Closing In on Cosmic Expansion

Supernovas, giant stellar explosions visible far out in the expanding universe, may finally be breaking a decades-long impasse over the elusive Hubble constant

The battle, apparently endless, has been a growing embarrassment. Ten years ago, John Maddox, the editor of *Nature*, lamented that cosmologists could not agree how fast the universe is expanding and hence how old it is. "The only remedy," Maddox concluded, "is the old remedy, more data." Since then, cosmologists have gathered a great deal more data. But as recently as this summer, the dispute still seemed irremediable.

One camp favored a slow expansion, which would imply that the universe has been slowing down for about 15 billion years since the big bang. The other argued for an expansion nearly twice that fast and a universe barely 8 billion years old—a figure with the alarming implication that the universe is younger than its oldest stars. Once again, Maddox wrote that the "two distinct and discordant" measurements were still "a source of acute embarrassment to cosmologists" and that "more data are the obvious solution." Maddox may not have to offer the same prescription yet again.

What could break the impasse are the stellar explosions called Type Ia supernovas. "Until the Ia's," says Bradley Schaefer, an astronomer at Yale University, "there was no sign of convergence in the field." Visible far out in the universe, Ia supernovas are an appealing "standard candle" for gauging cosmic distances—a prerequisite for measuring expansion. But although "Ia's had a lot of promise," says Schaefer, "they hadn't lived up to it." To use these standard candles, astronomers needed to know their absolute brightness and how much it can vary from supernova to supernova, and these measures have been hard to pin down.

Now, thanks to a flurry of new supernova observations and theoretical calculations, astronomers believe they know enough about Ia's to extract a reliable measure of the universe's expansion. And, in the hands of half a dozen different groups, the supernovas are yielding consistent results. If these groups are right, cosmic expansion actually proceeds at a seemly rate, midway between the extremes, and the universe now owns up to being older than its children.

Even so, consensus may not come easily to a field with such a long history of dispute. The search for the expansion rate began in 1929, when the astronomer Edwin Hubble found that light from other galaxies is displaced toward the red end of the spectrum, implying that they are all moving away from us. The fainter a galaxy, and hence farther away, the higher its velocity. Hubble's own estimate of the cosmic expansion rate—now known as the Hubble constant—was 500 kilometers a second per megaparsec (3.26 million light-years).

Astronomers now agree that Hubble's estimate of his constant was far too high. They have agreed on little else, however; some have put the constant near 50, others near 100. What fuels the disagreement is that while a galaxy's speed is easy to determine from its redshift, its distance—the other factor needed to calculate the Hubble constant—is less a measurement than a convoluted chain of logic. Astronomers reckon distance by comparing a star or galaxy's apparent brightness to its true brightness. Then, by knowing how brightness fades with distance, they calculate distance.

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Showy star death. Ia supernovas flare near distant galaxies. Supernova 1972E is shown above *(below galaxy)*; at top is SN 1994ae.

The problem is, observers can't actually measure an object's true brightness, and so they have searched for standard candles: types of stars or galaxies with one standard, inborn brightness. Astronomers have tried a host of different indicators, but until now, the only certified standard candle has been a kind of star called a Cepheid variable. Cepheid variables are giant stars near the ends of their lives, rhythmically puffing and shrinking so that their light brightens and dims. The longer the period of brightening and dimming, the greater the star's intrinsic brightness. The relation between period and brightness has been refined for the last 85 years, and by now, says Abhijit Saha of the Space Telescope Science Institute, "There's no dispute over the Cepheid distances." Allan Sandage of the Carnegie Observatories has been measuring Cepheids for decades and arrives at a Hubble constant in the 50s.

But Sandage's work has not settled the question, because Cepheids are visible only in relatively nearby galaxies. Like all galaxies, the Cepheids' home galaxies are tugging on each other gravitationally, generating "peculiar" motions. Because these galaxies are nearby and their velocity due to cosmic expansion is low, their peculiar motions are hard to sort out from the cosmic expansion. Last year, two teams studying Cepheids did try to get a measure of the expansion rate outside our cosmic neighborhood, out in what is called the Hubble flow. But their results only heightened the controversy.

Both teams—one led by Wendy Freedman of the Carnegie Observatories and the other by Michael Pierce of the University of Indiana—measured Cepheids in the nearby Virgo cluster of galaxies, which enabled them to fix its distance. Another galaxy cluster, Coma, is known from independent evidence to lie some six times farther away than Virgo; using that distance ratio, the two groups measured the Hubble constant out to the Coma cluster. The result: a constant in the 80s, sharply at odds with the Sandage team's result (*Science*, 28 October 1994, p. 539).

Standard bombs

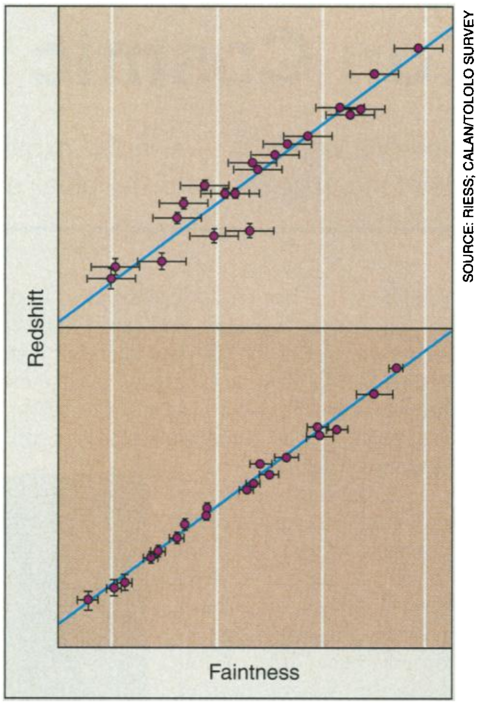
Even while the Cepheid battle was raging, Type Ia supernovas seemed to promise a more direct reading of the expansion rate. Ia's begin as a star, called a white dwarf, which has burned out and contracted to an extreme density. White dwarfs are limited by the rules of atomic physics to a mass no larger than 1.4 times that of our sun; any larger, and they collapse into superdense objects known as neutron stars. But some white dwarfs have companion stars, and every so often, a white dwarf leaches mass from its companion until it barely exceeds the 1.4 solar mass limit, collapses even further, and then blows up. Twenty days later, at the explosion's peak, the supernova is more than a hundred thousand times brighter than a Cepheid and is visible hundreds of times farther away. Because Ia supernovas start off with the same mass, they should reach the same brightness. Sandage calls them "standard bombs."

But no matter how consistent these explosions are, astronomers couldn't use their apparent brightnesses to measure distance without also knowing their intrinsic brightness. In 1992, Sandage had made an early effort to determine it. He and his collaborators used the Hubble Space Telescope (Hubble's name is all over this problem) to find Cepheids in several nearby galaxies in which Ia supernovas had also appeared. The team measured the Cepheids' distances, assumed similar distances for the Ia's, and used the apparent brightness of the Ia's to calculate their intrinsic brightness. Those intrinsic brightnesses let them extract distance from fainter, more distant supernovas and come up with a value for the Hubble constant: in the mid- to upper 50s.

Supernovas are rare in any one galaxy, however, and the six Ia's that Sandage's team calibrated had actually exploded years or decades before. Astronomers of the day had captured them on photographic plates, but, says Schaefer, "the photometry was outdated and cruddy, and the measurements disagreed by a factor of 2 in brightness." Recently, Schaefer went back to original plates for five of the supernovas, remeasured their apparent brightnesses, and then compared them to other stars on the plate, which still shine and can be measured. He then corrected the intrinsic brightness figures and applied them to other supernova data to come up with a cluster of Hubble constants: "Three in the 50s," he says, "one 65; the best is 63."

Earlier this year, David Branch, an astrophysicist at the University of Oklahoma, and his colleagues took a different approach to supernova brightness: calculating it instead of deducing it from measurements. Because lines in the spectrum of an expanding object are broadened by the Doppler effect, Branch and his colleagues could clock a Type Ia's expansion from its spectrum. Multiplying the expansion rate by the time from explosion to maximum brightness gave the Ia's radius. And from the radius and the temperature of the gases—indicated by the relative intensities of spectral lines—Branch and his colleagues could calculate how bright the Ia actually was.

As an independent check on that result, the group calculated the supernova's complement of nickel-56, a radioactive element made in large quantities by the explosion. They based their calculations on the intensity of the spectral lines produced by cobalt and iron—the decay products of the nickel-56. Because, as Branch puts it, "the radioactivity is what shines," working back to the nickel let them calculate the supernova's



Supernovas all in a row. Scatter in a plot of apparent brightness against redshift—relative distance—shows that Ia supernovas are not perfect standard candles *(top)*. Correcting for differences in their rate of dimming, however, refines the brightness-distance relationship.

absolute brightness. Since then, Peter Höflich at Harvard and Alexei Khokhlov at the University of Texas, Austin, have made more detailed nickel-56 calculations and arrived at much the same absolute brightness.

Not only do both computational approaches give the same absolute brightness, but this brightness is the same one the Sandage team finds by calibrating Ia's against Cepheids. Branch accordingly gets about the same value as Sandage's team for the Hubble constant, around 60 or a little lower; Höflich and Khokhlov's constant is a little higher, around 65. "There are two ways to understand brightness," Branch says, "and when they agree with each other and with Sandage's Cepheids, I get convinced."

Perfecting a standard candle

For Ia's to be accepted as reliable standard candles, however, astronomers need to know not only their absolute brightness, but also how it varies from one supernova to another. And astronomers at the Cerro Tololo Inter-American Observatory (CTIO) in Chile and the University of Chile found in a 1992 to 1994 supernova survey that these standard bombs aren't absolutely identical. After observing 27 Ia's, the group plotted the maximum apparent brightness of each supernova against its redshift. The points didn't all lie along a straight line, as they should if the supernovas were perfect standard candles.

But the CTIO team also found a way to compensate for the brightness differences: They learned that the brighter a Ia supernova is, the more slowly it declines. To make a supernova into a true standard candle, says Mark Phillips of CTIO, "just measure the speed of the decline and correct for the difference in brightness." A second team—Adam Riess, William Press, and Robert Kirshner of the Harvard-Smithsonian Center for Astrophysics (CfA)—applied a different statistical model to some of CTIO's supernovas to correct the brightnesses. And when both teams take their results and plug in Sandage's Cepheid-calibrated distances, says Kirshner, "we agree pretty well." CTIO gets a Hubble constant of about 61 or 62; CfA's constant is about 66 or 67.

All this agreement has astronomers who work on the Ia's uncharacteristically united in their enthusiasm. "Ia's were made for distances," says Branch. "Ia's are one of the very best distance-measuring tools in astronomy," says Kirshner. "Ia's really and truly give you distances," says Schaefer. And because those distances lie out of our neighborhood and into the Hubble flow, the supernova observers believe the Hubble constants they are coming up with stand a good chance of being close to the true value.

Even some astronomers who have found higher values for the constant are impressed. "The supernova results sound encouraging, very promising," says Freedman. But she adds that "with just one method, you can't tell if it has systematic errors." The true value, say Freedman and others, may still await the completion of Hubble Space Telescope's Key Project, which aims to calibrate all the distance indicators against each other: Cepheids, Ia's, and other, more error-prone methods.

If in the end the Ia's are right, and the universe is expanding at 55 to 65 kilometers a second per megaparsec, astronomers will have escaped from an uncomfortable problem. A higher Hubble constant, 70 or 80, would mean the universe could be as little as 8 billion years old. The oldest stars, dated by the amount of heavy elements they have produced, are 12 billion years old or more. The discrepancy has been made much of in the press, with some commentators even suggesting that it casts doubt on the big bang origin of the universe. With the Ia's converging between 55 and 65, however, the universe could be as old as the oldest stars, and the big bang is home free.

That resolution would come none too soon for observers outside the debate, who have seen it shift back and forth for decades. Says one astronomer who declined to be named, "I wish all these people would just shut up and go away and not come back until they know the answer." He may not have long to wait.

–Ann Finkbeiner

Ann Finkbeiner's forthcoming book is on the effects of parental bereavement.