SNLS – the Supernova Legacy Survey

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Abstract.

Type Ia supernovae (SNeIa) provide direct evidence for an accelerating universe, and for the existence of “dark energy” driving this expansion. The Supernova Legacy Survey (SNLS) will deliver many hundreds of SNIa detections, and well-sampled $g'r'i'z'$ light curves, over the next 5 years. Using these data, we will obtain a precise measurement of the cosmological parameters ($\Omega_{\text{mass}}, \Omega_\Lambda$); our goal is to determine the cosmological equation of state parameter $w$ to a precision better than ±0.10, and hence test theories for the origin of the universal acceleration.

SNLS uses the CFHT MegaCam imager (400 Megapixels, 1 deg$^2$) to image four fields around the sky in 4 filters, with typical time sampling of 3–4 nights. A total of 202 nights of CFHT time has been allocated over the next 5 years for these observations; a large program of followup spectroscopy is now underway at VLT, Gemini, Keck, and Magellan.

SNLS has been running since August 2003. There now exist about 330 reliable SN detections with excellent light curves out to beyond redshift 0.9, of which about 80 have been spectroscopically identified as Type Ia’s. See http://www.cfht.hawaii.edu/SNLS for up-to-the-minute information on the latest SN discoveries.

1. Introduction

In late 1998 two teams (Riess et al. 1998, Perlmutter et al. 1999) independently announced that the expansion of the Universe is accelerating. This remarkable discovery, which was made using observations of Type Ia supernovae, ranks as one of the most exciting developments in cosmology over the past 80 years. We now know from these, and other, observations that the geometry of the Universe is exquisitely flat; two-thirds of its energy content consists of a mysterious component known as “Dark Energy”, which drives the universal acceleration, and whose density decreases slowly, or not at all, as the Universe expands.

The key parameter in studying dark energy is the equation of state parameter $w$, which relates the pressure and the density of the Universe (through $w = P/\rho$). For instance, a classical fixed cosmological constant, $\Lambda$, as proposed by Einstein, yields $w = -1$, whereas other models (e.g. quintessence) yield values of $w > -1$ (e.g. Huterer and Turner 2001).

\footnote{See http://snls.in2p3.fr/people/snls-members.html for a complete list of SNLS collaboration members.}
The primary goal of the Supernova Legacy Survey (SNLS) is to distinguish between dark energy models (and hence strongly constrain the physics that might lead to dark energy) using luminosity distance measurements of supernovae. To do this requires a concerted program to find, and measure the properties of, many hundreds of type Ia supernovae at redshifts $0.2 < z < 0.9$ (lookback times of billion of years). Such a sample of supernovae represents an increase by a factor of order ten in the number of supernovae available for cosmological analysis; the chosen redshift range optimally spans lookback times that are most sensitive to the transition from a matter-dominated to a dark energy-dominated Universe.

SNLS will allow a high confidence discrimination between $w=-1$, the “Einstein value”, and $w=-0.8$, a value that is predicted in one of the simplest available quantum gravity field theories. Type II supernovae (massive star core collapse) will also reveal the star formation rate of the Universe in the distant past, and hence critically constrain the evolution of galaxies over more than half of the age of the Universe.

## 2. SNLS – an Overview

SNLS$^2$ is built on the Deep survey—the largest single component of the Canada-France-Hawaii Telescope Legacy Survey$^3$; CFHTLS is possible thanks to the availability of the $1\, \text{deg} \times 1\, \text{deg}$ MegaCam$^4$ mosaic imager at CFHT.

There are a number of attributes of SNLS that make it attractive for studies of supernovae.

| Field | RA(2000) | Dec(2000) | Other Observations |
|-------|----------|-----------|--------------------|
| D1    | 02:26:00.00 | $-04:30:00.0$ | XMM Deep, VIMOS, SWIRE, GALEX |
| D2    | 10:00:28.60 | $+02:12:21.0$ | Cosmos/ACS, VIMOS, SIRTF, XMM |
| D3    | 14:19:28.01 | $+52:40:41.0$ | Groth strip, Deep2, ACS |
| D4    | 22:15:31.67 | $-17:44:05.7$ | XMM Deep |

→ **Sampling and Total Observing Time** – More than 500 epochs will be obtained over 5 years on each of four 1 square degree fields (for a total of 202 nights of observing time). (Field coordinates are given in Table 1.) Typical photometric sampling of the supernova light curves is once every 3–4 days ($\sim 2$ days in the rest-frame of the supernova) during dark-grey time, and with bright time sampling gaps (when MegaCam is taken off the telescope) typically 11 days or less.

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1. [http://www.cfht.hawaii.edu/SNLS/](http://www.cfht.hawaii.edu/SNLS/)
2. [http://www.cfht.hawaii.edu/CFHTLS/](http://www.cfht.hawaii.edu/CFHTLS/)
3. [http://www.cfht.hawaii.edu/Instruments/Imaging/MegaPrime/](http://www.cfht.hawaii.edu/Instruments/Imaging/MegaPrime/)
Each field has a 6 month observing window per year, resulting in extensive light curves and improved survey efficiency (since a larger fraction of the supernovae that explode in a 6 month window will be useful for light curve fitting, compared to shorter observing windows). The time sampling is a key parameter in the survey design; it greatly improves the measurement of maximum brightness, and the light curve which is used to determine the intrinsic luminosity of the supernova. The observations are obtained in a “queue-scheduled” mode by observatory staff. Without queue scheduling and service observing, the time sampling and enormous amount of observing would be impossible to handle.

The field size of MegaCam has a multiplex advantage – it allows us to follow the late time light curves of supernovae at the same time that new discoveries are being recorded. The sampling cadence permits, for the first time, a detailed observation of the rising light curves of a large sample of high redshift SNe.

Figure 1 shows an example of a relatively low redshift (z=0.28) supernova found in the presurvey phase of observations. Fig. 2 shows some of our light curves of intermediate redshift objects that reached maximum in Sep–Oct 2003. It can be seen that, even in the presence of gaps in the light curves (due to bright of moon, when MegaCam is not mounted, and weather), maximum light can be measured quite accurately - typically to an accuracy much better than ±0.1 mag.

▷ Filter Coverage – SNLS obtains time-sequenced images in each of the filters $g'r'z'$, which are close to (though not identical with) the Sloan Survey filter set. Some observations are also taken in $u^*$. These observations permit excellent corrections from observed (redshifted) wavelengths to the fiducial restframe $B$ (440nm – blue light) band, and also allow corrections for internal absorption in the host galaxies due to dust absorption.

▷ The Team – SNLS is a large international collaboration led by scientists in Canada and France, with participants in the USA, UK, and elsewhere in Europe. The collaboration includes scientists at all levels, with 4 scientists in Canada/France assigned data-handling duties to keep up with the data flow and basic data reduction. The Chair of the Collaboration Board is Reynald
Figure 2. Composite light curves (brightness vs. time) from early SNLS data. Time 0d corresponds to 2003 Sep 14 UT. It is clear that the maximum brightness, on which cosmological analysis depends, can be measured to very high accuracy from these data.

Pain (LPNHE, U. Paris), and the CFHTLS Supernova Coordinator is Chris Pritchet (U. Victoria).

Data Analysis Pipelines – Starting from CFHT real-time preprocessed data (Magnier and Cuillandre 2004), two independent real-time analysis pipelines (run by the Canadian and French teams) analyze the data as it is arrives from Mauna Kea at the CFHT headquarters. These pipelines produce lists of candidates, and magnitudes, in about 4–6 hours, and agree quite well down to about $i'_{AB}=+24$ (redshift about 0.8 for a typical SNIa). The key element of these pipelines is matching the point spread function of an exposure to a reference image. This is done using the Alard (1997) algorithm for the French team, and using a non-parametric approach (Pritchet 2004) by the Canadian team. A complication is the large (≈1.5 arcmin) dithering pattern that is used to “fill in” the two 80 arcsec wide gaps in the MegaCam mosaic. This prevents the use of a chip-by-chip analysis of the mosaic, because much of the area of each CCD chip would be lost because of the dithering. Instead it is necessary to “swarp” (E. Bertin, private communication) each individual exposure of a sequence to an astrometric reference frame, prior to combining and PSF-matching.

Eventually our goal is to merge the two detection pipelines. However, we plan to maintain two independent paths for photometric analysis, since this is on a critical path to the derived cosmological model.

3. Spectroscopic Followup

Spectroscopy is vital in order to obtain SN redshifts, and to confirm the type of each SN. This requires observations on the world’s largest (8-10 metre class) telescopes, because of the faintness of the supernovae. Spectroscopic followup time has been committed for 2003-2005 at the European Southern Observatory Very Large Telescope (PI Pain), and time is also being used at Gemini North and South (PIs Hook/Pritchet/Perlmutter), the Keck Observatories (PI Perlmutter, with complementary spectroscopic followup observations PI’d by Ellis), and Magellan (PI Carlberg, with complementary IR observations by Magellan).
Figure 3. Spectra from our Sep 2003 Gemini 8m telescope observations with the GMOS-N spectrograph, overplotted with best-fitting local supernova templates. Left: a SNIa at z=0.697 ($i'=23.5$), observed in classical long slit mode for 3600s; right: an SNIa at z=0.866 ($i'=24.0$), observed in “nod and shuffle” mode for 4800s. Note the much-improved sky-subtraction for the fainter object observed with nod-and-shuffle (available only on Gemini).

In fact, more spectroscopic 6.5-8-10m telescope time has been allocated so far than CFHT discovery time! The organization of this spectroscopic followup campaign has been one of the major successes of the SNLS project.

A key element of the spectroscopic followup strategy is the queue-scheduling and rolling search discovery mode at CFHT. This leads to improved efficiency for spectroscopic followup because: (1) it allows us to monitor the rise of the object and trigger spectroscopy at maximum light; (2) the flux of the target is well known since it is measured one or two days before max; this allows us an improved estimate of exposure time; and (3) pre-maximum colours and fluxes allow good discrimination of SNeIa from other events (e.g. SNeII and AGN’s).

Another success story in the spectroscopic followup is the use of “nod and shuffle” observations at Gemini; this mode virtually eliminates systematic sky residuals for the faintest objects. See Fig. 3 for an example of this mode of observation.

It is conceivable in the future that some of the spectroscopic typing of supernovae will be replaced by multi-filter/multi-epoch typing. The ugriz filter observations of CFHTLS will play a pivotal role in defining photometric indices that may help to discriminate SNeIa from other classes of events. We emphasize, however, that this goal is still far from being realized. Furthermore, photometric redshifts do not yet have sufficient precision to permit their use in Hubble diagram cosmology; spectroscopic (though non-time-critical) z’s for SN hosts will still be required for the foreseeable future, even if multicolor SN typing were to become practical.
Table 2. Detections and Real-Time Analysis of Spectroscopy

| Run       | Detections | Spectra | SNIa* | SNII* |
|-----------|------------|---------|-------|-------|
| Pre-survey| 74         | 25      | 15    | 4     |
| 2003 Aug  | 18         | 10      | 5     | 3     |
| 2003 Sep  | 33         | 16      | 11    | -     |
| 2003 Oct  | 28         | 14      | 6     | 2     |
| 2003 Nov  | 18         | 4       | 3     | -     |
| 2003 Dec  | 17         | 10      | 6     | -     |
| 2004 Jan  | 42         | 13      | 6     | 1     |
| 2004 Feb  | -          | -       | -     | -     |
| 2004 Mar  | 37         | 18      | 8     | 1     |
| 2004 Apr  | 26         | 19      | 8     | 1     |
| 2004 May  | 29         | †       | †     | †     |
| All Runs  | 322        | 129     | 68    | 12    |

* Confirmed or probable typing.
† Final spectroscopic statistics not available.

4. Current Status of SNLS

The SNLS team is now routinely delivering web-based SN detections and photometry within 6–12 hr of data being taken. The reader is referred to the SNLS web pages (see the footnote in §2), with links to both the Canadian and French detection web sites.

Table 2 shows the current (May 2004) status of the observations. More than 300 candidate supernovae have been discovered; of these more than 120 have spectroscopy. A preliminary redshift distribution of some of the data, with a few explanatory notes, is shown in Fig. 4. Cumulative statistics of probable SN candidates and spectroscopic confirmation are shown in Fig. 5.

The weather at Mauna Kea since Oct 2003 has been the worst in more than 20 years; this resulted in one entire run being lost, poor detection statistics, and worse than expected light curve and filter sampling, through late 2003 and some of 2004. Weather problems have also affected image quality. However, there is also the underlying problem that the performance of the MegaCam corrector is not quite as good as expected, with a fairly noticeable degradation in the corners. The effect of this is quite difficult to quantify, but early indications are that it has not affected the numbers of detected supernovae, or the photometry, significantly.

One of the surprising issues to emerge from the Tucson DE meeting was the widespread concern about calibration. Of course, there are many “routine” (!) matters that must be addressed in calibrating a new instrument such as MegaCam, and work has only recently begun in earnest on these detailed calibration issues. Many of these issues are mitigated by the fact that we are continuously observing the same fields, and refer each SN to a grid of nearby secondary standard stars. We believe we will be able to achieve our goal of ±0.02 mag or better accuracy.
Figure 4. **Preliminary** numbers of SN Ia and probable SN Ia as a function of redshift, as of Feb 2004, compared with the expected numbers of Ia assuming a detection limit of $i'_{AB}=25.5$ (dotted line) and a spectroscopy limit of $i' = 24.5$ (full line). Expected numbers were computed assuming a flat $\Omega_m = 0.33$ Universe and a distant SNIa rate from Pain et al. (2002).

Beyond this, there exist a host of small systematic effects that may disturb our ability to $\sqrt{N}$ the errors for hundreds of SNe. These sources of error include: error in the relative absolute calibration of different filters; variations in color terms over the field of view (due to, for example, spatially variable wavelength response of the filters); and detailed (and difficult to determine) corrections for the convolution of the complex spectral energy distribution of a SNIa with the response characteristics of the filter+CCD.

5. **Science Goals**

The confirmed sample of SNeIa will be used to obtain a precise measurement of the cosmological parameters $\Omega_M$ and $\Omega_\Lambda$ (where $\Omega_M$ and $\Omega_\Lambda$ are the fraction of closure density in matter and vacuum energy; $\Omega_M + \Omega_\Lambda = 1$ represents a flat Universe). The SNeIa will be used to obtain a measurement of the dark energy parameter $w$ with a precision approaching $\pm 0.05$ when a prior on $\Omega_M$ is used – see Fig. 6.
Supernova observations can be subjected to many straightforward tests to check for systematic errors. The CFHTLS $u'g'r'i'z'$ data can be used to measure SN colours and hence test for reddening by comparison with colours for nearby SNe. (We have collaborative plans with Magellan staff to use IR data to obtain colour measurements out to $z \sim 0.6$.) In addition we will have a large enough sample to be able to study subsets divided by host galaxy type (derived from the host galaxy spectra or high resolution imaging), or galactocentric radius - this allows us to check for effects associated with changes in the underlying host galaxy population (metallicity, extinction, age), similar to the study of Sullivan et al (2003). The SN spectra themselves can be stacked to obtain a high S/N mean spectrum for different host galaxy types or $z$ ranges; these can be compared against local SN spectra to check for small evolutionary effects. Complementary spectroscopic observations at Keck (Ellis et al.) will also provide a detailed comparison of low- and high-$z$ SNe.

SNLS is an important step towards a precision measurement of the dark energy equation-of-state parameter $w$: it will assume constant $w$, and test the possibility that the dark energy is just the cosmological constant, i.e. the zero-point energy of the vacuum – perhaps the simplest, best known dark energy model. A more exhaustive study sensitive to time-variable $w$ may have to await the launch of the JDEM mission well into the next decade.

Acknowledgments. SNLS relies on observations with MegaPrime, a joint project of CFHT, CEA/DAPNIA, and HIA. The SNLS collaboration wishes to
Figure 6. Confidence region in the \((w-\Omega_M)\) plane, assuming a flat Universe. The blue region represents the SNe observed in Perlmutter et al. (1999). The red ellipse is the simulated 1σ contour for 300 SNe (SNLS mid-project), assuming that \(\Omega\) is measured independently. The simulation assumes \(w = -0.8\) and \(\Omega_M = 0.3 \pm 0.03\). This demonstrates the ability to test whether a cosmological constant fits the data, or whether some other form of dark energy is required.

gratefully acknowledge the assistance and co-operation of the CFHT Queued Service Observing team, headed by Pierre Martin; and Jean-Charles Cuillandre, Eugene Magnier, Christian Veillet, and Kanoa Withington for assistance and advice with CFHTLS data, calibration, and CFHT computer systems. The French collaboration members acknowledge support from CNRS/IN2P3, CNRS/INSU and CEA. Canadian collaboration members are funded and supported by NSERC and CIAR.

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