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Cosmological constraints from the 3rd year Supernova Legacy Survey data set

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Type Ia supernovae (SNe Ia) currently provide the most direct evidence for an accelerating Universe and for the existence of an unknown dark energy driving this expansion. The Supernova Legacy Survey (SNLS) is a five-year project which has delivered around 500 high-redshift SNe Ia light curves and spectra in the redshift range $0.2 < z < 1.0$ in order to constrain the dark energy equation of state, w. We present the cosmological results obtained with ~ 240 SNe Ia followed-up during the first 3 years of the survey. This supernova dataset is the largest homogeneous high redshift sample available today. It allows us to test for various systematic uncertainties potentially affecting our measurement and therefore derive robust cosmological constraints.

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1. Introduction

Measuring luminosity distances of distant Type Ia supernovae (SNe Ia) used as standard candles is a powerful approach to constrain the expansion of the universe. Indeed, the luminosity distance is an integral function of the expansion rate of the universe. It can be estimated from observations of distant SNe Ia fluxes as the ratio of their intrinsic to their observed luminosity. Observations over a large redshift range permit to distinguish cosmological models on a “distance vs redshift” diagram (the so-called Hubble diagram).

The Supernova Legacy Survey (SNLS) is a five year french-canadian project than ran from 2003 to 2008, dedicated to the measurement of distant ($0.2 < z < 1.0$) SNe Ia light-curves and spectra. It consisted in an imaging survey on the Canada France Hawaii telescope (CFHT) as part of the CFHT-Legacy Survey, and a spectroscopic survey on 8/10-m diameter telescopes. The SNLS imaging survey was a 5 yr "rolling search" using MEGACAM at the prime focus of the CFHT. Four 1 square degree fields were imaged five times per month in 4 filters for a total exposure time of $\sim$ 200 hours per field (see e.g., [1] for details). The SNLS spectroscopic survey primarily aimed at identifying the type of the SN and determining its redshift. It has also permitted detailed studies in the UV and optical part of SN spectra [2, 3]. Spectra have been obtained at the VLT (during two large programs in service observing mode for a total of 480 hours of spectroscopy time between 2003 and 2007), at Gemini North and South (60 hours per semester) and Keck (30 hours during one semester). Combined with other probes, the 1st year observations of SNLS have been used to constrain the equation of state of the universe parameter $w = p/\rho$ [4]. We present here preliminary results of the 3rd yr analysis.

2. Improvements over SNLS 1st year analysis

2.1 Photometric calibration

The SNLS 3rd year analysis has lead to a better control of focal plane non-uniformities. Dithered observations of dense stellar fields have permitted to solve the non uniformities of the instrumental response. Variations in the instrumental response up to 8% difference along the focal plane and in the effective wavelength of filter up to 4 nm have been found and taken into account[5].

2.2 SN flux calibration

A key feature of the SNLS Hubble diagram is that it relies on the comparison of low redshift SNe Ia with the high redshift homogeneous sample of SNLS SNe Ia. Low redshift SNe Ia are usually calibrated against the Landolt UBVRI system. To avoid introducing additional systematic uncertainties between distant and nearby SN fluxes, SNLS supernovae are also calibrated against Landolt stars. Color-color diagrams are used to translate Landolt UBVRI colors into Megacam *griz* colors using piece-wise linear transformations. To get ratios of distances of SNe at low and high redshift, the ratio of fluxes of a reference star spectrum used as a calibrator are needed. In SNLS 1st year, we used Vega as a reference. In SNLS 3rd year, we use BD+17^o 4708 for flux calibration instead of Vega. Indeed, BD+17^o 4708 colors fall in the same range as our observations of Landolt stars so that no extrapolation in colour-colour diagrams are required. This reduces the systematic uncertainty associated with flux calibration.

2.3 Light-curve fitter and distance estimate

To measure the flux ratio of SNe at different redshift in the same wavelength range and at the same phase, we interpolate light-curve measurements obtained in different rest-frame bands with various time sampling. We use an empirical model of the SNe Ia spectral sequence that takes into account the diversity of SNe Ia via three parameters: a global luminosity offset (rest-frame B-band magnitude at maximum light), a single shape parameter (related to the stretch s) and a global colour c (B-V at maximum light). In SNLS 1st year, we used the SALT [6] template, built from the template spectrum of Nugent[7] and trained with a set of well-measured nearby SNe Ia. For the third year analysis, we used two different light-curve fitters SALT2[8] and SiFTO[9]. Both models were trained on nearby and distant SNe Ia. Using high redshift SNe Ia permits to model the rest-frame UV emission and the regular redshift sampling yields an accurate photometric scan of the SNe Ia spectra. Note that the light-curve fit performed with this model is independent of any distance estimate

SALT2 is an empirical model of the SNe Ia spectral sequence $F(SN,\phi,\lambda)$ that reads:

$$F(SN,\phi,\lambda) = x_0[M_0(\phi,\lambda) + x_1 M_1(\phi,\lambda) + \ldots] \times \exp[c.CL(\lambda)] \tag{2.1}$$

where x_0, x_1 and c are the luminosity offset, shape and colour parameters discussed above, $CL(\lambda)$ is a colour variation law and M_i are linear principal components.

In SiFTO, the light curve shape variability is modelled with a time-stretching of the SED sequence about the date of maximum light in rest-frame B-band, with a wavelength-dependent stretch factor indexed by its value in B-band. SiFTO relies on linear colour relations for the broad-band wavelength dependent calibration of the SED sequence.

As a distance estimator, we use the distance modulus μ_B of SNe Ia in the B-band corrected for the empirical "brighter-slower" and "brighter-bluer" correlations:

$$\mu_B = m_B^* - M + \alpha(s-1) - \beta c \tag{2.2}$$

where M, α and β are empirical coefficients fitted along with cosmology. In particular, β accounts both for host galaxy dust extinction and any intrinsic colour properties of SNe Ia.

2.4 Spectroscopic identification

In SNLS 1st year, the identification of the SN type relied on the real-time processing of spectral data performed within a few days following the spectrum acquisition. VLT spectra of the SNLS 3rd year SNe Ia were analyzed with an optimized spectral extraction based on the use of the photometric profile of the host galaxy measured on deep stacked reference images as a model of the underlying galaxy. With this technique, host separation is very efficient in about 75% of cases[10]. In the remaining cases, no separate extraction of the SN and the host is attempted.

To identify the supernova type, a simultaneous fit of the SN light-curve and spectrum using SALT2 has been performed on each extracted SN spectrum. A host component is added to the SALT2 SN Ia model and the best-fit host contribution is obtained as a result of a χ^2 fit of the full spectrum. This procedure permits to separate the host from the supernova component at the stage of identification in the spectra for which no separate extraction was possible. Figure 1 shows such a case. On the left panel, the full (SN+host) spectrum is fitted using a Kinney template (also shown). The right panel shows the host subtracted spectrum along with the best fit SN Ia model.

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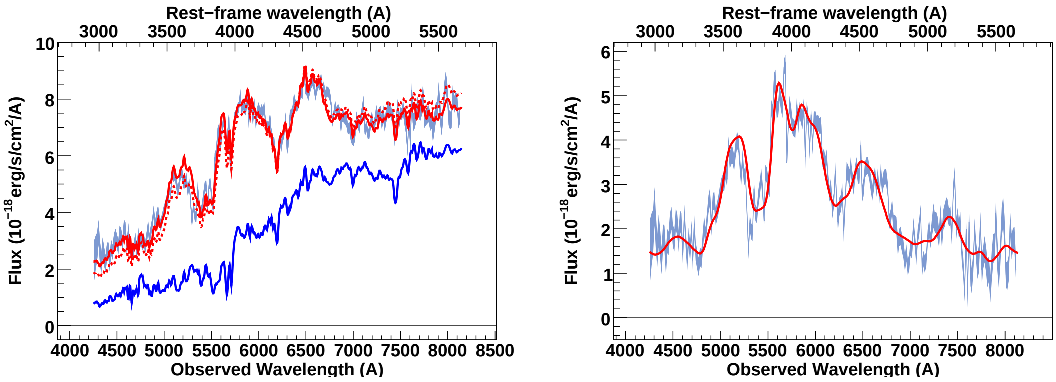

Figure 1: An example of host galaxy subtraction techniques developed for analysing VLT spectra of SNLS SNe Ia. The left panel shows the full spectrum (grey) and model fit (red), together with the best-fitting host galaxy spectrum (blue). Once the host galaxy is subtracted (right panel), the spectrum is ready for both classification and science analysis.

Table 1: Preliminary indicative uncertainty budget for the equation of state parameter *w* using a low redshift SNe sample, SNLS 3rd year SNe Ia and Baryonic Acoustic Oscillation constraints from Eisentein (2005). A flat universe is assumed.

Stat.	SNLS calib.	Low-z calib.	Low-z filters	Low-z select. bias	Light-curve fitter	Total syst.	Total (stat+syst)
0.077	0.053	0.032	0.016	0.022	0.02	0.071	0.104

2.5 Cosmological constraints from SNLS 3rd year and low-redshift supernovae

Figure 2 shows the SNLS Hubble diagram for the 1st year data (71 SNe Ia; left panels) and a preliminary diagram using the 3rd year data ($\sim$ 240 SNe Ia; right panels), along with cosmological predictions for given sets of cosmological parameters. Residuals are shown in the lower panels.

Most of the systematic uncertainties currently associated with the SNLS cosmological measurement originate from the comparison of high redshift SNLS supernovae with a low redshift sample assembled from data in literature. SNLS systematics are dominated by calibration uncertainties (~ 0.005 in *gri* and ~ 0.02 in *z* band). The uncertainties associated with the filter responses and selection bias are much smaller. The main uncertainties associated with the low redshift sample are calibration uncertainties (~ 0.02 in U-band, ~ 0.007 in BVR), filter uncertainties (~ 0.005 relative flux uncertainty) and selection bias as the low redshift sample is heterogeneous by construction (~ 0.01 uncertainty on the average distance modulus). Table 1 shows an indicative uncertainty budget for the equation of state parameter *w* (assumed constant) using SNLS 3rd year SNe Ia combined with the Baryonic Acoustic Oscillation (BAO) constraint from Eisentein (2005)[11] in a flat universe. Note that the level of systematic uncertainties reaches the one of the statistical uncertainties.

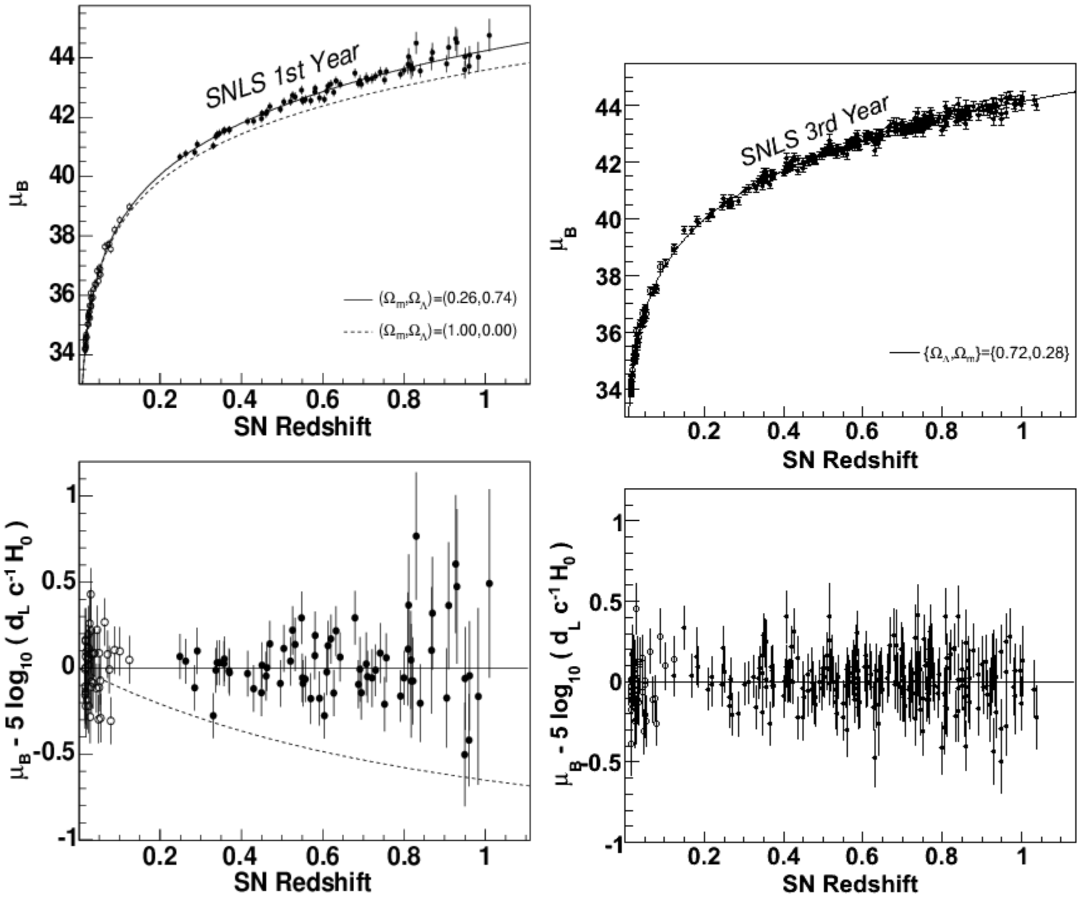

Figure 2: Preliminary SNLS Hubble diagrams (top panels) and residuals (bottom panels). Both 1st year data (71 SNe Ia; left) and 3rd year data (about 240 SNe Ia; right) are shown for comparison. The r.m.s. dispersion is $\sigma = 0.21$ for the 1st year data and $\sigma = 0.16$ for the 3rd year data.

3. Conclusion

We have presented preliminary cosmological results obtained with ~ 240 SNe Ia followed-up during the first 3 years of the SNLS project. This set is currently the largest homogeneous high redshift sample. Improvements over the analysis of the 1st year data have been discussed for various steps of the analysis and and indicative uncertainty budget for the equation of state parameter w using both SNLS 3rd year SNe and BAO constraints in a flat universe has been presented. The statistical uncertainty is limited by the low redshift sample. The systematic uncertainty is dominated by the difficult inter-calibration of the SNLS and low-redshift sample. This should be alleviated by combining in the near future the SNLS sample and the Sloan Digital Sky Survey low redshift sample.

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