Looking for Dark Energy Right Now

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Introduction

Type Ia supernovae appear to be an excellent way to map the relation between distance and redshift reaching more than half way back to the Big Bang [1][2]. Two groups, the High-Z Supernova Search Team and the Supernova Cosmology Project have used the unique properties of type Ia supernovae (SNIa) to show that the expansion of the Universe is accelerating [3][4]. This acceleration requires that a surprising dark energy component with a significant negative pressure dominates the Universe [5]. The need for an additional energy component is confirmed by observations of the Cosmic Microwave Background (CMB) anisotropy which indicate the critical density of the Universe is unity [6] while matter contributes less than half of that amount [7].

So what the heck is this dark energy? The easy answer is that Einstein's cosmological constant or non-zero vacuum energy is the source of the acceleration. But such a small vacuum energy density does not fit well with current particle physics models. Other means of explaining the acceleration such as rolling scalar fields ('quintessence'), domain walls, 'k-essence' have been proposed and there seems no end to what theorists can think up. It is up to observational astrophysics to devise experiments to reduce the number of possible dark energy sources.

Differentiating the Hubble Diagram to Differentiate Between the Theories

Every component in the Universe can be parameterized by the way its energy density varies as the Universe expands. For example, the density of ordinary matter falls as the cube of the cosmic scale factor (a), so $n = 3$ where $\rho \propto a^{-n}$. Through the conservation of energy, this exponent is related to the equation of state, $w = p/\rho = \frac{1}{3}n - 1$, where p is the pressure exerted by the component. So for matter, $w = 0$, while an energy component that does not vary with scale factor has $w = -1$, as in a cosmological constant. Domain walls would have an equation of state of $-\frac{2}{3}$. As shown by the the Friedmann equation,

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho(1 + 3w)\ ,$$

the expansion history of the Universe is determined by the energy density and the equation of state of each component.

The observed brightness of a type Ia supernova at redshift z depends on the expansion history of the Universe between z and now, so the Hubble diagram can be used to figure out the equation of state of the dark energy. Just detecting an acceleration implies that the dark energy has $w < -\frac{1}{3}$ and the current supernova observations combined with plausible values of the matter content restrict the effective equation of state to $w < -0.6$ [4][5].

In quintessence models w can vary with time (and redshift), so that a well-defined Hubble diagram covering a wide range of redshift could, in principle, be used to reconstruct $w(z)$. This is not as easy as it sounds for two reasons. First, the matter component is currently comparable to the dark energy component and uncertainties in the former has a major effect on estimating the equation of state of the latter. Second, knowledge of the equation of state depends on differentiating the Hubble diagram which means large numbers of supernovae are needed and systematic errors must be well controlled [9][10].

The SuperNova Acceleration Probe (SNAP) has been proposed to address the equation of state problem. Details of this mission are given in other parts of the Yellow Book. This satellite would carry a 2.0-m aperture telescope and 1 square degree imager and is expected to discover and study $\sim$ 2000 supernovae per year out to $z = 1.7$. In five years, this ambitious program has the potential of reconstructing the expansion history of the Universe and constraining the properties of the dark energy.

Faster — Cheaper — Pretty Good

It is often the case in experimental science that small steps provide hints of the answer before the complete experiment is done. A good example is the history of the CMB anisotropy measurements. After COBE, bits and pieces of the high frequency power spectrum were observed with a number of telescopes providing tantalizing evidence for the first acoustic peak. But the data had large error bars and firm conclusions were difficult to draw. The science was clearly exciting so a satellite mission (the Microwave Anisotropy Probe (MAP)) was approved which would measure the CMB spectrum to a high precision. The probe, on schedule, was launched in the middle of 2001. But through improved technology and perseverance, Earth-bound CMB experiments published excellent data on the first few acoustic peaks that place tight limits on the geometry, the baryon density and the matter density of the Universe. The parable simply illustrates that much can be done to understand type Ia supernovae and to limit the properties of the dark energy before the ultimate experiment is complete.

Much hard work is ahead. The properties of type Ia supernovae at high redshift are not well constrained. Differences in progenitor composition in the early Universe may make the explosions fainter by several percent without changing any other observable property. Grey dust remains a shadow on the supernova results. Understanding local, bright supernovae as well as obtaining a large sample of events at $z < 0.7$ will build confidence in SNAP results by limiting systematic effects.

Evidence that the acceleration is **not** due to a cosmological constant would be a spectacular discovery. It would mean that the Universe is dominated by stuff even more exotic than a repulsive vacuum energy. Such a first step may be possible using present techniques from the ground. There are two ways of testing for an exotic energy: show that the equation of state is not equal to -1, or show that the equation of state varies with z. Either of these results is incompatible with a cosmological constant and they provide a direction for immediate research with existing facilities.

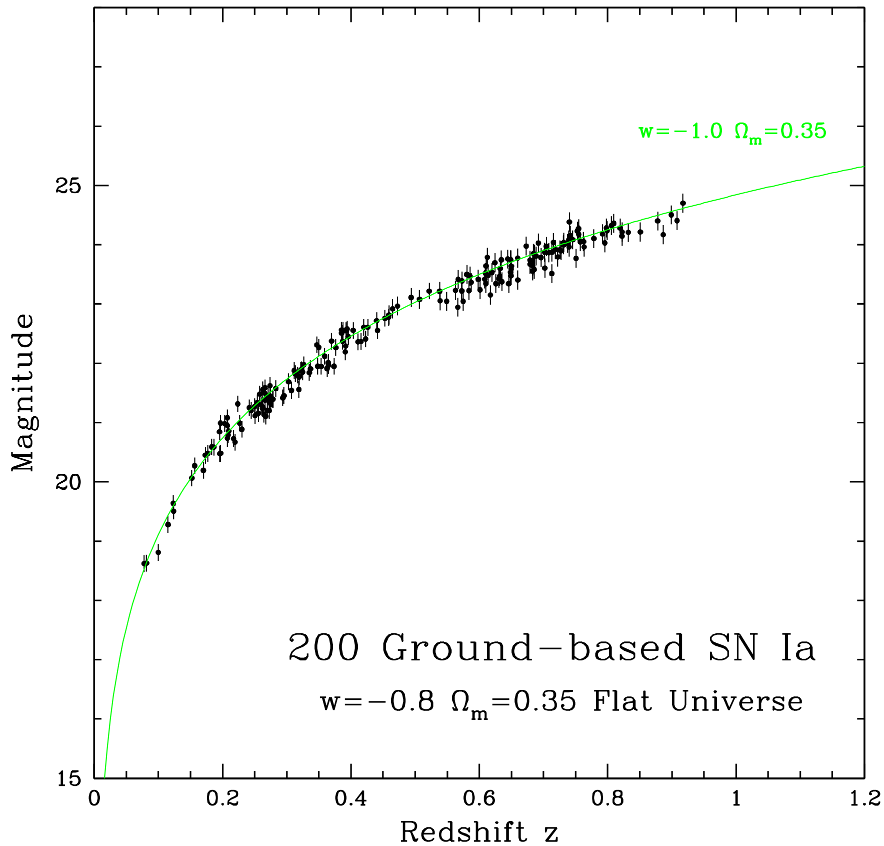

Figure 1: A simulated type Ia Hubble diagram for 200 supernovae studied from the ground. The search was optimized to find equal numbers of events around $z \sim 0.3$ and $z \sim 0.7$. The green line is the brightness expected for a flat Universe dominated by a cosmological constant and a matter density of 0.35.

The Short Term

A dedicated 4-m class telescope with a degree field would find several hundred type Ia supernovae per year out to $z \sim 1$ [11]. Unlike the current high redshift searches, the telescope would simultaneously discover new supernovae while obtaining light curves on older events. Spreading the observations out reduces disasters caused by weather and makes the search very efficient.

Building a 4-m telescope for a dedicated search is one possibility, but long stretches of time are becoming available as existing observatories reduce costs on smaller scopes and move resources toward 6 and 8-m facilities. For example, the 'Supermacho' program [12] will search for microlensing events toward the LMC using the CTIO 4-m telescope every other night for 3 months at a time. A similar arrangement would be ideal for supernova searching.

A continuous four month search with the CTIO 4-m and mosaic camera should yield about 100 supernovae per year. The redshift range of the discoveries can be adjusted by the search parameters such as cadence, exposure time and number of search fields. For $z \sim 0.3$ events, shallow exposures over a large number of fields is best while deep images in a few areas is optimal for $z \sim 0.7$. Over a two year program period the Hubble diagram for $0.2 < z < 0.9$ will be well-populated as shown in figure 1.

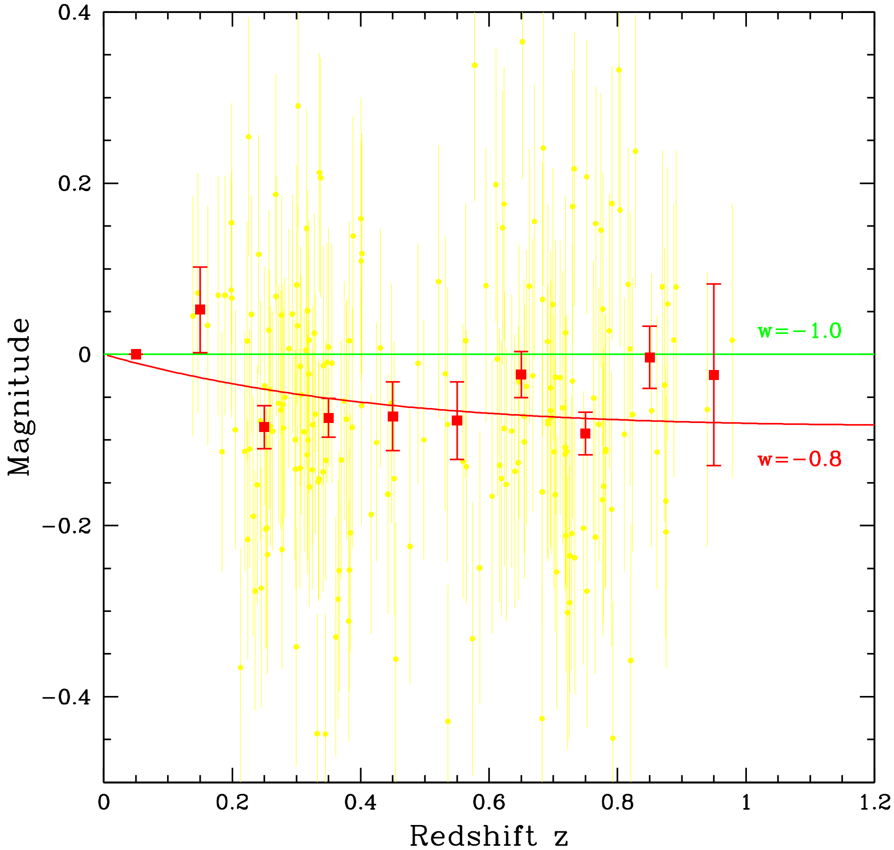

Figure 2: The plot shows results from the same search as in Figure 1, but here, the supernova brightness expected for a cosmological constant is subtracted off and the supernova flux averaged in redshift bins. The supernovae were drawn from a simulated universe with a dark energy component having a fixed equation of state $w = -0.8$.

Such a large number of measurements spread over the range $0.2 < z < 0.9$ has great potential. Systematic effects may become apparent or statistics of the host galaxies could provide clues to the progenitors of type Ia events. While 200 objects is probably too small to reconstruct the expansion history of the Universe, it should be possible to constrain the average equation of state out to $z \sim 1$. Figure 2 shows that after flux averaging the supernovae into redshift bins the difference between a cosmological constant and a $w = -0.8$ Universe is easily distinguishable for a fixed matter density.

Monitoring sections of sky to faint magnitudes has other benefits. These searches might reveal new transients such as orphan gamma-ray bursts or break-out shocks from core collapse supernovae. A Supermacho/Supernova search is a precursor to the Large-aperture Synoptic Survey Telescope (LSST) [13] and techniques developed to handle the large data rate might prove useful in LSST planning.

References

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