

The ESSENCE Project: A Supernova Survey Optimized to Constrain the Equation of State of the Cosmic Dark Energy

Abstract

The ESSENCE project is a multi-year ground-based supernova survey designed to observationally constrain the equation of state of the dark energy by measuring luminosity distances for a sample of ~ 200 type Ia supernovae at redshifts z with $0.2 \leq z \leq 0.8$. Our goal is to determine the value of w to within 10%. We see this as the next logical step in understanding the nature of the Dark Energy. The ESSENCE survey is well under way, now in its third year of operations, and we are making good progress towards our goals. We have already detected, with spectroscopic followup and redshifts, in excess of 90 distant type Ia supernovae. Specific strengths of the ESSENCE survey include

- Uniformity of photometry, from a single telescope/instrument,
- Experienced team, drawn from the High- z Supernova Team,
- A project focus on quantifying potential sources of systematic error,
- A novel calibration scheme for determining instrumental properties.

We have used extensive simulations to determine what observing strategy produces the tightest constraints on w , for fixed telescope time. The results show that the optimal strategy favors monitoring a wider area of sky with modest exposure times over deeper exposures of a narrower field. This suggests that for the constraints of the ground-based ESSENCE survey, it is worthwhile to sacrifice a small number of SNe at higher redshifts ($z > 0.7$) in order to obtain larger numbers of SNe at lower redshifts.

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1. Introduction

The ESSENCE ¹ program is aimed at answering the question: is the dark energy consistent with the cosmological constant, or must it be something else? If we measure $w \neq -1$ well enough, then Lambda would be ruled out as the dark energy. Even if w is measured to be consistent with -1 , the improved constraints that ESSENCE will provide by 2008 will restrict the range of allowed models.

Type Ia supernovae, whose luminosities are both intrinsically high and calibratable to $\sim 15\%$, are well suited to probing the expansion history during the epoch ($0 < z < 1$) in which the Universe makes a transition from deceleration to acceleration.

As in classical physics, the flux density from a cosmological source falls off as the inverse square of distance,

$$\mathcal{F} = \frac{L}{4\pi D_l^2}.$$

However, this “luminosity distance” depends upon how the universe expands as a photon travels from emitter to receiver, which in turn depends sensitively on the composition and properties of the constituents of the cosmic mass-energy density. Specifically, for a flat universe the luminosity distance $D_l(z)$ is given by

$$D_l = \frac{c(1+z)}{H_0} \int_0^z \frac{1}{\sqrt{(1-\Omega_{matter})(1+z')^{3(1+w)} + \Omega_{matter}(1+z')^2}} dz'.$$

In astronomy, it is conventional to use the distance modulus, which expresses luminosity distance in terms of bolometric magnitudes;

$$\mu(z) = 5 \log\left(\frac{D_l}{10pc}\right) = 5 \log(D_l) + 25.$$

The basic motivation behind the ESSENCE project is illustrated in Figure 1, which shows, for fixed Ω_M and Ω_Λ (0.3 and 0.7 respectively), how the $\mu(z)$ relation depends on redshift. This demonstrates that there is a significant w -dependent signal even at modest redshifts ($z \sim 0.5$), at which observations with a 4-meter class telescope can readily yield dozens of supernovae. Of course, observations such as the ESSENCE survey actually produce a complex set of constraints in cosmological parameter space, but the fact remains that the signals of interest are readily accessible at modest redshift.

¹"Equation of State: SupErNovae trace Cosmic Expansion"

We use the multiband light curves from the Blanco 4m with light-curve shape methods we have developed to find the distance to each supernova. Redshifts, from spectra of the supernovae and their host galaxies, provide the data to construct the Hubble diagram and to trace the history of cosmic expansion over the critical range from $0.2 < z < 0.8$ where the acceleration takes place and the properties of the dark energy are best revealed.

This project depends critically upon a well-sampled set of nearby supernovae, and the work described in the submission by R. Kirshner is an essential complement to ESSENCE. The CfA supernova program contributes to our understanding of SN phenomenology, to improved distance indicators, and links photometric to spectroscopic measurements.

The main strengths of the ESSENCE project are that we are well under way with a demonstrated technique, with a strong team, a mature analysis pipeline, and solid NSF support. We have been very successful in obtaining telescope time; the project has long term access to the CTIO 4m for the imaging survey, to a diversity of large aperture telescopes (vital for spectroscopy), and to space-based systems (both HST and SIRTf) that provide complementary IR observations.

Our main risks are 1) the impact of poor weather and conditions in Chile. The first year of the program was an el Nino season and the seeing and weather were simply awful. 2) The diverse sources of systematic error described in more detail below. Also, we need to appeal to other cosmological measurements in order to best constrain w . In particular we rely upon other determinations of Ω_m to complement the insight provided by the SN Hubble diagram. We expect to release initial results (based on roughly half the eventual sample) in early 2006, with final results in 2008.

We see the ESSENCE survey as a vital precursor to both JDEM and the LST. Our program is one of the world's leading projects in using supernovae as cosmological probes. Our progress in understanding systematics will have a direct bearing on all future SN cosmology projects, which includes both JDEM and LST. Our software pipeline is breaking ground in the automated processing of quality photometry, and our team members serve on the JDEM science team and are among the leaders of the LSST effort.

2. ESSENCE status

The ESSENCE survey is a long term project being undertaken through the NOAO survey initiative², with an initial allocation of 5 annual seasons of observing. Our main

²<http://www.noao.edu/gateway/surveys/>

imaging program makes use of the Blanco 4m telescope at CTIO, and the MOSAIC wide-field CCD camera³. We take repeated images in the R and I (and occasionally V) passbands of a series of fields near the celestial equator. By taking a succession of images with a cadence of a few days separation, we obtain light curves of all variable objects in the fields for three consecutive months each year.

We have elected to restrict the ground-based photometric data for light curves to that obtained from a single telescope, the Blanco 4m at CTIO. This greatly simplifies the interpretation of the data, as we can dispense with “color terms” and zeropoint differences that plague the integration of data taken with multiple telescope/instrument combinations. As discussed below, this reduces our sensitivity to systematic errors arising from differences in detector quantum efficiencies and filter transmission curves.

The MOSAIC camera images are run through a frame subtraction pipeline, and candidate supernovae are flagged for human inspection. We classify and rank the candidates and use multiple large aperture telescopes (Keck, VLT, Magellan, Gemini) to obtain spectra of the objects. These spectra are used to classify the objects and determine their redshifts; see Matheson et al, 2004 for a full description of ESSENCE spectroscopy. We will use the multiband light curves from the Blanco 4m to estimate a distance modulus to each object and, augmented by redshifts obtained from the spectra, construct a Hubble diagram which traces the expansion history over the range $0.2 < z < 0.8$.

We have obtained good data, both photometric and spectroscopic, on the type Ia supernova shown in Figure 2, which is a redshift histogram for the 92 type Ia supernovae we have detected and monitored (up through 2004).

3. Systematics

We are determined to understand, quantify and minimize potential sources of systematic error in the ESSENCE survey. To this end we have undertaken an extensive set of simulations and measurements, specifically to establish the survey’s potential for obtaining a misleading value of w . The list of concerns includes:

- *Evolutionary effects.* Changes in the mean astrophysical environment of supernovae as a function of time could potentially impact the physics of their explosions (for example, differences in mean metallicity over time).

³<http://www.ctio.noao.edu/mosaic/>

- *Selection effects, Malmquist bias.* The intrinsic dispersion in SN Ia luminosities and extinction of some SNe due to host galaxy dust leads to a biased selection of bright, unextincted objects, particularly at the faint limit of the survey.
- *Host galaxy extinction.* The composition of dust in distant galaxies, and thus the wavelength dependence of the extinction from it, may differ from that of the Milky Way, possibly even with some mean evolution over cosmic time. Accurate extinction estimates are essential, as these are highly covariant with the estimated distances.
- *Galactic (MW) extinction.* Clumpiness in dust in our own galaxy, below the resolution of current dust maps could lead to inappropriate corrections. Our fields are selected to have low Galactic extinction, typically well below 0.1 magnitudes.
- *Atmospheric extinction.* The atmospheric transmission of light from celestial sources is afflicted by aerosol scattering, Rayleigh scattering, and molecular absorption. Properly accounting for these effects is challenging, particularly at near-IR wavelengths.
- *Instrumental Artifacts.* Inaccuracies in flatfielding, fringing, and establishing consistent photometric zeropoints across the sky could lead to systematic error in our photometry. We are developing an innovative program to measure the instrumental throughput of the 4m system, using a tunable laser (400 nm to 1 μm) and a calibrated precision photodiode.
- *K-corrections.* Transforming observed broad-band flux measurements to the emitted flux in the supernova frame requires the integration of a template SN spectrum over the effective sensitivity functions of the apparatus. The quality of the sensitivity functions and template spectra are the limitations in this process and could potentially create systematic error with complicated redshift-dependence.
- *Gravitational Lensing.* Current estimates of the excess dispersion in SN Ia distance modulus due to line-of-sight lensing effects are at the level of 0.02 and 0.04 magnitudes at redshifts of 0.5 and 1 respectively ?. Our survey concentrates on modest redshift ($z < 0.8$) supernovae, at which we do not expect lensing to have a large effect.

While it is useful to tabulate individual sources of systematic error, the degree to which these impact the results will be more readily assessed from the survey data itself. A careful and comprehensive study of sources of systematic error will accompany any cosmological results from the survey. However, for the purposes of planning the project, a detailed description of these sources is not necessary. Instead, we adopt a few simple parametric models and assess how they impact the desired scientific results.

We begin by noting that any systematic error which results in a bias in the determined distances to all supernovae is functionally equivalent to uncertainty in the Hubble parameter or the intrinsic luminosity of type Ia SNe. Thus, it would effectively be subsumed into a “nuisance” parameter which we may marginalize out in the cosmological analysis.

Systematic errors which have a random distribution in a sample of supernovae are equivalent to a larger dispersion in the peak magnitudes of SNe Ia. For our survey simulations, we have chosen this to be $\sigma_m = 0.20$ mags, which is actually somewhat larger than current distance estimation methods can achieve for Hubble-flow SNe. Randomly distributed systematic error will decrease the accuracy of the measurement of w , but should not bias the best-fitting value.

The sources of systematic error which are most insidious are those which exhibit some redshift dependence, since it is precisely this redshift dependence of luminosity distance that we wish to measure. To this end, we have explored a class of systematic errors which would bias the mean measured distance modulus as a function of z with the form:

$$\delta(z) = a * z + b * z^2 + c * \sqrt{z}$$

The choice of this form is largely arbitrary, though we note that the square-root z -dependence closely mimics the form of the differences in distance modulus for various values of w (see Figure 2). Table 1 summarizes the effect of such a source of systematic error on the measurement of w for various values of the coefficients a, b and c . (Note that $a=0.1, b=c=0.0$ is a systematic which grows linearly to 0.1 mags at $z=1.0$.)

The statistical improvement over the initial set of distant type Ia supernovae is shown in Figure 3. We consider the control of systematic errors to be one of the main attributes of

a	b	c	<w>
0.10	-	-	-1.22
0.05	0.05	-	-1.19
-	0.10	-	-1.16
-	0.05	0.05	-1.12
-	-	0.10	-1.08
0.05	-	0.05	-1.16

Table 1: Impact of systematic errors from parametric description. The Table shows, as a function of the coefficients α, β and γ defined in the text, the magnitude of the mismeasurement of w produced a corresponding systematic error in luminosity distance.

the ESSENCE project.

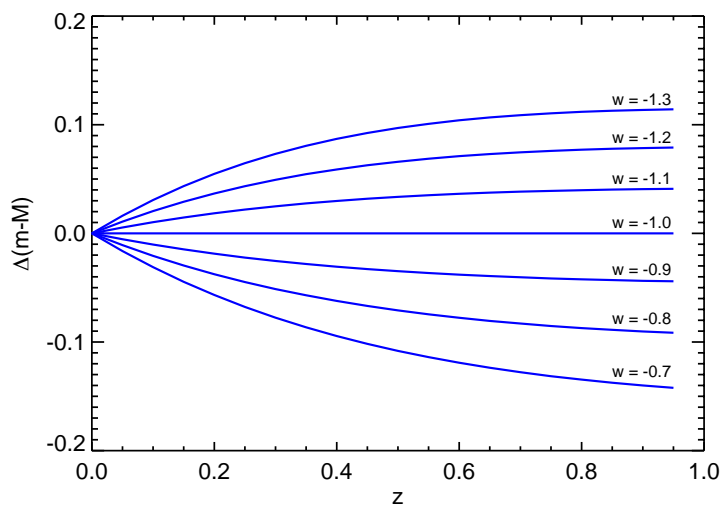


Fig. 1.— Differences in distance modulus for different values of w as a function of redshift, relative to $w = -1$. Note that a very significant fraction of the asymptotic signal strength is accessible at modest (<0.5) redshifts.

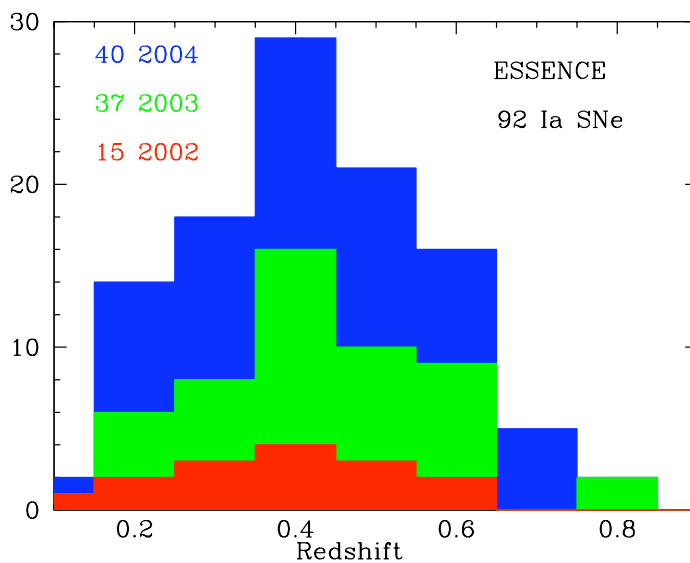


Fig. 2.— Redshift distribution of ESSENCE type Ia supernovae, through 6/2005.

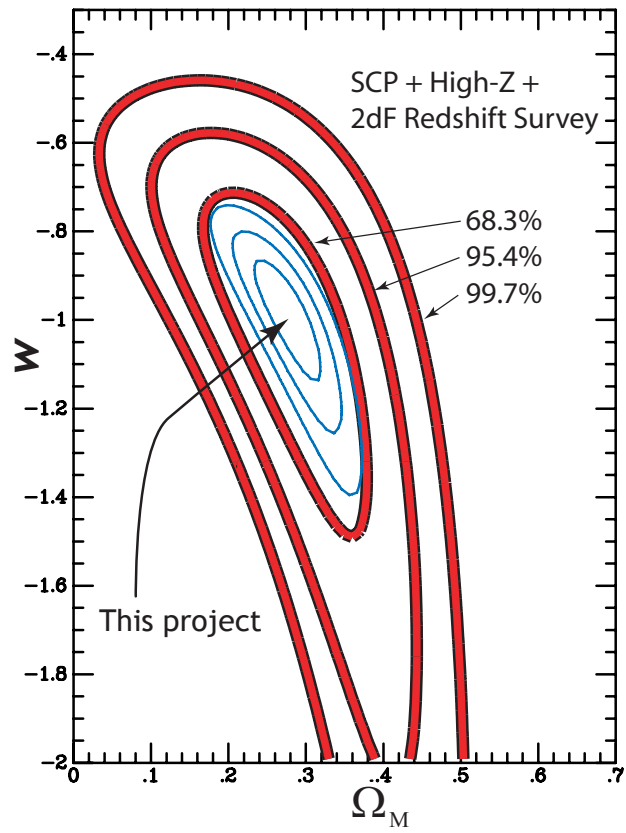


Fig. 3.— Anticipated ESSENCE contours in w and Ω_m plane