

Type Ia Supernovae and the Acceleration of the Universe: Results from the ESSENCE Supernova Survey

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Abstract. The ESSENCE project was a six year supernova search carried out with the CTIO 4-m telescope. We also obtained spectra with many of the world's largest ground-based telescopes and observed some of our SNe with the Hubble Space Telescope and the Spitzer Space Telescope. We achieved our goal of discovering over 200 Type Ia SNe in the redshift range 0.2 to 0.8. With these data we determined the cosmic equation of state parameter to ± 10 percent. The data are consistent with a geometrically flat universe whose dark energy is equivalent to Einstein's cosmological constant.

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1. Cosmology with Type Ia Supernovae

In the early- to mid-1990's astronomers expected that observations of standardizable candles such as Type Ia supernovae (SNe) would reveal to what extent the expansion of the universe was being decelerated by the gravitational attraction of all the matter in it. Some astronomers predicted that $\Omega_M \equiv \rho_0/\rho_{crit} = 1$, the so-called Einstein-de Sitter universe. From the dynamics of clusters of galaxies and studies of the large scale structure of the universe, others believed that $\Omega_M \approx 0.2-0.3$. Then Riess *et al.* (1998) and Perlmutter *et al.* (1999) independently showed that Type Ia SNe at a redshift of $z \sim 0.5$ were systematically “too faint” and that their faintness could be attributed to an acceleration of the universe caused by a non-zero vacuum energy density. We refer to this as dark energy.

Einstein (1917) introduced the cosmological constant (Λ) to characterize a universe that is neither expanding nor contracting. (This was 12 years before Hubble's discovery of the expansion of the universe.) Modern cosmologists describe the vacuum energy density by the dimensionless parameter $\Omega_\Lambda \equiv \Lambda c^2/3(H_0)^2$, where H_0 is Hubble's constant. $1/\sqrt{\Lambda}$ has units of length, the “length scale over which the gravitational effects of a nonzero vacuum energy density would have an obvious and highly visible effect on the geometry of space and time” (Abbott 1988). For $H_0 = 72 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ and $\Omega_\Lambda = 0.7$, the length scale is 2900 Mpc, more than half the size of the observable universe.

Supernova data, combined with the observations of the baryon acoustic oscillations (Eisenstein *et al.* 2005) or combined with WMAP satellite observations of the cosmic microwave background radiation (Komatsu *et al.* 2008), indicate that $\Omega_M + \Omega_\Lambda = 1$. In other words, the geometry of the universe is flat. The expansion of the universe was slowing down for the first ~ 7 billion years after the Big Bang. Since then it has been accelerating.

In order to investigate the nature of dark energy, we wish to characterize its equation of state. Let the equation of state parameter $w \equiv P/(\rho c^2)$, where P is the pressure and

ρ is the energy density. $w = +1/3$ for radiation. $w = -1$ for Einstein’s cosmological constant. However, more exotic possibilities are possible. $w > -1$ could indicate cosmic strings, and $w < -1$ could lead to the eventual instability of all particles in the universe (the so-called “Big Rip”).

The luminosity distance, measured in Mpc, is given by

$$d_{lum} = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3 + \Omega_\Lambda(1+z')^{3(1+w)}}} .$$

The distance modulus $\mu \equiv m - M = 5 \log(d_{lum}) + 25$. A plot of the distance moduli of supernovae vs. the redshifts (or logarithms of the redshifts) is called the Hubble diagram. Beyond a redshift of $z \sim 0.2$ the loci characterized by various combinations of Ω_M , Ω_Λ , and w begin to diverge from each other. If we can obtain accurate distance moduli and spectroscopic redshifts of SNe or their host galaxies, we should in principle be able to determine these parameters. It is also customary to pick one locus in the Hubble diagram as a reference and to plot the differences of the distance moduli with respect to that locus.

Determining the distance modulus of a given SN involves several steps: 1) imaging it in multiple filters; 2) transforming the photometry to observer rest frame apparent magnitudes; 3) determining the apparent magnitude(s) at maximum light; 4) correcting the apparent magnitudes for dust extinction along the line of sight; and 5) subtracting an estimate of the supernova’s absolute magnitude at maximum for each filter. Since the discovery of the brightness/decline rate relation by Phillips (1993) and the Cepheid-based calibration, using the Hubble Space Telescope, of the distances of nearby galaxies which have hosted Type Ia SNe (Suntzeff *et al.* 1999, Freedman *et al.* 2001), we have come to a greater understanding of the uniformity of the light curves and absolute magnitudes of these objects. It is important to note that without observations in at least two filters, no host galaxy extinction corrections can be made. Supernovae observed in only one filter should not be used for the determination of cosmological parameters. Observations of a Type Ia SN in four or more rest frame filters, especially if one is a near-infrared filter, allow an accurate determination of the dust extinction suffered by the SN, even if the dust is very unusual (Krisciunas *et al.* 2007).

2. The ESSENCE Supernova Survey

In order to measure the equation of state parameter to ± 10 percent we organized the ESSENCE supernova survey. Miknaitis *et al.* (2007) describe the motivation and logistics of the survey.

ESSENCE stands for **E**quation of **S**tate: **S**up**E**er**N**ovae trace **C**osmic **E**xpansion. The ESSENCE team presently consists of 32 astronomers from the United States, Chile, Germany, Sweden, and Australia. We observed for six seasons (October through December) with the 4-m telescope of the Cerro Tololo Inter-American Observatory, using the prime focus Mosaic II camera. The camera contains eight $2K \times 4K$ CCD chips, each read out with two amplifiers. The field of view is 36×36 arcmin. We had 32 principal fields. Observing every other half-night during dark and grey time, we typically observed 16 fields each night.

Over the course of the survey we observed on 191 nights and took 5458 *R*- and *I*-band images. Depending on the redshift of the SN, this corresponded to rest frame *UB* or rest frame *BV* imaging. We found over 2000 flux transients. Using the Magellan 6.5-m telescopes, the Gemini 8-m telescopes, the Very Large Telescope, and Keck, we took spectra of 400 targets. Some of these objects turned out to be Active Galactic Nuclei,

supernovae other than Type Ia, or variable stars in our Galaxy. Roughly 220 targets were confirmed to be Type Ia SNe or possible Type Ia SNe.

Analysis of the spectra is ongoing. Matheson *et al.* (2005) discussed spectra of the first two years of the survey. Blondin *et al.* (2006) used line profile shapes to test the fraternity of Type Ia SNe at high and low redshifts. Foley *et al.* (2008) showed that there is no strong evidence for evolution of these objects out to redshift $z = 0.8$. Bronder *et al.* (2008) and Ellis *et al.* (2008) independently came to the same conclusion using spectra from the Supernova Legacy Survey (SNLS), a supernova search being carried out year-round on the 3.6-m Canada-France-Hawaii Telescope at Mauna Kea.

Some of our SNe were also observed with HST or with the Spitzer Space Telescope. Krisciunas *et al.* (2005) discuss nine ESSENCE SNe observed with HST in three rest frame optical bands. Most of these turned out to be very slowly declining (i.e. overluminous) objects. In the 2006 and 2007 observing seasons we used HST to observe ten ESSENCE SNe with $z \approx 0.35$ at $1.65 \mu\text{m}$, which is to say in the rest frame J -band ($1.25 \mu\text{m}$).

Using data from the first three years of the ESSENCE survey Wood-Vasey *et al.* (2007) found that $w = -1.07 \pm 0.09$ (statistical) ± 0.13 (systematic). We found $\Omega_M = 0.267^{+0.028}_{-0.018}$. The first year SNLS data (Astier *et al.* 2006) lead to very similar values: $w = -1.023 \pm 0.090$ (statistical) ± 0.054 (systematic); $\Omega_M = 0.263 \pm 0.042$.

In Fig. 1 we show the preliminary Hubble diagram and a differential Hubble diagram

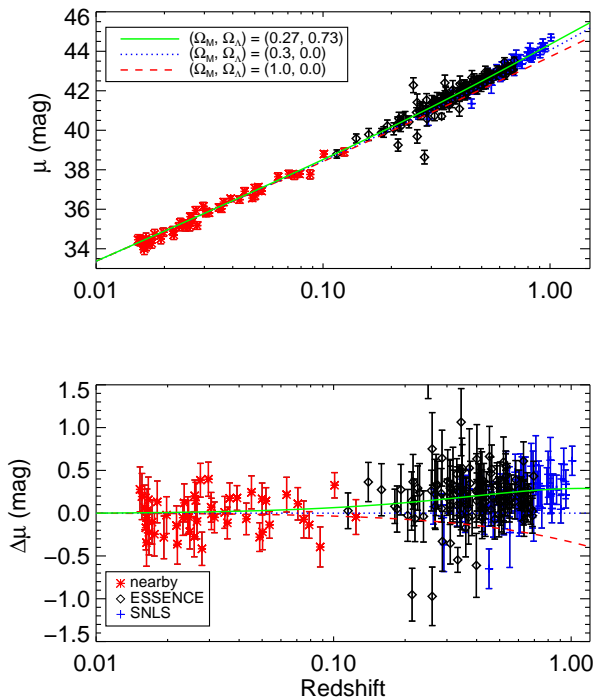


Figure 1. *Top:* Preliminary Hubble diagram of ~ 200 ESSENCE Type Ia SNe (black diamonds), nearby objects (red asterisks), and SNe from the first year of the Supernova Legacy Survey (blue pluses). The solid green line, with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, gives the best fit. Also shown are two models with zero cosmological constant ($\Omega_M = 0.3$ and 1.0 , respectively). *Bottom:* Differential Hubble diagram using the “open” model ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.0$) as reference.

of our ~ 200 ESSENCE Type Ia SNe, along with nearby objects and those from the first year of SNLS. We clearly have some outliers. These could be due to “bad” photometry, incorrect extinction corrections, or incorrect redshifts. Some of these objects could be members of new sub-classes of SNe, so the adopted absolute magnitudes are wrong. Still, the data are consistent with a flat universe containing dark energy. Our final value of the equation of state parameter requires further analysis, but will likely be statistically consistent with $w = -1$.

3. Other Results from the Collaboration

The ESSENCE database has enabled other interesting research. Davis *et al.* (2007) scrutinized exotic cosmological models using ESSENCE SNe and higher- z objects discovered by Riess *et al.* (2004). We found that, “the preferred cosmological model is the flat cosmological constant model, where the expansion history of the universe can be adequately described with only one free parameter describing the energy content of the universe. Among the more exotic models that provide good fits to the data, we note a preference for models whose best-fit parameters reduce them to the cosmological constant model.”

Blondin *et al.* (2008) investigated time dilation effects in multi-epoch high redshift Type Ia SN spectra. By comparing the rest frame age of each spectrum (determined through cross-correlations with a database of spectral templates) with the observed elapsed time, we found an aging rate consistent with the expected $1/(1+z)$ factor.

ESSENCE discovered *moving* objects in our solar system as well. Becker *et al.* (2008) report the discovery of 15 trans-Neptunian objects. Several have orbits which are highly elliptical (up to 0.85) or substantially inclined to the plane of the ecliptic. Two have aphelia of 352 and 582 AU, respectively.

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