PROCEEDINGS OF SCIENCE

Seeing Dark Energy (35’+5’)

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Identification of dark matter 2008
August 18-22, 2008
Stockholm, Sweden

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[†] A footnote may follow.

PoS(idm2008)043

1. Background

This talk is largely based on the work now published in Riess et al. (2007).

The accelerating cosmic expansion first inferred from observations of distant type Ia supernovae (SNe Ia; Riess et al. 1998; Perlmutter et al. 1999) indicates unexpected gravitational physics, frequently attributed to the dominating presence of a "dark energy" with negative pressure.

(For students of the history of science, a copy of my lab notebook page from 1997 showing where I recorded the first indication that the data pointed to present acceleration and dark energy can be found in Symmetry Magazine,Fall 2007, http://www.symmetrymagazine.org/cms/?pid=1000557)

Increasingly incisive samples of SNe Ia at $z < 1$ have reinforced the significance of this result (Tonry et al. 2003; Knop et al. 2003; Barris et al. 2004; Conley et al. 2006; Astier et al. 2006). Using the new Advanced Camera for Surveys (ACS) and refurbished NICMOS camera on the *Hubble Space Telescope (HST)*, our collaboration secured observations of a sample of the most-distant known SNe Ia. These half-dozen SNe Ia, all at $z > 1.25$, helped confirm the reality of cosmic acceleration by delineating the transition from preceding cosmic deceleration during the matter-dominated phase and by ruling out simple sources of astrophysical dimming (Riess et al. 2004b, hereafter R04). The expanded sample of 23 SNe Ia at $z \geq 1$ presented here are now used to begin characterizing the early behavior of dark energy.

Other studies independent of SNe Ia now strongly favor something like dark energy as the dominant component in the mass-energy budget of the Universe. Perhaps most convincingly, observations of large-scale structure and the cosmic microwave background radiation provide indirect evidence for a dark-energy component (e.g., Spergel et al. 2006). Measurements of the integrated Sachs-Wolfe effect (e.g., Afshordi, Loh, & Strauss 2004; Boughn & Crittenden 2004; Fosalba et al. 2003; Nolta et al. 2004; Scranton et al. 2004) more directly suggest the presence of dark energy with a negative pressure. Additional, albeit more tentative, evidence is provided by observations of X-ray clusters (Allen et al. 2004) and baryon oscillations (e.g., Eisenstein et al. 2005).

The unexplained existence of a dominant, dark-energy-like phenomenon presents a stiff challenge to the standard model of cosmology and particle physics. The apparent acceleration may result from exotic physics such as the repulsive gravity predicted for a medium with negative pressure or from entirely new physics. The explanation of strongest pedigree is Einstein's famous "cosmological constant" Λ (i.e., vacuum energy; Einstein 1917), followed by a decaying scalar field similar to that already invoked for many inflation models (i.e., quintessence –Wetterich 1995, Caldwell, Davé, & Steinhardt 1998; Peebles & Ratra 2003). Competitors include the Chaplygin gas (Bento, Bertolami, & Sen 2002), topological defects, and a massless scalar field at low temperature. Alternatively, alterations to General Relativity may be required as occurs from the higher-dimensional transport of gravitons in string theory models (Deffayet et al. 2002) and braneworlds, or by finely-tuned, long-range modifications (e.g., Cardassian type, Freese 2005; or Carroll et al. 2004; see Szydlowski, Kurek, & Krawiec 2006 for a review). Empirical clues are critical for testing hypotheses and narrowing the allowed range of possible models.

SNe Ia remain one of our best tools for unraveling the properties of dark energy because their individual measurement precision is unparalleled and they are readily attainable in sample sizes of order 10^2, statistically sufficient to measure dark-energy-induced changes to the expansion rate of $\sim$1%. Specifically, the equation-of-state parameter of dark energy, w (where $P = w\rho c^2$) determines both the evolution of the density of dark energy,

$$\rho_{DE} = \rho_{DE,0} \exp\{3 \int_a^1 \frac{da}{a}(1+w(a))\},$$

and its gravitational effect on expansion,

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

where $\rho_{DE,0}$ is the present dark-energy density. Measuring changes in the scale factor, a, with time from the distance and redshift measurements of SNe Ia,

$$\frac{d_l(z)}{c(1+z)} = \int_t^{t0} \frac{dt'}{a(t')} = \int_0^z \frac{dz'}{H(z')},$$

constrains the behavior of $w(a)$ or $w(z)$ and is most easily accomplished at $z < 2$ during the epoch of dark-energy dominance.

Ideally, we seek to extract the function $w(z)$ for dark energy or its mean value at a wide range of epochs. Alternatively, we might constrain its recent value $w_0 \equiv w(z=0)$ and a derivative, $dw/dz \equiv w'$, which are exactly specified for a cosmological constant to be $(-1,0)$. Most other models make less precise predictions. For example, the presence of a “tracker” dark-energy field whose evolution is coupled to the (decreasing) dark matter or radiation density may be detected by a measured value of $w' > 0$. In truth, we know almost nothing of what to expect for $w(z)$, so the safest approach is to assume nothing and measure $w(z)$ across the redshift range of interest. SN Ia at $z > 1$ are crucial to constrain variations of w with redshift. These measurements can only be made from space, and we report here on that endeavor. We have discovered and measured 21 new SN Ia with HST and used them to constrain the properties of the dark energy.

2. Higher-z SNe Ia

In Figure 1 we show the Hubble diagram of distance moduli and redshifts for all of the *HST*-discovered SNe Ia in the Gold and Silver sets from our program. The new SNe Ia span a wide range of redshift ($0.21 < z < 1.55$), but their most valuable contribution to the SN Ia Hubble diagram remains in the highest-redshift region where they now well delineate the range at $z \geq 1$ with 23 SNe Ia, 13 new objects since R04. This territory remains uniquely accessible to *HST*, which has discovered the dozen highest-redshift SNe Ia known, and its exploration is the focus of the rest of this paper.

In the inset to Figure 1 we show the residual Hubble diagram (from an empty Universe) with the Gold data uniformly binned. Here and elsewhere, we will utilize uniform, unbiased binning achieved with a fixed value of $n\Delta z$, where Δz is the bin width in redshift and n is the number of SNe in the bin.[1] In Figure 1 we use $n\Delta z = 6$ which yields seven bins for our sample. Although binning is for illustrative purposes in the Hubble diagram, there are some specific advantages of binning such as the removal of lensing-induced asymmetrical residuals by flux averaging (Wang

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[1] The last bin ends abruptly with the highest-redshift SN; thus, its $n\Delta z \leq$ value is smaller than the rest.

2005) and the ease of accounting for systematic uncertainties introduced by zeropoint errors in sets of photometric passbands used at similar redshifts.

The distance-redshift relation of SNe Ia is one of few powerful tools available in observational cosmology. A number of different hypotheses and models can be tested with it, including kinematic descriptions of the expansion history of the Universe, the existence of mass-energy terms on the right-hand side of the Friedman equation, and the presence of astrophysical sources of contamination. Testing all interesting hypotheses is well beyond the scope of this paper and is best left for future work. Instead, we now undertake a few narrowly posed investigations.

3. Alternatives to Dark Energy

After the detection of the apparent acceleration of cosmic expansion (and dark energy) by Riess et al. (1998) and Perlmutter et al. (1999), alternative hypotheses for the apparent faintness of high-redshift SNe Ia were posed. These included extragalactic gray dust with negligible telltale reddening or additional dispersion (Aguirre 1999a,b; Rana 1979, 1980), and pure luminosity evolution (Drell, Loredo, & Wasserman 2000).

In R04 we found that the first significant sample of SNe Ia at $z > 1$ from *HST* rejected with high confidence the simplest model of gray dust by Goobar, Bergstrom, & Mörtsell (2002), in which a smooth background of dust is present (presumably ejected from galaxies) at a redshift greater than the SN sample (i.e., $z > 2$) and diluted as the Universe expands. This model and its opacity was invented to match the 1998 evidence for dimming of supernovae at z 0.5 without invoking dark energy in a universe with $\Omega_m = 1$. This model is shown in the inset of Figure 1. The present Gold sample (at the best fitting value of H_0) rejects this model at even higher confidence ($\Delta\chi^2 = 194$, i.e., 14 σ), beyond a level worthy of further consideration.

3.1 Dark Energy

Strong evidence suggests that high-redshift SNe Ia provide accurate distance measurements and that the source of the apparent acceleration they reveal lies in the negative pressure of a "dark energy" component. Proceding from this conclusion, our hard-earned sample of SNe Ia at $z > 1.0$ can provide unique constraints on its properties. Strong motivation for this investigation comes from thorough studies of high-redshift and low-redshift SNe Ia, yielding a consensus that there is no evidence for evolution or intergalactic gray dust at or below the current statistical constraints on the average high-redshift apparent brightness of SN Ia (see Filippenko 2004, 2005 for recent reviews). We summarize the key findings here. (1) Empirically, analyses of SN Ia distances versus host stellar age, chemical abundance, morphology, and dust content indicate that SN Ia distances are relatively indifferent to the evolution of the Universe (e.g., Sullivan et al. 2003; Astier et al. 2006; Wang et al. 2006; Riess et al. 1999). (2) Detailed examinations of the distance-independent properties of SNe Ia (including the far-UV flux, e.g., as presented in the last section) provide strong evidence for uniformity across redshift and no indication (thus far) of redshift-dependent differences (e.g., Sullivan et al. 2005; Howell et al. 2005; Blondin et al. 2006). (3) SNe Ia are uniquely qualified as standard candles because a well understood, physical limit (the Chandrasekhar limit) provides the source of their homogeneity. Based on these studies, we adopt a limit on redshift-dependent systematics is to be 5% per $\Delta z = 1$ at $z > 0.1$ and make quantitative use of this here.

Many have studied the constraint placed by the redshift-magnitude relation of SNe Ia on the parameter combination Ω_M-w, where w (assumed to be constant) is the dark energy equation-of-state parameter. There are few models for dark energy that predict an equation of state that is *constant*, different from the cosmological constant, and not already ruled out by the data. On the other hand, a prominent class of models does exist whose defining feature is a time-dependent dark energy (i.e., quintessence). While the rejection of $w = -1$ for an assumed constant value of w would invalidate a cosmological constant, it is also possible that apparent consistency with $w = -1$ in such an analysis would incorrectly imply a cosmological constant. For example, if $w(z)$ is rising, declining, or even sinusoidal, a measured derivative could be inconsistent with zero while the average value remains near -1. Therefore, when using $w(z)$ to discriminate between dark-energy models, it is important to allow for time-varying behavior, or else valuable information may be lost. Here, we seek to constrain the value of $w(z > 1)$ and bound its derivative across the range $0.2 < z < 1.3$. This is unique information afforded by the *HST*-discovered SN Ia sample.

Finally, we may consider whether three additional parameters to describe $w(z)$ are actually needed to improve upon a flat, Λ-cold-dark-matter (ΛCDM) model fit to the data. To determine this we can calculate the improvement to the fit,

$$\chi^2_{eff} \equiv -\Delta(2\ln\mathscr{L}) = 2\ln\mathscr{L}(w = -1) - 2\ln\mathscr{L}(w_i = \mathscr{W}_i), \tag{3.1}$$

with i additional free parameters. For the weak, strong, and strongest priors we find an improvement of $\chi^2_{eff} = 4$, 5.5, and 5.5, respectively, for the three additional degrees of freedom, in no case requiring the additional complexity in dark energy (improvements of > 14 would be noteworthy). Likewise, there is no improvement at all for the Akaike Information Criterion (i.e., ΔAIC=$\Delta\chi^2 - 2i$; Liddle et al. 2004) with changes of -2, -0.5, and -0.5, respectively which fail to overcome the penalty of increased complexity in the model.

4. Conclusions

(1) We present 21 new *HST*-discovered SNe Ia and an improved calibration of the previous sample from R04. Together this sample contains 23 SNe Ia at $z \geq 1$, extending the Hubble diagram over 10 Gyr.

(2) We derive uncorrelated, model-independent estimates of $H(z)$ which well-delineate current acceleration and preceding deceleration. The *HST*-discovered SNe Ia measure $H(z > 1)$ to slightly better than 20% precision.

(3) The full *HST*-discovered SN Ia sample, presented here, provides a factor of two improvement over our present ability to constrain simple parameterizations of the equation-of-state parameter of dark energy (w) and its evolution.

(4) Stronger priors and tighter constraints on the preferred cosmological model can be extracted from independent measurements tied to the surface of last scattering, but the use of these requires assumptions about the behavior of dark energy across a wide range of redshift ($1.8 < z < 1089$). The strongest of these priors, like the simplest dark energy parameterizations, appears unjustified in the presence of our current ignorance about dark energy. Assuming the effect of dark energy at $z > 1.8$ is minimal, we derive meaningful constraints on the early properties of dark energy: $w(z > 1) = -0.8^{+0.6}_{-1.0}$ and $w(z > 1) < 0$, i.e., negative pressure, at 98% confidence.

(5) At present, we find that the use of additional parameters to describe $w(z)$ does not provide a statistically significant improvement to the fit of the redshift-magnitude relation over the use of a simple cosmological constant.

(6) An analysis of the $z > 1$ sample-averaged spectrum shows it to be consistent with the mean spectrum of SNe Ia over the last 10 Gyr, failing to reveal direct evidence for SN Ia evolution.

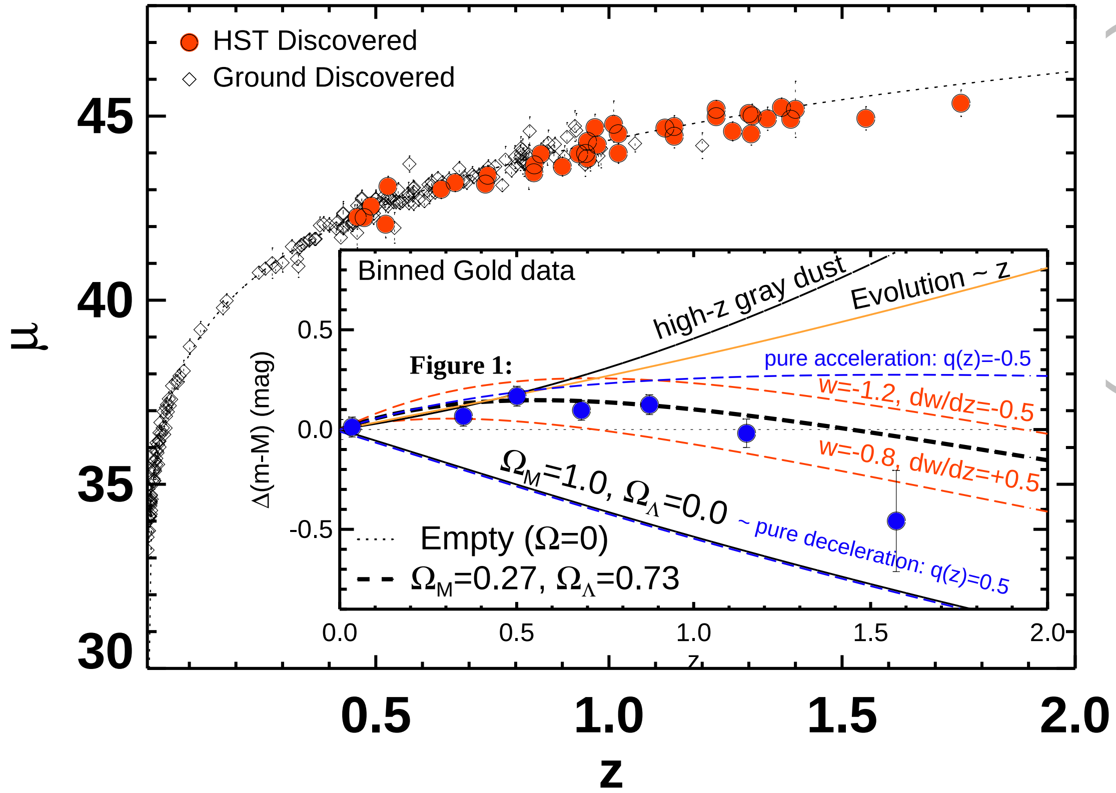
HST Discovered
Ground Discovered
45
40
35
30
μ
0.5
1.0
1.5
2.0
z
Binned Gold data
high-z gray dust
Evolution ~ z
pure acceleration: q(z)=-0.5
w=-1.2, dw/dz=-0.5
w=-0.8, dw/dz=+0.5
Ω_M=1.0, Ω_Λ=0.0
~ pure deceleration: q(z)=0.5
Empty (Ω=0)
Ω_M=0.27, Ω_Λ=0.73
Δ(m-M) (mag)
0.5
0.0
-0.5
0.0
0.5
1.0
1.5
2.0
z

Figure 1: