New Light on Fate of the Universe

Exploding stars seen billions of light-years away have given a preliminary verdict: The universe may be doomed to expand forever

In the flash of stellar explosions seen halfway back to the big bang, two groups of astronomers have read clues to the future of the universe. With the orbiting Hubble Space Telescope and ground-based observatories, they have analyzed light from these remote cataclysms to estimate their distances and determine how fast the stars were rushing away from Earth billions of years ago when they exploded. Their goal is to learn how the universe's expansion rate has changed over time—whether it has been slowed by gravity, or perhaps boosted by large-scale repulsive forces. The groups, longtime rivals, have been working independently, but their results agree: The universe's expansion rate has slowed so little that gravity will never be able to stop it.

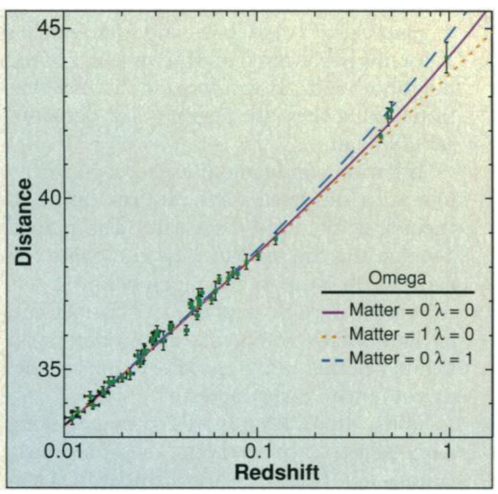
The new results imply that the universe contains far less mass than many theorists had hoped: less than 80% of the amount that would be needed to slow its expansion to a halt, and perhaps far less than that. The results even leave open the possibility that a so-called cosmological constant—a hypothetical property of empty space that might generate repulsive forces—is at work, giving the universe an expansive antigravity boost. "The results are very exciting and the method is very promising," says Neta Bahcall of Princeton University.

Bahcall points out that the small numbers of stellar explosions, or supernovae, analyzed by the groups mean that the conclusions are not definitive. But the agreement between the two results, coming on the heels of other hints of a low-density universe, has many cosmologists taking them seriously. And because the supernova technique directly measures how the makeup of the universe is affecting its evolution, says astrophysicist Michael Bolte at the University of California, Santa Cruz, "I think this is the surest way to make some of these measurements."

GARNAVICH ET AL./HIGH-Z SUPERNOVA SEARCH TEAM

Distant fire. A supernova and its host galaxy at the center of this Hubble Space Telescope image are shown enlarged at upper right.

Both groups stress that they need to analyze more supernovae to reduce the uncertainty in their results, reported in two just-completed papers. One of the papers, by the Supernova Cosmology Project led by Saul Perlmutter of Lawrence Berkeley National Laboratory and the University of California, Berkeley, is in press at *Nature*. The other, by the High-Z Supernova Search Team led by Brian Schmidt of Mount Stromlo and Siding Spring Observatory in Australia, was under review at *Astrophysical Journal Letters* as *Science* went to press but is publicly available on the Los Alamos National Lab electronic preprint server (http://xxx.lanl.gov).



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Trend setters. The relation between distance and redshift (recession velocity) for the four most distant supernovae suggests a low-mass universe.

If the results hold up as the groups add more supernovae to their samples, they could have a major impact on how theorists picture the universe's first few moments. Already, as word of these developments makes its way through the astrophysics community, the findings are adding to a growing sense that the simplest version of the reigning cosmic creation theory, known as inflation, may not work. Inflation traces key features of the universe to a burst of exponential growth in the first fraction of a second after the big bang, and its simplest version predicts a universe that contains just enough matter for gravity to stop the big-bang expansion after an infinite time—a mass density that would make the large-scale geometry of space-time "flat."

"What we are finding is that matter cannot be the only source of a flat universe," says Peter Garnavich of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, lead author of the High-Z Supernova Team's paper. The results still leave an opening for some theories in which matter plus its equivalent in energy, supplied by the cosmological constant, add up to a flat universe. But that picture is far less palatable to most astronomers. "If I were a theorist, I'd be getting worried at this stage," says Alexei Filippenko of Berkeley, a co-author on the Garnavich team's paper.

Candles in the dark

Both groups are looking for clues to the fate of the universe by extending a simple line, which plots the distance of far-off objects against their velocity as they are swept from Earth by cosmic expansion. Nearby, within a few hundred million light-years, astronomers already know that the line is straight. The recession velocity of galaxies increases steadily with distance from Earth, implying that space itself is expanding at the same rate everywhere. But objects seen at greater distances, billions of light-years away, emitted their light much earlier in cosmic history. The line should subtly bend at great distances, and the bending should reveal how gravity or a cosmological constant has changed the expansion rate over time.

Measuring how fast an object in the distant universe is flying away from Earth is straightforward: Just determine the "redshift" of its light, a stretching of its wavelengths analogous to the drop in pitch of a receding train's whistle. Measuring distance is another matter, requiring objects that can be seen far out in the universe and have a roughly constant intrinsic brightness, so that their apparent brightness can be taken as a distance indicator. That's where the exploding stars called type Ia supernovae enter the picture.

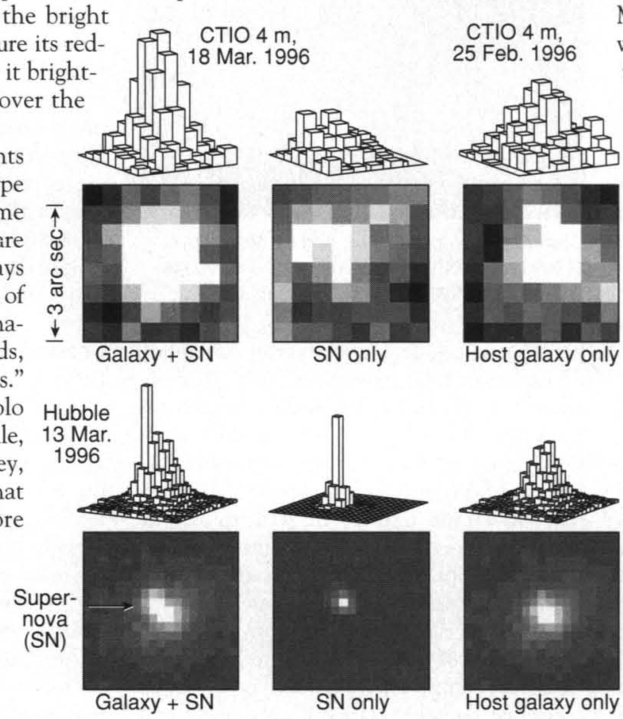
Type Ia's are thought to be white dwarf stars that suck material from a companion star until they blow up as a star-sized hydrogen bomb. "They're very bright, so you can see them across the universe," says Michael

Turner of the University of Chicago. And because white dwarfs all have about the same mass, all type Ia's should have roughly the same intrinsic brightness, turning them into appealing "standard candles."

Both teams now have identified dozens of type-Ia supernovae in the distant universe using an efficient discovery technique developed by the Perlmutter group. Researchers compare survey images of the same regions of sky, made weeks apart. A computer "subtracts" one image from the other, and any new point of light in the hundreds of galaxies in each image pair jumps out. Then the teams go to large ground-based observatories like the 10-meter Keck Telescope in Hawaii or, lately, to the Hubble Space Telescope. There they confirm that the bright spot really is a new type Ia, measure its redshift, and record its light curve as it brightens to a peak and then declines over the following months.

Collecting those measurements is just the beginning. Because type Ia's don't reach exactly the same peak brightness, "they certainly are not ideal standard candles," says Mario Hamuy of the University of Arizona, a co-author of the Garnavich paper. Fortunately, he adds, "we can correct for the variations." Mark Phillips of the Cerro Tololo Inter-American Observatory in Chile, co-author Adam Riess of Berkeley, Hamuy, and others have shown that the "light curve" declines more slowly for intrinsically brighter supernovae. By studying about 30 nearby supernovae, Hamuy and Riess tightened up the relationship so that observers can use it to correct each new supernova's brightness.

Both groups have used these data to calibrate their supernovae. They also have had to beware of other factors that might prevent the explosions from serving as perfect standard candles—for example, the dimming of their light by interstellar dust between a supernova and Earth. "You spend a lot of time making sure you get [the corrections] right," says Perlmutter of the Berkeley Lab.



Unblurring a supernova. Compared to a ground-based telescope *(top)*, the Hubble Space Telescope does a much better job of sorting a supernova's light from that of the host galaxy.

SOURCE: PERLMUTTER *ET AL.*; DONAHUE *ET AL.*

Last year, Perlmutter and his colleagues in the Supernova Cosmology Project finally worked through the corrections for a handful of supernovae observed from the ground. The supernovae had redshifts of up to about 0.4—a few billion light-years away. When the researchers plotted brightness against distance, the line had a slope that was broadly consistent with a flat universe, containing a full complement of matter (*Science*, 4 April, p. 37). But the game changed just after those results became public, when both teams were granted observing time on the Hubble.

"The Hubble is a much more precise instrument than ground-based telescopes for measuring these light curves," explains Gerson Goldhaber of Berkeley and the Berkeley Lab, a co-author of the *Nature* paper. Hubble observations of a supernova over its months-long fade aren't plagued by moonlight scattered in the atmosphere. And Hubble's high resolution makes it much better at separating the light of a supernova from the shine of its host galaxy.

Universe without end

When the Supernova Cosmology Project added just one Hubble supernova to its sample, at a redshift of 0.83 (a distance of roughly 7 billion light-years), the future of the universe began to look different. The data are now most consistent, says Perlmutter, with a universe containing far less than the critical density of matter. If the universe is flat, matter may account for only 40% to 80% of the critical density, with the cosmological constant making up the rest. If the universe lacks any cosmological constant, the supernovae imply that the mass density of the universe, known as omega-matter, is still lower, and the universe is destined to expand forever.

Those conclusions match those of Garnavich and his colleagues, who analyzed Hubble observations of three type Ia's—the most distant at a redshift of 0.97—and one seen only from the ground. Their analysis suggests still lower mass densities for a flat universe (10% to 70%), but the error bars for the two sets of results easily overlap. "The fact that we're coming out with [omega-matter] numbers that are pretty consistent and low is very exciting," says Filippenko of Berkeley.

Even so, Perlmutter says, kernels of doubt remain. Although the spectrum from his most distant event is "strikingly similar" to those of nearby supernovae, he says, the mix of galactic environments may have been quite different at those remote times. Such differences might have an effect on the relationship between the light curve and the peak brightness. And then there are the small numbers of supernovae behind the conclusions. Four Hubble events, says Berkeley's Marc Davis, who was not involved in the work, "are not enough to define the solution to a long-standing cosmological puzzle."

But Davis adds: "I think it's fairly clear this is going to be the way to do it." Chicago's Turner agrees: "For me, the exciting thing is what's to come. We have a very promising standard candle, and we have two groups [using] it; this is the tip of the iceberg." The teams say they are seeking more Hubble time and now are analyzing many more ground-based observations.

And it escapes no one's attention that these first conclusions fall broadly in line with an increasing number of other observational hints that the cosmic mass density may be low. One of the most recent appeared in the 20 August *Astrophys. J. Lett.*, where Princeton's Bahcall and two colleagues showed that massive clusters of galaxies have changed little over recent cosmic history, implying that large-scale gravitational forces are feeble and pointing to a matter density of just 40% of the critical value. Other hints of a low-density universe emerge from computer simulations of how different mass densities would affect the formation of giant clusters of galaxies, and from searches for invisible dark matter in our cosmic neighborhood. "If you look at the observational data, they all suggest a low density," says Bahcall.

Inflation can be modified to cope with a low-mass universe, says Andrei Linde, a theorist at Stanford University who helped develop the theory. But "at some point you can't patch a theory too much before it gets too ugly to accept," says Bolte of Santa Cruz. "That's what's going to come under fire, I think: whether inflation is the correct model or not for the early universe."

With those debates still to come, along with plenty more supernovae, "it's early times, my friend," says Princeton University's Jim Peebles. "You shouldn't start paying off your bets."

–James Glanz