Throwing Light on Dark Energy

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Supernova observations show that the expansion of the universe has been speeding up. This unexpected acceleration is ascribed to a dark energy that pervades space. Supernova data, combined with other observations, indicate that the universe is about 14 billion years old and is composed of about 30% matter and 70% dark energy. New observational programs can trace the history of cosmic expansion more precisely and over a larger span of time than has been done to date to learn whether the dark energy is a modern version of Einstein's cosmological constant or another form of dark energy that changes with time. Either conclusion is an enigma that points to gaps in our fundamental understanding of gravity.

Observations of exploding stars halfway back to the Big Bang reveal a surprising phenomenon: The expansion of the universe has been speeding up in the past 7 billion years. We attribute this effect to the presence of a dark energy, whose energy density helps make the universe flat and whose negative pressure produces cosmic acceleration. On the basis of observations of supernova brightness, of the dark matter that makes galaxies cluster, and of the angular scale of primordial freckles in the glow from the cosmic microwave background (CMB), we infer that about 28% of the universe is matter and 72% is dark energy. In the self-proclaimed age of "precision cosmology," we know the amount of each component to a few percent, but in the spirit of "honest cosmology" we also have to admit we do not know precisely what either of them is. But we are not helpless. We can observe light emitted by supernova explosions to trace the history of cosmic expansion to learn more about the invisible forces that shape the universe.

Evidence for the nature of the dark energy comes from the observed brightness of a particular class of supernova explosions called type Ia supernovae (SN Ia's). Defined empirically from their spectra (*1*), these events mark the thermonuclear destruction of white dwarf stars. A white dwarf, stable when solitary up to 1.4 solar masses, can accrete matter from a companion when it is in a binary system. A white dwarf in a binary will explode violently, destroying the star, when accreted mass provokes the carbon and oxygen in its interior to erupt in a runaway thermonuclear explosion (*2*, *3*). SN Ia's are infrequent events, erupting roughly once per century in a galaxy, and found in all types of galaxies. SN Ia's are useful for probing the history of cosmic expansion and the nature of dark energy because they are very bright, typically about 4×10^9 times the luminosity of the Sun. With careful measurements of the color and the apparent brightness during the month when a SN Ia shines most brightly, the distance to an individual explosion can be derived to better than 10% (*4–6*). This precision makes SN Ia's the best standard candles in extragalactic astronomy: Observations of nearby and bright SN Ia's help determine the present rate of cosmic expansion, the Hubble constant, H_o, of 72 ± 8 km s^{-1} Mpc^{-1} (*7*, *8*). Observations of the brightness and spectra of these objects measure the relation between distance and redshift for the universe. The redshifts of supernovae at different distances reveal changes in the rate of cosmic expansion that have developed while the light was in flight to us from explosions over 7 billion light-years away. The observed effect is that supernovae at a redshift of $z = 0.5$ (roughly one-third of the way back to the Big Bang) appear about 25% dimmer than they would in a universe without cosmic acceleration: Acceleration increases the distance the light must travel to reach us.

The first clues from distant supernovae were contradictory (*9–11*), but, by 1998, evidence from supernova distances favored a universe that was accelerating (*12*, *13*). Present work includes a widening stream of supernova discoveries at low redshift (*14*), diligent follow-up (*15*), and a growing body of well-observed cases to compare with the high-redshift data (*16*, *17*). In addition, recent results (*18*) independently confirm the 1998 results, whereas the analysis of supernovae and their host galaxies (*19*) showed persuasively that uncorrected extinction by dust in galaxies, a possible source of systematic error, most likely does not produce the observed dimming of distant SN Ia's.

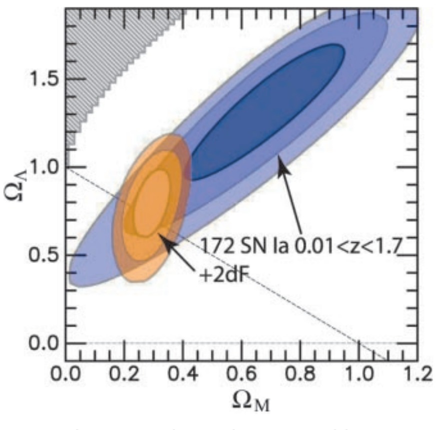

Fig. 1. The concordance diagram. In blue, 1-, 2-, and 3σ confidence contours for Ω_Λ and Ω_m based on 172 SN Ia's from (*18*). The smaller orange error ellipses result from combining supernova data with information from large-scale structures in a flat universe (*49*, *50*).

The published sample of high-*z* supernovae has now been extended to the decisive redshift range of $z \sim 1$ (*18*, *20*, *21*), where the effects of cosmology begin to change sign from making supernovae dim to making them a little brighter than they would otherwise appear. These observations sample directly the epoch when the balance between dark energy and dark matter tilted from cosmic deceleration because of dark matter to cosmic acceleration caused by dark energy. This opens the prospect of learning how the dark energy behaves as the universe expands on the basis of careful observations in the era at the onset of cosmic acceleration.

Improved evidence for dark energy from supernovae has boosted these results from a startling possibility to conventional wisdom in just the past 5 years. The general acceptance of this new picture of a universe dominated by dark energy derives from the neat fit of supernova data with other cosmological measurements, including galaxy clustering as a measure of dark matter, the ages of stars, and measurements of the CMB. Each of these strands in the web of inference has grown more secure, and the pleasant result has been a trend toward greater concordance from independent directions. These results converge on a universe that is 13.6 ± 1.5 billion years old and expanding at a present rate of 72 ± 8 km s^{-1} Mpc^{-1}, which is composed of 28 ± 5% matter and 72% dark energy (*18*, *22*) (Fig. 1).

Nature of the Dark Energy

One possible explanation is that dark energy is the modern version of Einstein's cosmological constant (*23–25*). In 1917, Einstein introduced a curvature term to produce static, eternal solutions to his field equations, in accord with the view then current that the Milky Way was the entire universe and the observational fact that the motions of its stars showed no systematic expansion or contraction. Legend holds that Einstein, after learning of Hubble's work on cosmic expansion based on galaxies outside the Milky Way, smote himself on the forehead and declared the cosmological constant his greatest

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blunder. This phrase does not occur in any of Einstein's writings but is derived from a line in Gamow's autobiography, in which Gamow, describing his own early studies of general relativity in St. Petersburg, says that "much later" Einstein called the cosmological constant "perhaps the biggest blunder of my life" (*26*). Einstein's own comments, written with the astronomer DeSitter, are more sensible than Gamow's legend. In 1932, they wrote about the cosmological constant: "An increase in the precision of data derived from observations will enable us in the future to fix its sign and determine its value" (*27*). But there isn't any doubt that Einstein felt the cosmological constant was repugnant as well as repulsive. In a 1947 letter to Lemaitre, he wrote, "Since I introduced this term, I had always a bad conscience. . .. I am unable to believe that such an ugly thing should be realized in nature" (*28*).

Following Zel'dovich (*29*, *30*), the modern interpretation of the cosmological constant regards it not as a curvature but as a vacuum energy density (*31*). This vacuum energy has quite unintuitive properties, most notably a negative pressure, P. If the vacuum energy density is really constant, then if you imagine a cylinder bounded by a piston with this stuff in it, and you wish to expand the volume by an increment dV, you will need to pull on the piston to do an amount of work PdV that will result in an increased energy inside the cylinder (because the energy density stays constant) (*32*). This negative pressure has important consequences for cosmic expansion, expressed in the standard Friedmann equations for the cosmic scale factor, $a(t)$, which describes the evolution of distances between galaxies in the universe (*33*). The gravitational acceleration in general relativity, which determines the sign of the second time derivative of a, a'', depends on the quantity $\rho c^2 + 3P$, where c is the speed of light. Matter has positive pressure (and very little of it in the present universe), which, along with positive density, ensures that a universe made of matter will always decelerate. But a cosmological constant can produce a negative pressure that changes the sign of $\rho c^2 + 3P$ to produce repulsive effects as long as $P < -1/3\rho c^2$.

In 1917, Einstein chose a value for the pressure that made the universe static, but this was an unstable equilibrium. For the cosmological constant (or any dark energy that changes slowly enough as the universe expands), P is negative and effectively constant. This makes an expanding universe accelerate: As the matter density decreases, the negative pressure does not, and eventually this will make the universe expand exponentially. In 1932, Arthur Eddington did not think the cosmological constant was a blunder; he thought the observed Hubble expansion might well be just the first-order view of a universe accelerating from rest because of a cosmological constant (*34*). The 1998 supernova results point to a dark energy that has negative pressure, so that galaxies separating after the Big Bang and gently decelerated by dark matter for the next 7 billion years are presently accelerating exponentially away from one another.

Although there is no particular conceptual problem with dark energy in the form of either a cosmological constant or some other energy that changes slowly with time, there are two serious quantitative problems. The data require a dark energy, which can be expressed as a fraction of the energy density of the universe as $\Omega_\Lambda = 0.7$ (*35*). One theoretical problem this poses is that the natural scale for the energy of the vacuum for gravitation is set by the Planck mass (M_{Planck}) at $\rho_{\mathrm{vacuum}} = M_{\mathrm{Planck}}{}^4\ c^3\ h^{-3}$ (where h is the Planck constant) which is 120 orders of magnitude larger than the astronomically observed value. This discrepancy can be ameliorated by cutting off the energy scale at the point where current knowledge of high-energy physics fades, but we are still left with a 55-orders-of-magnitude difference between theory and observation (*36*).

Another quantitative theoretical problem is that the present value of Ω_Λ implies that 70% of the energy in the universe is now in the form of dark energy. The sum of Ω_Λ and Ω_{matter} stays the same as the universe expands: If it is 1.000 today, it was 1.000 yesterday and will be 1.000 tomorrow. But the ratio $\Omega_\Lambda/\Omega_{\mathrm{matter}}$, about 2 today, changes briskly as the universe expands, because the vacuum energy stays constant whereas the mass density scales as a^{-3}. Even a modest exploration of the past, back to redshift $z \sim 1$, where $a^3 \sim (1 + z)^3$ is 8, means we will be looking back to the regime where dark matter dominated the balance of cosmic energy by as much as dark energy does today. The shift about 7 billion years ago from a decelerating universe dominated by dark matter to an accelerating universe dominated by dark energy means we just happen to live at the unique moment when this is true. When the universe attains twice its current age, we will have $\Omega_\Lambda/\Omega_{\mathrm{matter}} \sim 10$, and, when it was half its current age, we had $\Omega_\Lambda/\Omega_{\mathrm{matter}} \sim 1/10$. Why do we live at exactly the moment (where "moment" means a span from 7 billion years in the past to 14 billion years in the future) when the vacuum energy is about the same as the mass energy density? Nobody knows. Einstein thought the cosmological constant was ugly, and, in their hearts, modern theoretical physicists agree, but the astronomical observations seem persuasive that the universe is constructed in this extravagant way and that this problem cannot be wished away. Other forms of dark energy that change over time in a different way can avoid this problem and have been proposed (*37*–*40*).

Observing the Era of Acceleration

Although theorists are bothered by the coincidence of our era with the shift from a decelerating universe to an accelerating one, observers are delighted. Because this change is recent, it is potentially within view, and, by using the best of current technology, it provides a direct test of whether unforeseen systematic shifts in the intrinsic luminosity of supernovae are producing an illusion of cosmic acceleration. If unaccounted-for dust, or changes in the ages of stars, or drifts in the chemical composition of stars, rather than cosmology, make distant supernovae dim, then going to higher redshift should exacerbate those problems and make them fainter still. But, if the universe shifted from deceleration to acceleration at some time in the not-too-distant past, we would expect the sign of the effect on apparent magnitude to change. SN Ia's at $z \sim 0.5$ are dimmed by the effect of cosmic expansion, but we should expect SN Ia's beyond redshift 1 to appear a little brighter than they would otherwise if the universe were decelerating at the epoch of their detonation. This is a test that the supernova observations could fail.

The observational problems of finding and measuring supernovae at $z \sim 1$ are challenging. Because the entire spectrum is redshifted by a factor of $1 + z$, this means that the ordinary visible wavelength bands of optical astronomy provide measurements of the ultraviolet light emitted by SN Ia's, whereas the bulk of the flux is received at longer wavelengths. Large arrays of silicon-based charge-coupled devices (CCDs), such as the MOSAIC camera at Cerro Tololo Inter-American Observatory, the SUPRIME camera at Subaru, or the MEGACAM at the Canada-France-Hawaii Telescope (CFHT), are today's best tools for supernova searches. By searching in the reddest bands where these devices work well, in the range from 800 to 900 nm, and increasing the exposure times enough to detect objects with apparent magnitudes in the I band ~ 24 magnitude, a search can be tuned to emphasize the high-z supernovae, as reported by (*18*). Obtaining spectra of these most distant objects to get the redshift and to confirm that the object is a SN Ia is also a challenge. Because the brightness of the supernova is only a few percent of the brightness of the night sky, it typically takes hours of integration with the largest telescopes, such as Keck, Gemini, or the European Southern Observatory's Very Large Telescope (VLT), to obtain spectra of these faint objects. Photometry from the ground requires precise subtraction of the background galaxy, which is typically several times brighter than the SN Ia. This can be done from the ground, but Hubble Space Telescope (HST) observations, with their exquisite resolution, are much easier to use. The evidence to date (Fig. 2), though slim at $z \sim 1$, favors the view that we are seeing past the era of acceleration at $z \sim 0.5$, back to the timeof cosmic deceleration near $z \sim 1$.

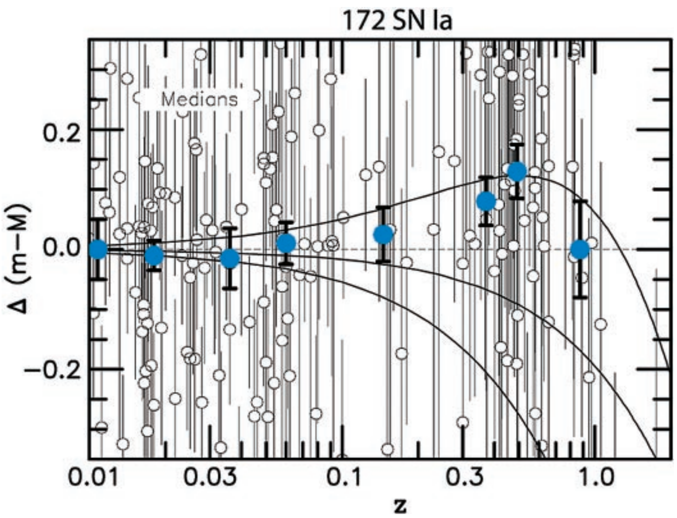

Fig. 2. Residual Hubble diagram: apparent magnitude difference between the expected magnitude in an empty universe and the observed magnitude of supernovae at each redshift (*18*). Individual points are shown with their quoted error bars. For clarity, medians in redshift bins are shown in blue. The theoretical lines shown correspond to Ω_Λ, Ω_m pairs of (0.7, 0.3), (0, 0.3), and (0, 1). The highest redshift bin may show signs of cosmic deceleration, as predicted by the top line.

Searches from the ground have the advantages of large telescope apertures (Subaru, for example, has 10 times the collecting area of HST) and large CCD arrays [the CFHT has a 378-million-pixel camera, compared to the new Advanced Camera for Surveys (ACS) on HST, which has 16 million pixels]. The advantages of space include avoiding the bright and variable night sky encountered in the near-infrared; the potential of much sharper imaging for point sources, like supernovae, to distinguish them from the galaxies in which they reside; and better control over the observing conditions, which need not factor in weather and moonlight. During December 1997 and into early 1998, a repeat exposure of the Hubble Deep Field (HDF) was carried out (*41*, *42*), followed by repeated imaging with its infrared camera. Without knowing it, the infrared camera team had selected as their target field the site of SN 1997ff, which was subsequently recognized and extracted from the data archive (*43*). The observations do not include a spectrum of either the supernova or the galaxy, but the observed colors were used to estimate the redshift at $z = 1.7 \pm 0.1$. The apparent magnitude of SN 1997ff is about 1 full magnitude brighter than expected in a universe with no acceleration or deceleration. Although nobody regards SN 1997ff as a conclusive demonstration of cosmic deceleration, the data are in good accord with what would be expected if the universe really did change from deceleration to acceleration. If many such objects could be measured well, and they traced the expected path in the plot of apparent magnitude and redshift, they would tell us whether we are really seeing back to the age of cosmic deceleration (*44*).

The installation of ACS on HST has made it practical to search for supernovae with HST itself. The new camera has twice the area on the sky, sampling of the images that is twice as fine, and throughput that is five times better than HST's previous imager. In an early test, two SN Ia's at $z = 0.47$ (SN 2002dc) and $z = 0.95$ (SN 2002dd) were discovered with HST, which subsequently gathered beautiful light curves and spectra (*21*). The Great Observatories Origins Deep Survey (GOODS) program to reimage the HDF with ACS was optimized to detect transient events, especially high-redshift supernovae, by adopting a different approach to scheduling. Instead of relentlessly observing the HDF for 342 images over 10 days, as done in 1995, successive GOODS observations were spaced by 45 days, providing 5 epochs of data on two fields, HDF north and south. Whereas the GOODS team adds these images to build a superdeep field, the Higher-*Z* Team, led by Adam Riess (but with an active cast of dozens), subtracted the accumulated template image from each incoming frame. The Higher-*Z* Team has detected 42 supernovae, with redshifts ranging from $z = 0.3$ to $z = 1.8$, and 10 of these have $z \geq 1$ (*45*, *46*). When these exquisite data are fully analyzed, we can expect a much firmer report from the epoch of cosmic deceleration (Fig. 3). The HST is a powerful tool for discovery and measurement of supernovae that are too difficult to find and follow from the ground.

The Essence of Things

The era of cosmic acceleration is quite recent. This means that the observed effect of dimming SN Ia's has its largest amplitude in the relatively easily observed range from $z = 0.3$ to $z = 0.7$, where most of the present sample of high-z supernovae has already been accumulated. Tonry *et al.* (*19*) analyzed data for 230 SN Ia's with redshifts and distances. Most of these are in the nearby universe ($z < 0.1$), where the effects of acceleration are too subtle to detect: The signal to determine the best value of Ω_Λ comes from higher redshifts. The typical internal errors on the measurement of distance for each supernova are larger than we get for the best observed cases (Fig. 2). It would be good to construct a larger, more uniform sample with smaller errors.

If the dark energy is the cosmological constant, we know precisely what to expect for its behavior: The energy density remains unchanged. However, dyspepsia caused by the cosmological constant is strong enough to inquire whether the dark energy could have some other nature. For example, if the dark energy comes from some slow-changing energy field, as in quintessence models (*37*–*40*), then it would be of great interest to determine the properties of that field in the manner advocated by Einstein and DeSitter: from observation.

A simple parameterization of the possible forms of dark energy uses the idea of the cosmic equation of state (*47*). Suppose the dark energy density changes with the scale factor, a, as a power law $\rho \sim a^{-n} \sim (1 + z)^{-3(1 + w)}$. Here, w is the effective equation-of-state index, because by examining the way pressure changes with cosmic expansion, you can write an equation of state that connects the energy density to the pressure: $p = w\rho c^2$. Familiar values of w include $w = 0$, for ordinary matter and for

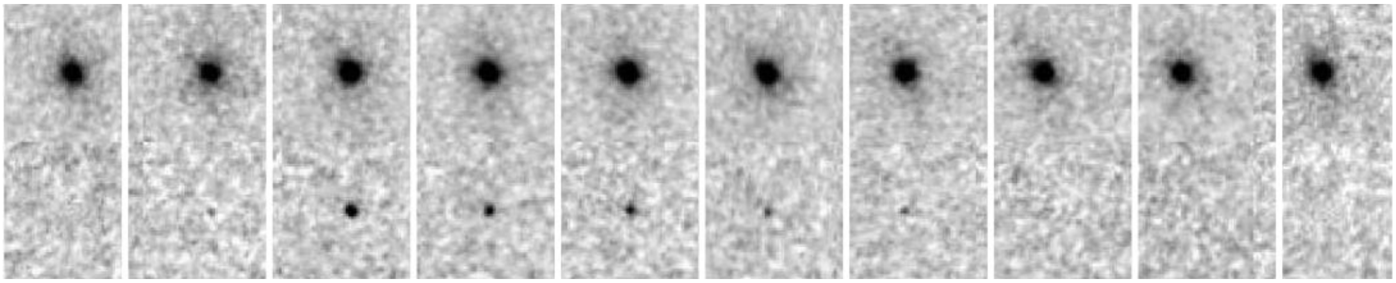

Fig. 3. The rise and fall of Thoth (SN 2002hp), a high-redshift supernova discovered and observed with the ACS on the HST by the Higher-*Z* Team.

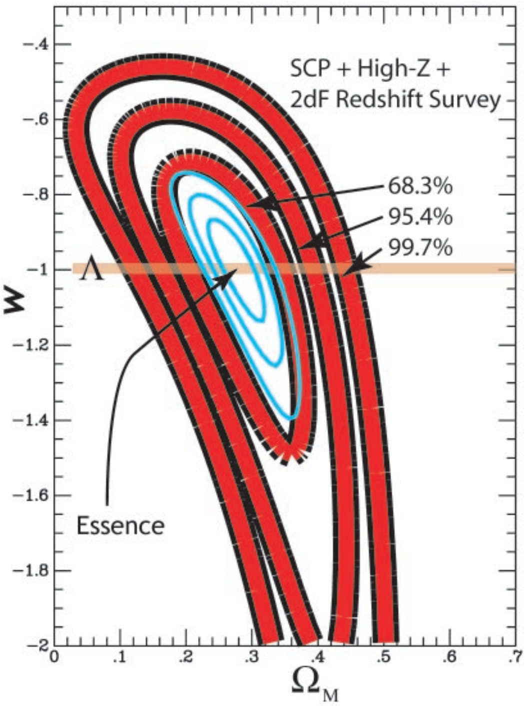

Fig. 4. The cosmic equation of state. Outer contours (red) give the current constraints from SN Ia's according to (*18*). Inner contours (blue) show the expected improvement in precision to be expected from completing the 200–SN Ia's catalog of the ESSENCE program.

cold dark matter that just gets diluted by expansion, and $w = 1/3$, for radiation that gets diluted and redshifted. For a true cosmological constant, $w = -1$. Other forms of dark energy might have different values of *w* that could be determined from careful observations of the onset of acceleration. On the basis of the 1998 supernova observations, the cosmic equation of state is consistent with $w = -1$ (*48*), but the precision of these early results was not very high. The current state of the art based on combining supernovae with constraints from galaxy redshift surveys (*19*, *49*, *50*) is shown in Fig. 4. The observed constraints in the $\Omega_m - w$ plane assume that $\Omega_m + \Omega_\Lambda = 1$. The data favor a value of $\Omega_m = 0.28$, consistent with independent methods (*49*, *50*) and also consistent with a value of $w = -1$. The 95% confidence interval on *w* is formally in the range $-1.48 < w < -0.72$. If we are bold enough to assert that $w > -1$, which seems sensible enough on the basis of energy conditions [but see (*51*) for an exploration of what it might mean to have $w < -1$], then the 95% confidence upper limit on *w* is $w < -0.73$. These constraints are similar to those reported using results from the Wilkinson Microwave Anisotropy Probe (WMAP) satellite, where the early results give $w < -0.78$ at 95% confidence (*22*).

So far, so good. But a larger, more homogeneous data set would have the potential to do much better at this investigation of the nature of the dark energy. A program to build that data set, dubbed ESSENCE [Equation of State: SupErNovae trace Cosmic Expansion (*52*); pronounced “SNs”], is under way at the Cerro Tololo Inter-American Observatory. With the use of a powerful data pipeline developed by Chris Stubbs of the University of Washington and a wide range of collaborators from the High-*Z* Team, led by Chris Smith and Nick Suntzeff at Cerro Tololo, the program aims to find and measure 200 SN Ia's in the redshift range of interest, $0.15 < z < 0.7$, in the next 5 years. Substantial spectroscopic backup to the program, to get the redshifts and to assure that the objects are really SN Ia's, comes from the use of Gemini, Magellan, VLT, Keck, and MMT Observatory. Figure 5 shows a sample of spectra obtained with the use of the Gemini spectrograph from the past year's observations. The inner contours of Fig. 4 show the expected improvement in the precision of measuring *w* that will result from completing the full ESSENCE program by 2006. This observing program cannot fail to be interesting. Either the contours will shrink around $w = -1$, in which case the cosmological constant will be an even stronger candidate for the dark energy, or they will converge on some other value that is different from –1, which would be even more exhilarating.

On the other hand, just learning the value of *w* is not the whole story on the dark energy. As several authors have pointed out (*53*, *54*), there are many conceivable forms of the dark energy, and no conceivable set of observations will rule out all the devious constructions of unchecked theoretical imagination.

What Next?

Supernovae have led the way in revealing cosmic acceleration. Quantitatively, the results agree with the independently measured values for Ω_m from large-scale structure and the result for $\Omega_m + \Omega_\Lambda$ from the CMB. The supernova results also place a strict limit on the cosmic age that fits with other lines of evidence. From the Tonry *et al.* compilation (*19*), if $w = -1$, then $H_o t_o$, the dimensionless expansion time, is 0.96 ± 0.04. For a value of $H_o = 72$ km s^{-1} Mpc^{-1} based on Cepheids and SN Ia's (*9*), this makes the elapsed time since the Big Bang, taking into account both the bygone era of deceleration and the modern era of acceleration, $13.6 \times 10^9 \pm 1.5 \times 10^9$ years. This is in good accord with an age of 12.5×10^9 years from 17 metal-poor globular clusters (*55*). If these systems began to form around $z = 8$, which corresponds to an incubation time of 0.6×10^9 years, this gives a cosmic age based on stellar evolution of 13.1×10^9 years. The expansion age from supernovae is also in good accord with the age inferred from WMAP of $13.7 \times 10^9 \pm 0.2 \times 10^9$ years (*23*)

All of this good news should not be a source of complacency. There are many aspects of SN Ia's that are poorly understood and that could affect their use as cosmic yardsticks in subtle ways (*56*). We do not know which stars become SN Ia's, and there may be a mix of supernovae of different types in any sample that we are lumping together and treating in the same way. We do not know how the chemical evolution of the parent population and the white dwarfs they form affects the luminosity of the supernovae they produce or how this should vary over time (*57*).

All of this is hidden beneath the surface and may create a floor of systematic variation that cannot be eliminated simply by increasing the sample size. One good path forward is to continue the discovery and study of SN Ia's in nearby galaxies, which includes a wide range of local chemical abundances and star-formation histories.

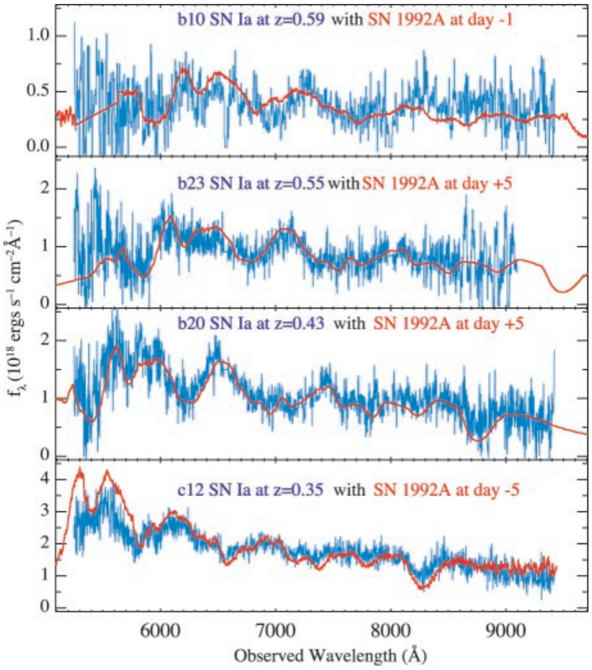

Fig. 5. Spectra of ESSENCE SN Ia's (blue) compared to a well-observed low-redshift SN Ia, SN 1992A (red). These data, from the Gemini Multi-Object Spectrograph at the Gemini south, show that the spectra of distant SN Ia's are well matched by nearby objects.

The present stream of discoveries from the Katzman Automatic Imaging Telescope (82 very nearby supernovae in 2002 alone), plus the valuable contributions of dedicated amateurs coupled with dogged follow-up, is the way forward. We know that the use of the light-curve shape helps decrease the scatter in supernova Hubble diagrams, and we may find that spectra help too. The really good photometric sample at low z now numbers $\sim$100 objects (*16*), and a spectroscopic sample of 845 spectra of 67 SN Ia's has been compiled (*58*). For the near term, we can use these data sets to investigate systematic effects. Larger samples will be forthcoming from the Legacy Survey (*59*) at CFHT and from the SN Factory (*60*) if they can provide adequate follow-up. These surveys will find fainter supernovae than the nearby searches. Follow-up will require a much larger investment of time to yield light curves and spectra of the same quality as those that can be observed for the nearby objects. The comparison of truly distant supernovae to the nearby sample shows no obvious differences in their spectra (*61*), as illustrated for some ESSENCE supernovae (Fig. 4), but pushing the systematic variations below 5% will require understanding subtle differences among the SN Ia's. All of this will have to come from semi-empirical work. First-principles computation of SN Ia explosions, luminosities, and spectra is, at present, too crude to predict directly the variations with epoch.

Rapid progress in measuring the CMB has come from a variety of approaches, including ground-based observations from high desert sites and from the South Pole, balloons, and WMAP. In the future, this field will be further advanced by elaborate satellites like Planck. In a similar way, the sustained observation of nearby supernovae, ground-based programs like ESSENCE, and straightforward extrapolation of the Higher-*Z* program on HST are certain to make progress in constraining dark energy. A wide-field imager, to make HST a truly formidable supernova harvester in an extended mission (*62*) and a quick, ruthlessly simple satellite could gain some of the needed data and sharpen the questions for the field in just a few years. The program described by the Supernova/Acceleration Probe (SNAP) collaboration (*63*) would be an extraordinary leap beyond these modest ideas. They propose a formidable 2-m telescope (about the size of HST) with a billion-pixel detector (120 times the size of ACS on HST) and an infrared spectrometer of unprecedented efficiency dedicated to supernova studies. The idea is to measure thousands of supernovae with excellent control of the systematics to reveal the fine details of cosmic acceleration and to infer more thoroughly the properties of the dark energy.

Theorists may be wary of the coincidence between the present and the onset of cosmic acceleration. Observers are delighted by this coincidence and by the coincidence between our own brief lives and the instant when technology has made these measurements possible. We are incredibly lucky to be working just at the moment when the pieces of the cosmic jigsaw puzzle are falling into place, locking together, and revealing the outline of the pieces yet to come. Dark energy is the biggest missing piece and a place where astronomical observations point to a gaping hole in present knowledge of fundamental physics.

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