

in 25-fs bursts. To image the diffracted photons, the team used a CCD camera. It recorded every photon, but with a readout time of a few seconds, not a few femtoseconds. The burst of light that accompanies the target's destruction would have been detected too, but was deflected by a multilayer mirror designed by Livermore's Saša Bajt. The mirror is tuned to reflect the beam's photons, which, after elastically scattering off the target, are directed by the mirror toward the CCD. Photons from the explosion don't have the right energy for reflection and miss the CCD. Direct, unscattered photons also miss

the CCD; they fly off through a hole in the center of the mirror.

Figure 2 shows the diffraction pattern obtained last year at FLASH, while figure 3 shows both the original test object and its faithful reconstruction. "Without a doubt this is a major milestone," comments Cornell University's Veit Elser. "Up to now the entire enterprise—of using totally destructive imaging events to reconstruct a target—was a fond dream supported by some calculations and simulations."

Graduating from micron-sized membranes to nanometer-sized proteins isn't just a matter of using a harder, brighter

beam. Unlike a crystal, a single-protein sample is invisible. But, as Chapman points out, a free, isolated protein would barely move during the experiment's femtosecond time scale. The molecules could be wafted across the beam until one of them gets hit.

Charles Day

References

1. H. N. Chapman et al., *Nat. Phys.* **2**, 839 (2006).
2. D. Sayre, *Acta Crystallogr.* **5**, 60 (1952).
3. J. R. Fienup, *Opt. Lett.* **3**, 27 (1978).
4. J. Miao, P. Charalambous, J. Kirz, D. Sayre, *Nature* **400**, 342 (1999).
5. R. Neutze, R. Wouts, D. van der Spoel, E. Weckert, J. Hajdu, *Nature* **406**, 752 (2000).

High-redshift supernovae indicate that dark energy has been around for 10 billion years

A puzzling dark energy is presumed to be driving the present acceleration of the Hubble expansion. But what was it doing before it became the dominant component of the cosmos?

Since its discovery in 1998, the acceleration of the cosmic Hubble expansion has generally been attributed to some sort of pervasive dark energy that works against the decelerating pull of ordinary gravity. The big question is, What is the nature of that dark energy? Is it simply the unvarying vacuum energy density implied by the cosmological constant Λ that Albert Einstein introduced into general relativity to avoid universal gravitational collapse—and later discarded when the Hubble expansion was discovered? Or is it a more dynamic energy, changing with time as some cosmic scalar field slowly settles into an equilibrium configuration?

A variety of such putative scalar fields have been invoked as so-called quintessence alternatives to Einstein's vacuum energy.¹ One might regard the quintessence scenarios as weak, slow-motion replays of inflation, the primor-

dial scalar-field settling that is thought to have expanded the linear scale of the universe by at least 26 orders of magnitude in its first split second.

The original evidence that the Hubble expansion was speeding up came from the redshifts and luminosities of a few dozen type 1a supernovae, with redshifts $z \equiv \Delta\lambda/\lambda$ up to 0.9, measured by two teams of observers.² A type 1a supernova, the thermonuclear explosion of a white dwarf star, serves as an effective standard candle; one can deduce its distance from its apparent brightness and duration. Both teams found that their higher-redshift supernovae were systematically fainter—that is, more distant—than one would expect for a cosmos whose expansion has recently been slowing down, or even coasting. (See the article by Saul Perlmutter in *PHYSICS TODAY*, April 2003, page 53.)

Looking way back

To explore the nature of the dark energy that now drives the acceleration by overcoming gravitational braking, cosmologists seek to find out how effective it was in much earlier epochs. That means looking for type 1a supernovae at very high redshifts. A supernova observed now with redshift z would have exploded when the linear scale of the cosmos was $1/(1+z)$ of its present size. In cosmology, z often serves as a surrogate for time.

The Higher-Z Supernova Search Team led by Adam Riess of Johns Hopkins University recently reported new data and a new analysis that includes 23 type 1a supernovae with $z > 1$ discovered with the *Hubble Space Telescope* (see figure 1).³ Earth's atmosphere makes it difficult to find and adequately measure such very distant supernovae with ground-based telescopes. The highest

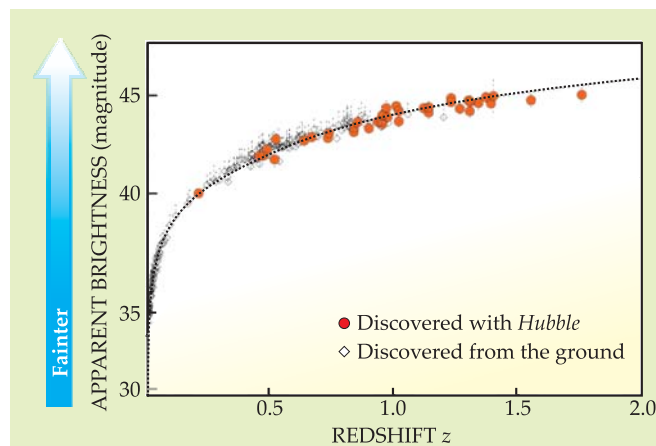


Figure 1. Hubble diagram plotting apparent brightness against redshift for the sample of type 1a supernovae used by the Higher-Z Supernova Search Team to seek evidence, from earlier epochs, of the putative dark energy that now accelerates the cosmic expansion. Particularly useful were the supernovae at redshifts above 1 discovered with the *Hubble Space Telescope*. The curve is a concordance-model fit to the data that assumes the dark energy to be vacuum energy whose density doesn't change as the cosmos expands and now exceeds the mean matter density. (Adapted from ref. 3.)

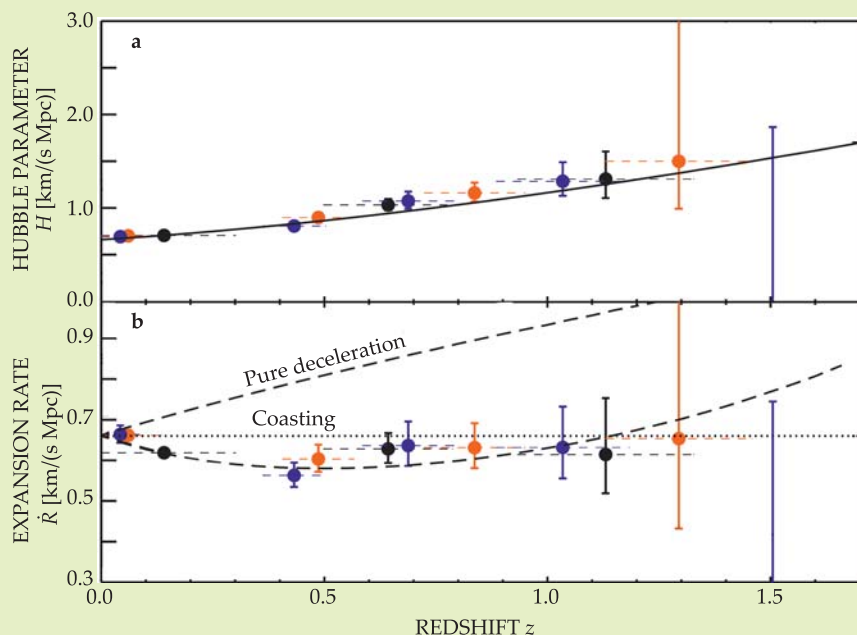


Figure 2. History of cosmic expansion deduced from the supernova data. (a) The Hubble “constant” H that would have been measured by observers at different times as denoted by redshift. (1 pc = 3.26 light-years.) A z of 1.3 corresponds to about 9 billion years ago. Colors indicate different supernova-data binnings designed to avoid correlated errors between points of the same color. The curve is a concordance-model fit to a wide variety of cosmological observations. (b) The cosmic expansion rate $\dot{R}$, given by $H/(1+z)$. Positive and negative slopes indicate, respectively, decelerating and accelerating expansion. A cosmos whose closure density is supplied entirely by matter, with no dark energy, would follow the curve marked “pure deceleration.” If both matter and dark energy were negligible, the cosmic expansion would coast. The curve that roughly guides the eye through the data transits from deceleration to acceleration at $z = 0.5$, that is, about 5 billion years ago. (Adapted from ref. 3.)

redshift in the sample is 1.8, which—assuming the favored parameters of the cosmologists’ concordance model—corresponds to a time of just 3.6 billion years after the Big Bang. That is, the supernova exploded 10 billion years ago. The new *HST* harvest begins to reveal something of the history of dark energy that far back.

Cosmic expansion is usually described in terms of the arbitrarily normalized scale factor $R(t)$, which can be thought of as the growing distance between two large, widely separated galaxy clusters. It’s proportional to $1/(1+z)$, and its time dependence is given by the Friedman equation of general-relativistic cosmology

$$\ddot{R}/R = (-4\pi/3)G(\rho + 3P),$$

where ρ is the mean mass–energy density of all matter and fields—and possibly of the vacuum itself—and P is the sum of their pressures. So any positive pressure or energy density tends to

slow down the Hubble expansion. What’s so peculiar about dark energy is that its pressure is *negative*; it tends to speed the expansion up.

How do the various contributions to ρ and P change with time? The density ρ_m of matter (both ordinary and dark) simply falls like $1/R^3$ as R expands, and its contribution to pressure is negligible. The energy density ρ_{em} of the cosmic electromagnetic radiation field falls like $1/R^4$, the extra factor of R coming from the fact that as the density of photons falls, each photon’s wavelength is also stretched. Therefore ρ_{em} and its radiation pressure (given by $+\rho_{em}/3$) have had negligible effect on cosmic expansion since long before the first stars appeared.

Equation of state

To discuss the time dependence and pressure of dark energy, one uses the equation-of-state parameter $w \equiv P/\rho$, the ratio of pressure to density for any particular component of the cosmos.

For the electromagnetic field, w is $+1/3$, and for nonrelativistic matter it’s essentially zero. The density of any component of matter or energy falls like $R^{-3(1+w)}$ as the scale factor grows. If the dark energy is simply the vacuum energy described by Einstein’s cosmological constant, its w equals -1 forever. In that case, the dark-energy density ρ_{de} would remain constant, and so would its negative pressure.

In most quintessence models, the dark energy’s density decreases over time. But if such a model is to explain the present accelerated expansion, the Friedman equation tells us that w_{de} must now be more negative than $-1/3$. Any negative w_{de} implies that ρ_{de} decreases more slowly than ρ_m . So there would have been a past, more crowded epoch when ρ_m dominated over ρ_{de} and the cosmic expansion was indeed slowing down.

Three years ago the Higher- Z team, using a sample of type 1a supernovae that included eight from the *HST* with $z > 1$, reported the first evidence of the expected crossover from the earlier deceleration epoch to the present accelerated expansion (see *PHYSICS TODAY*, June 2004, page 19).⁴ The team estimated the crossover to have been near $z = 0.5$. That’s about 5 billion years ago, and it’s consistent with $w_{de} = -1$, given the consensus—from a variety of observational realms—that the dark-energy density nowadays exceeds ρ_m by a factor of about 2.4.

Why now?

Cosmologists don’t like unexplained coincidences. Finding that the matter and dark-energy densities just happen to be of the same order in the present epoch appears to be such a coincidence. If w_{de} is perpetually -1 , the matter density will one day be negligible compared to ρ_{de} , just as ρ_{de} was once much less than ρ_m . So why are they now so comparable? Some quintessence models address that coincidence by positing a dynamical coupling between the time dependence of ρ_m and a quintessence field. The other principal argument against a simple cosmological constant is that the present mean dark-energy density (a few proton masses per cubic meter) is many orders of magnitude smaller than one would naively expect for quantum-fluctuation contributions to vacuum energy.

Since their previous analysis, Riess and company have trebled their sample of *HST* type 1a supernovae with $z > 1$. Much of that increase is due to the high sensitivity and wide field of view of the

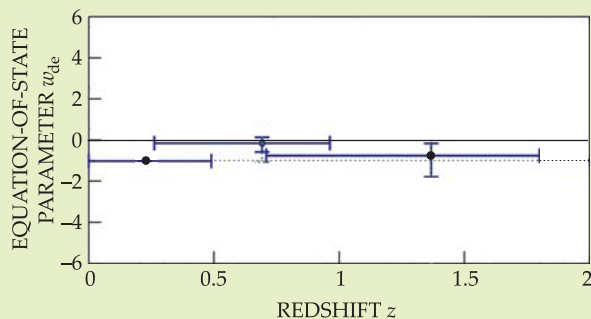


Figure 3. Evolution of w_{de} , the dark energy's ratio of pressure to energy density, as determined from the supernova data. Negative pressure tends to accelerate the cosmic expansion. If the dark energy is the vacuum energy of Einstein's cosmological constant, w_{de} is -1 forever (dotted line). Competing quintessence models let w_{de} change over time. The Higher-Z team concludes, with 98% confidence, that w_{de} was already negative from redshift 1.8 to 1.0, that is, from 10 to 6 billion years ago. (Adapted from ref. 3.)

Advanced Camera for Surveys installed on the *HST* in 2002. The team has also refined the calibration of its earlier *HST* sample. And it has availed itself of a large number of lower- z type 1a's recently discovered with ground-based telescopes.⁵ "We've used this hard-earned collection of supernovae to provide some constraints on the properties of dark energy in the very distant past," says Riess.

Because the various quintessence models do not suggest a common parameterization for the time dependence of w_{de} , the Higher-Z team performed a model-independent analysis of the supernova data to determine $\dot{R}$ and w_{de} for various redshift bins. The team doesn't compare its results with any particular quintessence model.

The changing Hubble constant

The Hubble parameter $H \equiv \dot{R}/R$ was dubbed a constant in the days when observed galactic redshifts were so small that z appeared to be simply proportional to distance. But even if the cosmic expansion were coasting, neither slowing down nor accelerating, H would increase with look-back time like $1+z$. Figure 2a shows $H(z)$ as deduced from the supernova data for various redshift bins. The point at redshift 1.3, for example, is presumed to be the Hubble "constant" that an observer living about 9 billion years ago would have measured.

The concordance model assumes, provisionally, that w_{de} is indeed -1 and constant. And it assumes that $\rho_m + \rho_{de}$ precisely equals the time-dependant "closure" density that makes the cosmic geometry flat. Normalized to the closure density, the two densities in the present epoch are conventionally labeled Ω_m and Ω_Λ . The curve in figure 2a shows the evolution of H predicted by the concordance model with $\Omega_m = 0.29$ and $\Omega_\Lambda = 0.71$, the best overall fit to the supernova data plus other cosmological observations. To show more clearly how the supernova data demonstrate

the transition, some 5 billion years ago, from earlier deceleration to the present epoch of accelerated expansion, figure 2b plots $H/(1+z)$, which is just $\dot{R}$.

Dark energy long ago

Extracting cosmological parameters from the supernova data is complicated by some degree of degeneracy between $w_{de}(z)$ and Ω_m . So Riess and company constrained their fits with complementary results from other observational regimes such as galaxy-redshift surveys and the cosmic microwave background. Figure 3 summarizes the team's best estimate, from the type 1a data, of what dark energy has been doing over the past 10 billion years. The binning in z was arranged to provide three independent measurements of past w_{de} , free of correlated errors. If one lifts the constraint provided by the CMB data, the size of the error bar on the highest z bin trebles.

It's been known for several years that w_{de} in the present epoch is within about 10% of -1 . The new data are, thus far,

consistent with the eternal $w_{de} = -1$ of Einstein's Λ . "They're inconsistent with any quintessence model that would posit dramatic variation in time," says Caltech theorist Sean Carroll. "But they can't exclude a modest time dependence." At the present level of supernova statistics, the Higher-Z team doesn't find it meaningful to quote any explicit estimate of dw_{de}/dz .

"Our principal finding is that dark energy with negative pressure has been around for at least 10 billion years," says Riess. "That's long before the present epoch of accelerated expansion. And for that discovery, the 23 *HST* supernovae with redshifts above 1 were crucial."

In the absence of strong time dependence, dark energy's effect on cosmic expansion would have been negligible in the crowded epoch before $z = 2$, when ρ_m had 27 times its present value. "Therefore," says Saul Perlmutter of the rival Supernova Cosmology Project, "the principal effort of both teams now is to increase statistics and minimize

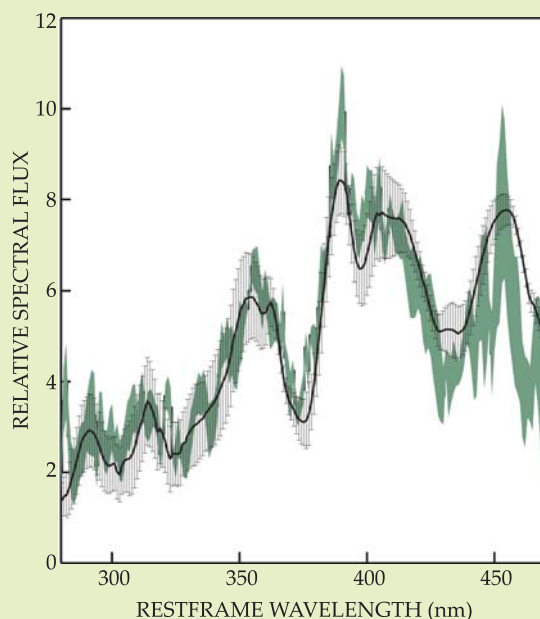


Figure 4. Ancient and recent spectra of type 1a supernovae show no evolutionary change over 10 billion years. The green band is a composite spectrum of the Higher-Z team's 13 best-measured supernovae with redshifts z above 1, transformed into each exploding star's rest frame. The black curve with gray error bars is a template used to verify the type 1a designation for supernovae with redshifts less than 0.1, which would have exploded within the past billion years or so. (Adapted from ref. 3.)

systematic errors at redshifts below 2 rather than to look much farther back." To that end, several collaborations are proposing to build a telescope that would fly aboard a satellite dedicated to finding type 1a supernovae.

The use of type 1a supernovae to chart the history of cosmic expansion assumes that a 10-billion-year-old distant type 1a is much the same as one that happened recently in our neighborhood. Figure 4 addresses that crucial assumption. The figure compares a composite spectrum of the Higher-Z team's best-measured supernovae at $z > 1$, transformed into the exploding star's rest frame, with a spectral template used to verify the type 1a classification of supernovae with redshifts less than 0.1. "Across a span of 10 billion years," says Riess, "we find no discernible change in the type 1a spectrum."

"For me," says stellar astrophysicist Lars Bildsten (University of California, Santa Barbara), "that's their most interesting result." Not only does it strengthen confidence in type 1a supernovae as uniquely useful mileposts at cosmological distances. It also indicates that the continuing enrichment of interstellar media with heavier elements over time has had little effect on the mechanism by which white dwarfs explode.

Bertram Schwarzschild

References

1. For a recent review of quintessence models, see M. Sydlowski et al., <http://arxiv.org/abs/astro-ph/0604327>.
2. A. G. Riess et al., *Astron. J.* **116**, 1009 (1998); S. Perlmutter et al., *Astrophys. J.* **517**, 565 (1999).
3. A. G. Riess et al., <http://arxiv.org/abs/astro-ph/0611572>.
4. A. G. Riess et al., *Astrophys. J.* **607**, 665 (2004).
5. P. Astier et al., *Astron. Astrophys.* **447**, 31 (2006).

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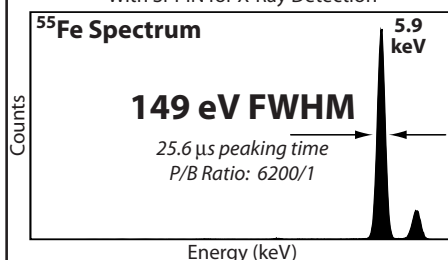
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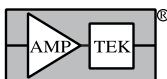
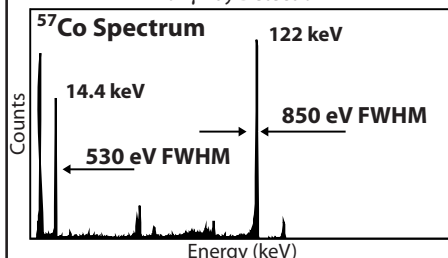
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