitudes ranging from 21.3 to 24.0 mag, and redshifts fairly uniformly distributed from 0.2 to 0.84.
2.3. Addressing Systematic Effects

In an era of precision cosmology, where 10% accuracy on the measurement of $w$ and 15% on $w'$ are desired goals, minimizing the effects of systematic errors becomes the central issue to be addressed. Observations and careful study to date have demonstrated that such systematic effects cannot explain away the observed differences in supernova luminosities for the high- and low-redshift samples. However, the requirement for increasing measurement accuracy – and the lack of a detailed theoretical understanding of type Ia supernovae, the current observations at restframe optical colors, the difficulty of obtaining accurate $K$-and filter-corrections – mean that even previously small effects become important to characterize and eliminate.

**Reddening:** An advantage of longer-wavelength photometry is the decreased sensitivity to reddening. The ratio of total-to-selective absorption increases toward shorter wavelengths:

$$R_{\lambda} = \frac{A_{\lambda}}{E(B-V)}$$

where the ratio of total-to-selective absorption, $R$, decreases from $\sim 5$ for the U-band, to $\sim 4$ for the B-band, to 1.7 for the I-band (Cardelli et al. 1989). Thus, the U-band absorption is a factor of 3 greater at U than at I. In practice, this means that even for very small reddenings, where $E(B-V) < 0.03$, the corrections to the restframe U-band magnitudes may be 0.15 mag; that is, comparable to the cosmological effect being measured. Hence, at bluer restframe wavelengths, the reddening corrections are more uncertain. One of the key goals of the CSP is to minimize the effects of reddening in the Hubble diagram, and ensure that the rest-frame ($BVI$) bandpasses being observed at low redshift match those for a sample at higher redshift, so that reddening corrections can be applied in a uniform way.

**Metallicity / Age:** Nearby SNIa occur in widely different stellar environments, with varying ages and metallicities of their stellar populations. The multiwavelength nearby CSP dataset will provide an excellent resource for addressing the question of whether there are systematic differences due to metallicity or age of the progenitors between the high- and low-redshift samples.

The effects of age and metallicity on the observed properties of SNIa have been modeled by a number of investigators (e.g., Höflich et al. 1998, Lentz et al. 2000). These models suggest that pre-explosion metallicity can have a significant effect on the observed SNIa spectra. For example, the models of Lentz et al. (2000) indicate that scattering in the atmospheres is greatest in the U-band, and decreases through the optical to infrared. However, predictions from models to date have not yet converged on the sign or the magnitude of such effects, and therefore, empirical constraints are critical to minimize potential systematic effects in measurements of the distances to SNIa.

To date, empirical searches for environmental dependences that might correlate with the age of the supernova progenitor (host galaxy morphology, color, position in the galaxy on supernova distances have led to null results (e.g., Williams et al. 2003, Sullivan et al. 2003).

**Other Systematics:** Comparison of high- and low-redshift supernovae for the measurement of cosmological parameters requires accurate transformations of
photometric bandpasses. The K-corrections in use today are based on observations of a few low-redshift SNIa whose overall spectral shapes from the ultraviolet through the near-infrared are adjusted to match observed broad-band colors (e.g., Nugent et al. 2002). Unfortunately, errors as large as 0.3 mag are possible for some SNIa in the $I$ band (Strolger et al. 2002), and large uncertainties remain in the U-band due to intrinsic variations in the supernovae themselves, as well as due to the larger extinctions. One of the goals of the CSP is to increase the sample of SNIa with a range of luminosities and decline rates, with well-observed spectra and multiwavelength photometry for the purpose of improving the K-corrections.

In addition, Stritzinger et al. (2002), have alarmingly found that the peak magnitudes of supernovae can differ by up to 0.05 mag for data taken at different telescopes, despite reducing the photometry to the same local standards around the supernovae using the color terms derived for each site and instrument. Since a shift of 0.05 mag in the $B-V$ color can introduce a 0.20 mag error in the extinction corrected peak $B$ magnitude of a supernova, this is an additional uncertainty that needs to be minimized when attempting to measure cosmological parameters with higher precision than previous measurements. A critical aspect of our low-redshift program is to monitor our photometric systems in order to compute the spectral corrections (S-corrections) required to bring the instrumental magnitudes onto the standard photometric system, and decrease such systematic effects.

3. Ongoing Supernova Searches

Low Redshift:

• LOTOSS: The source of low-redshift supernovae for the CSP is primarily the Lick Observatory and Tenagra Observatory Supernova Searches (LOTOSS). LOTOSS is discovering supernovae over the redshift range $z=0.003-0.15$, and obtaining $UBVRI$ light curves. Since 1998, this survey has led to the discovery of about 400 supernovae. The survey efficiency has continued to increase with time so that over half of the supernova discoveries have occurred in the past 18 months. In 2003, a collaboration between CSP and LOTOSS astronomers (Filippenko and Li) was begun, and the LOTOSS search fields were shifted to include more galaxies in the southern hemisphere, suitable for follow-up by the CSP. The collaboration allows the LOTOSS group to concentrate its effort on the search, without the extra tax in telescope time for follow-up, and the CSP is set up to carry out the optical and near-infrared follow-up observations on the 1-m and 2.5-m LCO telescopes.

High Redshift:

Our high-redshift supernova targets are coming from the Supernova Legacy Survey (SNLS) and the ESSENCE Project.

• The Legacy Survey is a Canadian/French collaboration, which has been using the CFHT as of Feb. 2003 to obtain deep optical (ugriz) images for 4 fields totaling 16 square degrees around the equator. The SNLS is revisiting each field every second night during a 5-month campaign per semester for the next 5
years. Their goal is to discover 2000 type I supernovae out to redshifts in excess of one, with 900 of those having $z < 0.9$. They are finding on average about 15 supernovae per month. In the week preceding CSP Magellan observations, CSP and SNLS team members consult on candidates observed to be on the rise, with spectra confirming types and providing redshifts. Carlberg and Pritchet of the Legacy project are CSP collaborators.

- ESSENCE is using the CTIO 4-m telescope to survey at VRI wavelengths over the redshift range between $z=0.15-0.75$. They revisit each field every second night during one 3-month (Oct-Dec) campaign per year, and aim to produce optical light curves for 200 SNIa over 5 years (2002-2007). The Essence Project discoveries are also being made available to us in real time: targets, classifications and redshifts. Suntzeff is the PI of this project, as well as a collaborator on the CSP.

4. Summary

The Carnegie Supernova Project will go into full swing in the fall of 2004, with the goal of obtaining $UBVRIYJHK_s$ light curves and optical spectroscopy for 225 low-redshift types I and II supernovae; and $RIYJ$ photometry for 120 high-redshift type Ia supernovae over the next 5 years. This dataset will allow us to determine extinction corrections, to constrain evolutionary effects due to age and metallicity, and to minimize errors in supernova distances by providing improved S-corrections. These data will provide an independent measure of the Hubble constant, and a restframe I-band Hubble diagram. The ultimate goal of this research is to characterize accurately the expansion history of the Universe, and to elucidate the nature of the dark energy and its equation of state, $w$, to a precision of better than 10%.

References

Cardelli, J. A., Clayton, G. C. & Mathis, J. S., 1989, ApJ, 345, 245
Elias, J. H. et al. 1985, ApJ, 296, 379
Hillenbrand, L.A., Foster, J.B., Persson, S.E., & Matthews, K., 2002, PASP, 114, 708
Höflich, P., Wheeler, J. C., & Thielemann, F. K. 1998, ApJ, 495, 617
Knop, R. A., et al. 2003, ApJ, accepted, astro-ph-0309368
Krisciunas, K., Phillips, M. M. & Suntzeff, N. B. 2004, astro-ph/0312626
Lentz, E. J., Baron, E., Branch, D., Hauschildt, P. H., & Nugent, P. E. 2000, ApJ, 530, 966
Meikle, W. P. S., 2000, MNRAS, 314, 782
Nugent, P., Kim, A. & Perlmutter, S., 2002, PASP, 803
Page, L., et al. 2003, ApJ Suppl, 148, 175
Perlmutter, S., et al. 1999, ApJ, 517, 565
Riess, A. G., et al. 1998, AJ, 116, 1009
Riess, A. G., et al. 2004, ApJ, accepted, astro-ph-0402512
Spergel, D. et al. 2003, ApJ Suppl, 148, 175
Stritzinger, M. et al. 2002, AJ, 124, 2100
Strolger, L.-G. et al. 2002, AJ, 124, 2905
Sullivan, M., et al., 2003, MNRAS, 340, 1057
Tonry, J. L. et al. 2003, ApJ, 594, 1
Williams, B. F. et al., 2003, AJ, 126, 2608