Farthest Supernova Strengthens Case for Accelerating Cosmic Expansion

Extraordinary claims demand extraordinary evidence. A recent paper by Adam Riess (Space Telescope Science Institute) and colleagues[1] plays out just such a confrontation. The extraordinary claim, now three years old, asserts that the Hubble expansion of the cosmos is actually speeding up. Surely, one would have thought, the expansion is steadily being slowed down by gravity. The extraordinary new evidence reported by Riess and company comes from the discovery and measurement of by far the most distant supernova ever seen.

Among the authors of the new paper are members of the two groups (the High-Z Supernova Search Team and the Supernova Cosmology Project) that reported the original evidence of accelerated cosmic expansion. (See PHYSICS TODAY, July 1998, page 17.) Both groups had discovered and measured several dozen supernovae of moderately high redshift ($0.3 < z < 0.9$), and found that they appeared fainter than one would expect if the cosmic expansion were slowing down or even coasting. (The Doppler redshift z is $\Delta\lambda/\lambda$, where λ is the rest-frame wavelength.)

These results have been taken quite seriously. Implying that the dynamics of the cosmos are at present dominated by some sort of "dark energy" that works against ordinary gravity at large distances, the acceleration claim has spawned a thriving cottage industry of theoretical speculation.

The simplest of these dark-energy scenarios would be the vacuum energy implied by the cosmological-constant term (Λ) that Einstein inserted into the field equation of general relativity to stabilize a steady-state cosmos against gravitational collapse. But later, when the Hubble expansion was discovered, Einstein concluded that the cosmological constant had been a mistake. This famous "mistake" has been revived by the observational claim of accelerating expansion and by theoretical notions of quantum-vacuum energy density. General relativity tells us that vacuum energy, as distinguished from matter or electromagnetic radiation, would be gravitationally repulsive.

> A 10-billion-year-old stellar explosion, serendipitously recorded by the Hubble Space Telescope's infrared camera, seems to show the cosmic expansion slowing down before it eventually sped up.

A blast from the distant past

An observational claim of such profound import cries out for more confirmation and the closing of possible loopholes. By improbable good luck, the Hubble Space Telescope (HST) recorded the most distant supernova, dubbed SN 1997ff, in sufficient detail to greatly strengthen the conclusion that the Hubble expansion is indeed accelerating. Its astonishing redshift ($z = 1.7 \pm 0.1$) tells us that the expanding cosmos was barely a third of its present linear size and less than a quarter of its present age when this supernova burst forth and blazed for a few weeks.

Almost all the theories that address the Hubble acceleration in the present epoch conclude that, if we look back that far, we should find a more crowded epoch of *decelerating* Hubble expansion in which gravitational attraction was stronger than the dark energy's repulsive counterforce.

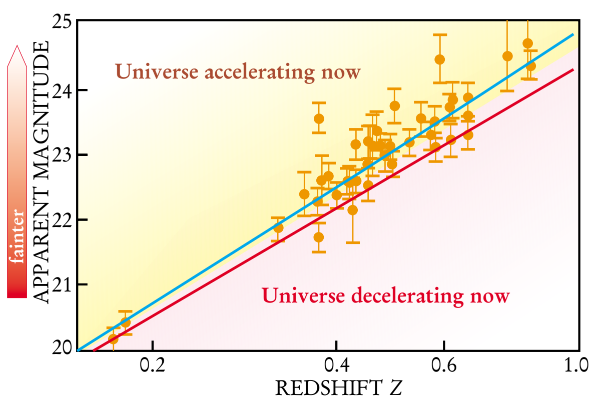

FIGURE 1. HUBBLE PLOT of the Supernova Cosmology Project's accumulation of type-Ia supernovae. The best fit (blue curve), corresponding to cosmological parameters $\Omega_m \approx 0.35$ and $\Omega_\Lambda \approx 0.65$, describes a cosmic expansion that has been accelerating for the last 6 billion years. The red curve ($\Omega_m = 1, \Omega_\Lambda = 0$) describe a cosmic expansion that has never stopped slowing down. (Adapted from ref. 2.)

As its name implies, SN 1997ff was discovered in a supernova search at the end of 1997 by the HST's wide-field optical camera. But observations in the visible are of very limited use for a supernova whose light is so strongly redshifted. It would be another year before Riess and colleagues realized that NICMOS, an HST infrared camera with a much narrower field of view, had quite unintentionally been looking at SN 1997ff several times during the supernova's brief appearance. And then it took another year of number crunching to make sense of the infrared data.

This lucky find comes at an opportune moment. Both supernova search teams have amassed enough statistics at redshifts $z \lesssim 1$ to find themselves approaching the limits imposed by systematic uncertainties that will not be allayed before a new generation of orbiting telescopes becomes available. With existing telescopes, supernovae with redshifts well above $z = 1$ will continue to be rare finds. But they will be important. Whatever the dark energy turns out to be, the theories presume that its density falls more slowly than the mass density as the cosmos expands. Beyond $z = 1$, we should be seeing an earlier time when mass density was dominant.

The measurement of SN 1997ff's redshift and apparent brightness provides the first direct evidence of the transition from the earlier deceleration epoch to the present accelerating expansion. Perhaps more important, it renders very implausible two worrying caveats about the evidence for the current Hubble acceleration. Cautious astrophysicists had raised the concern that the unexpected faintness of supernovae between $z = 0.4$ and 0.9 might not, after all, be a manifestation of accelerating cosmic expansion. It might just be an artifact due to peculiar intergalactic dust or the paucity of heavy elements in early epochs of star formation. But neither of those two rather prosaic alternatives would mimic the transition from deceleration to acceleration implied by the relatively high apparent brightness of SN 1997ff.

Standard candles

In their quest to pin down the key cosmological parameters, the two high-redshift search teams use only "type-Ia" supernovae. Besides being the brightest of the supernovae, they also have the great observational virtue of being *almost* standard candles. That is, they all explode with roughly the same intrinstic luminosity. And the small luminosity variation from one type-Ia explosion to another correlates closely with the outburst's decay rate. So one gets an excellent measure of the distance of any particular type-Ia supernova simply by measuring its apparent brightness and decay curve. Type II "core collapse" supernovae are nothing like standard candles.

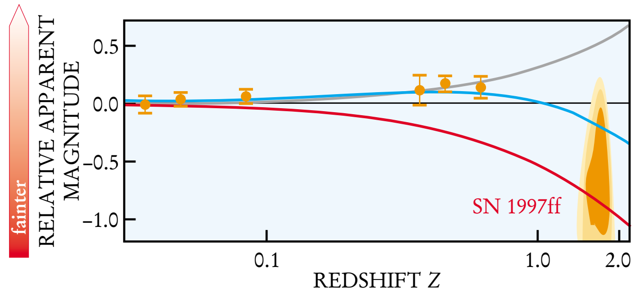

FIGURE 2. EXTENDING THE HUBBLE PLOT of figure 1 to $z = 2$ shows that the best-fit (blue) curve begins to turns down before $z = 1$, indicating an earlier epoch of cosmic deceleration. In this figure, apparent magnitudes are plotted relative to what one would expect for an essentially empty cosmos (the horizontal line). Beyond the data points summarizing the previous supernova observations, the plot shows the new highest-z supernova. Its outer contour, the 99% confidence limit, excludes the gray curve that describes what one would expect if the apparent cosmic acceleration were an artifact of dust or chemical evolution. The red curve, though it fits SN 1997ff, does not fit the lower-z supernovae. (Adapted from ref. 1.)

The cosmological information comes from plotting the apparent brightness of distant type-Ia supernovae against the Doppler redshifts due to their recession from us in the expansion of the universe. (To make the type-Ia's better standard candles, the apparent brightness is corrected for outburst decay rate.) For small redshifts ($z < 0.1$), plotting apparent magnitude (a logarithmic measure of apparent faintness) against log z yields the familiar straight line that attests to the Hubble expansion. But beyond redshifts of about 0.2, things become more interesting, as we see in figure 1. For different cosmic mass and dark-energy densities, the cosmological predictions begin to diverge.

Cosmologists use the conveniently normalized, dimensionless parameters Ω_m and Ω_Λ, respectively, for the matter density and dark-energy density of the cosmos. Their sum, Ω_T, determines the large-scale curvature of the cosmos. If $\Omega_T = 1$, as required by the widely accepted inflationary version of Big Bang cosmology, the spatial geometry of the universe is flat, that is to say, Euclidean. Measurements of fluctuations in the cosmic microwave background (CMB) provide strong evidence that Ω_T is indeed very close to 1. (See PHYSICS TODAY, July 2000, page 17.) While the supernova data are particularly sensitive to the *difference* $\Omega_\Lambda - \Omega_m$, the complementary CMB data provide a better measure of Ω_T.

But geometry is not the whole story. Both theoretical curves in figure 1 presume that $\Omega_T = 1$. But the lower (red) curve, which describes a *decelerating* universe, takes Ω_m to be 1, ignoring the possibility of a nonvanishing Ω_Λ. That was indeed the prevalent opinion in the early 1990s, before the evidence began to accumulate for Hubble acceleration *and* for a mass density less than half of what would be required for a flat universe in the absence of any Ω_Λ. The blue curve is the best fit to the type-Ia supernova observations for redshifts below $z = 0.9$. Yielding $\Omega_m \approx 0.35$ and $\Omega_\Lambda \approx 0.65$, it describes the accelerating Hubble expansion that has been in vogue for three years now.

Expanding the Hubble plot out to $z = 2$, figure 2 shows where SN 1997ff fits in. Here all the apparent magnitudes are plotted relative to what they would be in the constant expansion of an otherwise empty universe ($\Omega_m = \Omega_\Lambda = 0$). The blue curve, which was the best fit to the lower-z supernovae, shows the prediction for $\Omega_m = 0.35$ and $\Omega_\Lambda = 0.65$ at higher redshifts. It turns over below $z = 1$ from the present accelerating phase to an earlier decelerating phase. The new SN 1997ff data point, despite the rather large uncertainty in its measured apparent magnitude, is quite consistent with that predicted epoch of deceleration.

More important, it appears to be *inconsistent* with the upward curving gray curve, which describes what one should see if the anomalous faintness of the $z < 0.9$ supernovae were due to either of the two cautious astrophysical alternatives to cosmological dark energy. If it were due to pervasive intergalactic "gray dust" that does not reveal itself by reddening what it obscures, one would expect the supernovae to appear more and more faint, relative to the empty-universe case, with increasing redshift. Much the same is true if one imagines that the anomalous faintness is due to some peculiarity in the chemical composition of older type-Ia supernovae that makes them intrinsically less luminous than more recent ones.

In both cases the supernovae should seem ever fainter with increasing age or intervening dust. One would certainly not see the turnover to increasing brightness predicted for the dark-energy scenarios and now apparently confirmed by SN 1997ff. One could cobble together elaborate chemical-evolution or dust scenarios to fit all the supernova data above $z = 0.4$. "But that would involve so much fine tuning as to render them quite implausible," says Peter Nugent (Berkeley), an author of the SN 1997ff paper.

Some caveats are in order. The conclusion that SN 1997ff is indeed a type-Ia supernova comes from its color distribution, temporal behavior, and the nature of its host galaxy. At less spectacular redshifts, a supernova's type can generally be identified more directly from its spectral details. Also, to estimate the intrinsic luminosity of SN 1997ff from its light curve, Riess and company had to assume that the correlation between intrinsic luminosity and decay rate didn't change significantly in the 2 billion years between $z = 1.7$ and 0.9.

"We'll learn a lot as we add more supernovae beyond $z = 1$," Riess told us. Both supernova search teams have recently observed a handful of such precious events. But further analysis and follow-up measurements of host galaxies will be required before they show up on the Hubble plots.

Some wags point out that the accelerating Hubble expansion lends particular urgency to the enterprise of cosmological observation. They suggest that astronomers warn congressional funders that, if we delay more than 150 billion years, all galaxies beyond our local cluster will have disappeared irretrievably below the horizon imposed by the finite speed of light.

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References

1. A. Riess et al., *Astrophys. J.*, to be published, http://arXiv.org/abs/astro-ph/0104455.
2. S. Perlmutter et al., *Astrophys. J.* **517**, 565 (1999).