Very Distant Supernovae Suggest that the Cosmic Expansion Is Speeding Up

Two rival groups of observers have concluded that the gravitational slowing of the Hubble expansion is being opposed by a repulsive cosmological constant, or something even more exotic.

To determine the rate at which the cosmos is expanding, one has to measure the redshifts and brightnesses of objects very far away. To seek out the *derivative* of that rate—the expected deceleration, or perhaps even an acceleration, of the cosmic expansion—one has to look out much farther still. That's precisely what two competing groups of astronomers and physicists undertook to do a few years ago. And now both groups have come up with the same astonishing, if still somewhat tentative, conclusion: The present mean mass density (ρ_0) that acts to slow down the Hubble expansion by gravitational braking appears to be overmatched by some ethereal agency that is actually speeding it up.

"If these observations are correct," says University of Chicago theorist Michael Turner, "a nonvanishing cosmological constant is, of course, the first thing that comes to mind. But that would be the least interesting explanation." The field equations of general relativity have room for an empirical parameter, Λ, which Einstein called the cosmological constant. He invoked it to work against gravity on cosmological scales and thus allow for a steady-state solution, but later abandoned it when he learned of the Hubble expansion. A finite positive Λ, which has the dimensions of an inverse length squared, is equivalent to a uniform, constant vacuum energy density with the peculiar negative pressure that opposes gravitational deceleration in the field equations.

As of this writing, reports of the observations, though not yet accepted for publication, have caused quite a stir. On the first weekend in May, a workshop at Fermilab on "The Missing Energy in the Universe" thrashed out the observational uncertainties and a variety of provocative theoretical alternatives to the venerable cosmological constant.

Collecting high-z supernovae

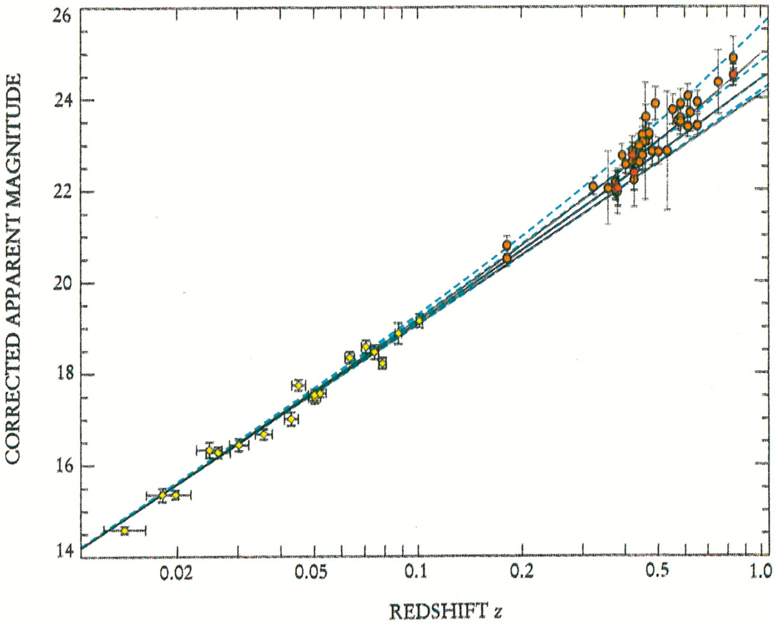
The Supernova Cosmology Project, now an international collaboration led by Saul Perlmutter, began this business a decade ago at the Lawrence Berkeley National Laboratory. Perlmutter and company had to develop a strategy for finding adequate numbers of high-redshift type Ia supernovae promptly enough to catch them before they reached peak brightness, and reliably enough so that scarce telescope time for the essential followup monitoring could be booked well in advance of each hunt. By now the Berkeley group has harvested light curves and spectra for about 80 such supernova explosions with redshifts $z \equiv \Delta\lambda/\lambda$ ranging from 0.18 to 0.86. The group's impending paper[1] detailing its evidence for a significant Λ is based on the completed analysis of 42 of these supernovae.

The rival High-*Z* Supernova Search Team, a worldwide collaboration of astronomers organized in 1995 and headed by Brian Schmidt of the Mount Stromlo observatory in Australia, brings to the quest a lot of expertise in the realm of supernova observation. The High-*Z* Team's paper, submitted to the *Astronomical Journal* in March, is based on 16 type Ia supernovae.[2]

For both teams, the statistical errors are already smaller than the remaining systematic uncertainties: Can they be sure, for example, that particularly mischievous dust obscuration is not making the supernovae seem more distant than they really are? Has cosmological evolution made recent supernovae and their galactic environs significantly different from the ancient ones they see at high redshift? Is there an unintended bias in favor of atypically bright events?

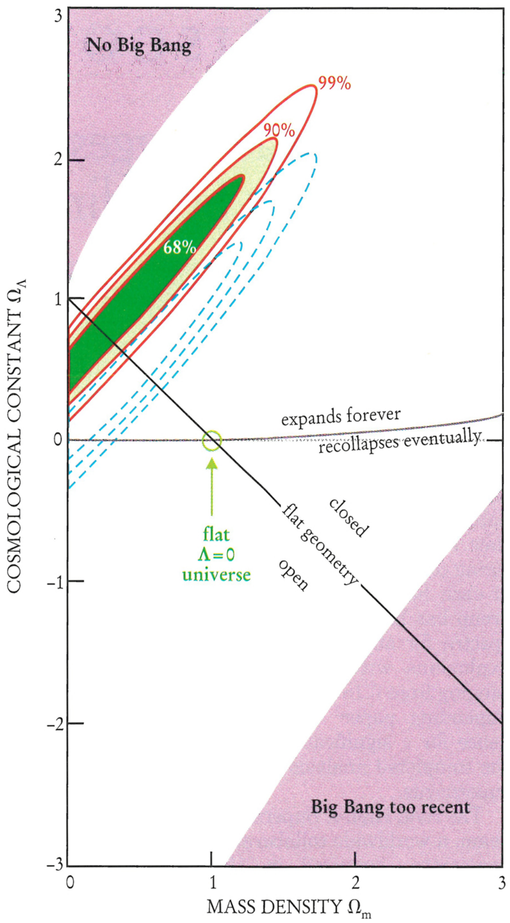
Why type Ia?

Type Ia supernovae are the brightest of all, and therefore visible at the greatest distances. Even more important is the fortunate fact that they, unlike other supernovae, are almost standard candles whose individual deviations from the mean peak luminosity of the class can be deduced from their light curves—the records of their sudden



HUBBLE PLOT of distance vs. redshift for type Ia supernovae. Distance is measured by apparent magnitude corrected for light-curve shape. The 40 high-*z* supernovae (shown orange) are from the Supernova Cosmology Project[1] and the 18 at lower-*z* are from Hamuy *et al.* Curves indicate predictions for different values of $(\Omega_m, \Omega_\Lambda)$. From bottom to top at the high-*z* end, they range from (2,0) to (0,1). (Adapted from presentation by Perlmutter *et al.* at Jan. 1998 AAS meeting, Washington, DC.)

PARAMETER PLANE of Ω_m and Ω_Λ is narrowed down (inside the red ellipses labeled by confidence level) by fitting to 40 high-z supernovae from the Supernova Cosmology Project.[1] Dashed ellipses indicate worst-case systematic error. The inflation requirement of flat geometry ($\Omega_m + \Omega_\Lambda = 1$) is indicated by the black diagonal. The purple curve curling up from $\Omega_\Lambda = 0$ separates eternal expansion from the Big Crunch.



waxing and ultimate waning: The intrinsically brightest ones take longest to decay after they peak. So by monitoring the apparent brightness of a type Ia supernova in the weeks before and after it peaks, one can deduce its distance with surprising accuracy. This calibration technique was pioneered by Mark Phillips of the Cerro Tololo Observatory in the Chilean Andes. He is now a member of the High-Z Supernova Search Team.

Aside from these light curves, one also needs to measure the supernova's spectrum, for a number of reasons. First of all, one wants to know the redshift. Fitting the precise dependence of z on distance is what reveals the cosmological parameters: the present Hubble constant H_0 at modest z, and ρ_0 and Λ, or something that simulates a Λ, at the higher redshifts.

Furthermore, it's the details of the supernova spectrum, particularly the absence of hydrogen lines, that distinguish type Ia supernovae. They are thought to be approximate standard candles because they manifest the explosion of spent white dwarf stars very close to the Chandrasekhar limit—1.4 solar masses.

One also needs z in order to take account of the relativistic time dilation of the calibrating light curve. "These light curves are, by the way, the clearest evidence ever of relativistic time dilation in a macroscopic system," says Berkeley group member Gerson Goldhaber. "It puts to rest the assertion one occasionally hears, that the large redshifts are 'tired light' rather than real Doppler shifts."

Search strategy

Type Ia supernovae are wonderful probes of the distant cosmos, but nature is stingy with them. A typical galaxy produces less than one per century, and they are fleeting. After rising to peak brilliance in the first few weeks after the explosion, they fade to obscurity after another month or so.

To garner enough high-z, type Ia events to observe evolutionary changes in the Hubble expansion, Perlmutter and company developed a routine that nowadays bags about two dozen in every semiannual observing cycle: Twice a year, just after a new moon, they record about 100 celestial patches with a CCD camera at the 4-meter Cerro Tololo telescope. Each such image contains almost a thousand high-redshift galaxies. Three weeks later, they image the same fields again and do a computer subtraction that points up any bright new point sources that weren't there before. Spectra of these new sources and their host galaxies are then taken at the 10-meter Keck telescope. Those that prove to be high-z, type Ia supernovae (the great majority) are then followed up for as long as possible by various large telescopes, to produce light curves in two colors. Recording the light curves in two colors provides a handle on any significant reddening of the supernova image by obscuring dust in the host galaxy or our own.

Schmidt and his collaborators collect their high-z supernovae in a similar way. For the very highest redshift events, both groups are able to avail themselves of the Hubble Space Telescope. "But we do a lot of things differently," says Robert Kirshner, leader of the High-Z Team's Harvard contingent. "That's good, because it means our data are independent. It strengthens the case that we've found out something about the universe, not just about filter systems."

The Hubble plot

For distances large enough so one can ignore local motion but not so large that one has to worry about a time derivative of the Hubble constant, a log–log plot of the distances of celestial objects against their redshifts should yield the straight line dictated by Hubble's law. If the objects are standard candles, one can replace distance by magnitude, an inverse logarithmic measure of apparent brightness.

The Hubble plot on page 17 shows just this expected linear relation for 18 type Ia supernovae with z between about 0.01 and 0.1. These moderate-redshift supernovae were measured several years ago by Mario Hamuy and colleagues at Cerro Tololo. Hamuy's type Ia supernovae were made to serve as pseudo-standard candles by correcting for the greater peak luminosity of the longer-lasting supernovae. So were the Berkeley group's high-redshift events, 40 of which are seen in this plot at z above 0.18.

Light that arrives redshifted by z is presumed to have left its source when the cosmos was $1/(1+z)$ of its present linear size. The precise departure time depends on cosmological details, but for $z = 0.5$, it's something like one-third of the way back to the Big Bang. Over such cosmological times one expects the Hubble plot to begin to depart from linearity. The most straightforward expectation is that gravity is the only player ($\Lambda = 0$), so that the Hubble plot will begin to curve downward with increasing z as we look farther and farther back to a time when gravity had not yet slowed the cosmic expansion to its present rate. The greater the present mass density of the universe, the more we expect the Hubble plot to curve downward.

But that's not what either group finds. Instead of curving downward with increasing z, their Hubble plots appear to be turning subtly upward, suggesting that the cosmic expansion has been accelerating, at least in the epoch since $z = 1$. Even if one assumes that the mean mass density of the universe is much smaller than anyone believes, the data still seem to require the repulsive agency of a positive cosmological constant or some nonconstant dynamical property of the vacuum that simulates it in the present epoch.

Geometry and destiny

If one ignores, for the moment, anything more complicated than a cosmological constant, the observational evidence is best summarized in the parameter plane of Ω_Λ versus Ω_m, which are conveniently normalized, dimensionless measures of the cosmological constant and the present mean mass density, respectively. (See the figure on page 18.) Ω_m is ρ_0 divided by $3H_0^2/8\pi G$, the "critical" mass density required now to bring the Hubble expansion asymptotically to a halt after infinite time, in the absence of a cosmological constant. Ω_Λ is $\Lambda c^2/3H_0^2$.

The sum $\Omega_m + \Omega_\Lambda \equiv \Omega_T$ determines the spatial geometry of the cosmos in general relativity. If $\Omega_T = 1$ (the diagonal black line in the figure), space is flat on the cosmological scale. This flatness is, in fact, what the widely accepted "inflationary" version of Big Bang cosmology dictates. Above that diagonal, the cosmic geometry would be closed, like the surface of a hypersphere. Below it, we would have a geometrically open cosmos, with a negative curvature like that of a saddle.

When considering the possibility of a cosmological constant, it is important to distinguish between the spatial geometry of the cosmos and its *dynamical* fate. A geometrically closed universe can nonetheless expand forever, just as an open one can recollapse in a final Big Crunch. These two fates are divided by the purple line in the figure. At low mass density, any positive Ω_Λ forces the cosmos to expand forever. But above the critical mass density ($\Omega_m = 1$), the cosmological constant required for eternal expansion grows with increasing density.

Contours of confidence

How do the supernova observations constrain all this eschatological speculation? Fitting Ω_Λ and Ω_m to the Hubble plot of their 40 high-Z supernovae plus the lower-z Hamuy events, the Perlmutter group arrived at the region of the parameter plane inside the nested red ellipses that indicate various confidence levels. The dashed blue ellipses indicate the group's estimate of the worst-case scenario of maximal systematic errors all ganging up in the same direction. Schmidt and company have arrived at very much the same result, with slightly fatter ellipses because of their lower statistics. But their estimate of a possible sytematic error due to dust extinction is smaller than Perlmutter's.

Both groups conclude that the point ($\Omega_m = 1, \Omega_\Lambda = 0$), heavily favored until recently by most theorists, is strongly excluded by the fits. The theorists favored this point because they liked inflation and disliked the cosmological constant. If one continues to believe in inflation, the best fit on the $\Omega_T = 1$ diagonal is something like ($\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$), and the "deceleration parameter" $q_0 = (\Omega_m/2) - \Omega_\Lambda$ is clearly negative, implying that the Hubble expansion is in fact speeding up.

Theoretical aversion

Why have theorists shied away from the cosmological constant? Quantum field theory yields vacuum energy density terms on the order of the reciprocal square of the Planck length—10^{-35} meters. That corresponds to a cosmological constant more than 100 *orders of magnitude* larger than is permitted by the simple fact that we can see distant galaxies. For such enormous terms to yield a small sum is, the argument goes, an absurdly improbable case of fine tuning—unless the cosmological constant is forced by some higher principle to vanish identically.

Theorists are also leary of temporal coincidence: If Ω_m is less than 1 now, it will get very much smaller as the universe continues to expand. At the same time, Ω_Λ will continue to grow. Is it plausible, they ask, that we just happen to be living in the brief epoch when the two competing cosmological parameters are comparable?

That's why speculative dynamical alternatives to a cosmological constant were much in evidence at the May Fermilab workshop. The negative pressure indicated by the supernova observations need not have the spatial and temporal constancy of Einstein's Λ. If it is due to something dynamical, like a tangle of light cosmic strings, a frustrated topological defect or a current epoch of mini-inflation, one can hope to find a good reason for its present level without invoking unseemly coincidence. "It would confront us with some really new and interesting physics," says University of Pennsylvania theorist Paul Steinhardt.[3]

An underdense universe

In the last few years, a variety of observations have been pointing toward an Ω_m well below 1, but not so small as to make nonbaryonic dark matter unnecessary. Neta Bahcall's Princeton group, for example, arrives at an Ω_m of about 0.3 by counting large clusters of galaxies as a function of redshift.[4] But getting a handle on Ω_Λ has been much more difficult. In fact, some cosmologists have used the low measured values of Ω_m as an argument against inflation, which requires that $\Omega_m + \Omega_\Lambda = 1$. That's one reason why the new high-z supernova results are receiving such attention.

The much anticipated MAP (Microwave Anisotropy Probe) orbiter, scheduled for launch two years from now, should be quite helpful in this regard. (See PHYSICS TODAY, November, page 32.) MAP will be particularly sensitive to the sum $\Omega_m + \Omega_\Lambda$. Thus it should nicely complement the supernova searches, whose greatest sensitivity is to the *difference* $\Omega_m - \Omega_\Lambda$, as one can see from the orientation of the confidence ellipses in the figure on page 18.

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Are Stripes a Universal Feature of High-T_c Superconductors?

Do the spins and charges associated with copper and oxygen atoms in high-temperature superconductors arrange themselves in orderly rows in the copper oxide plane? Recent studies suggest that not just one but several families of the cuprates may feature such stripes, although in most cases the stripes are not static but fluctuate with time and position.

As if the superconducting copper oxides weren't mysterious enough, experiments within the past decade have revealed a magnetic structure—at least in members of the lanthanum strontium copper oxide family—whose period is different from that of the underlying lattice. One explanation that has attracted increasing attention is the possibility that stripe phases may form spontaneously when experi-