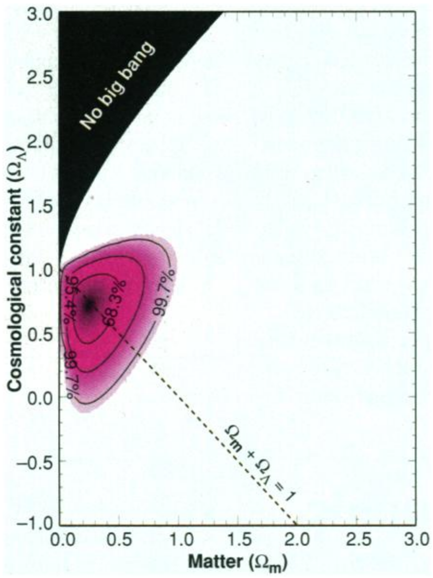
ASTRONOMY

Exploding Stars Flash New Bulletins From Distant Universe

In just the past few months, astronomers have glimpsed an extraordinary new picture of the universe in the glare of the cosmic flashbulbs called supernovae. Everyone from theoretical physicists to philosophers of science is struggling with the startling implication that emerged after observers laboriously discovered and studied scores of these distant, exploding stars: A mysterious repulsive force has been at work over billions of years, counteracting gravity and speeding up the cosmic expansion rate (*Science*, 27 February, p. 1298; 30 January, p. 651). Now the light of these same supernovae is adding some intriguing new details to this picture.

After further analyzing their observations of how fast these beacons are rushing away from Earth, the two teams that made the original discovery are now ready to report a cascade of new findings about how the universe behaves both in our own cosmic neighborhood and over the largest scales. They have found evidence that we might live in a "Hubble bubble"—a region that is expanding slightly faster than the universe as a whole. They have also picked up clues to just what kind of energy might be filling space and causing the acceleration and have offered a preliminary assessment of the universe's total density of energy and matter. "We have a tool that can be used to approach cosmology from another angle," says Saul Perlmutter of Lawrence Berkeley National Laboratory and the University of California, Berkeley, the leader of one of the teams. Perlmutter's team has squeezed yet another finding from the supernova data: large-scale confirmation that time itself runs slower when objects—in this case, the supernovae—are traveling at a large fraction of the speed of light because of the expansion of the universe.

Both the Perlmutter group and the other team, the High-z Supernova Search Team led by Brian Schmidt of the Mount Stromlo and Siding Spring Observatory in Australia, stress that the data are far from conclusive for most of these claims. But the findings testify to the power of so-called type Ia supernovae as cosmic probes. These exploding white dwarf stars all blow up with nearly the same brightness, acting as "standard candles," whose apparent brightness as seen from Earth can be translated into distances. The supernovae can be seen across most of the visible universe, at distances corresponding to earlier times in cosmic history.



SOURCE: GARNAVICH *ET AL.*/HIGH-Z SUPERNOVA SEARCH TEAM

It all adds up. Analyses of supernovae and the microwave background suggest that the universe's total matter and energy density, or omega (Ω), equals one.

By plotting the distances of the supernovae against the speed at which expansion is carrying them away from Earth—easily found from the redshift, or stretching, of their light—astronomers can see how cosmic expansion has changed over time. For nearby supernovae, that plot is nearly linear, implying no change in the expansion rate, or Hubble constant. Farther away the line subtly bends in a direction that shows the expansion has accelerated since the light was emitted.

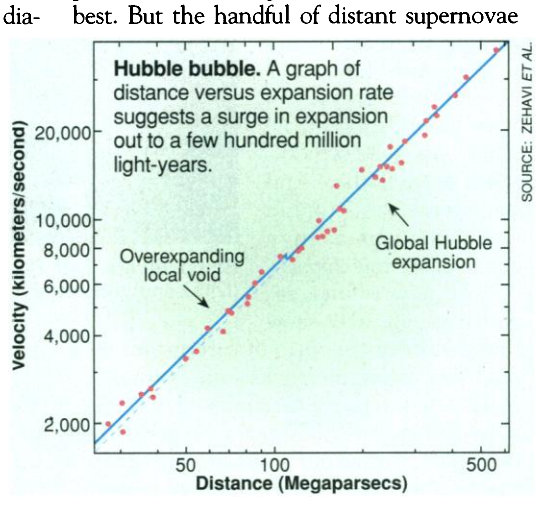
Last year, the Perlmutter team concluded from such "Hubble diagrams" that the universe is expanding roughly uniformly around us on scales of billions of light-years. But Idit Zehavi and Avishai Dekel of The Hebrew University in Israel and Adam Riess of Berkeley and the High-z team noticed a slight shift in the diagrams at a few hundred million light-years or so from Earth. They say the shift may indicate that our region is expanding about 6% faster than the universe at large.

The location of the shift caught their eye: It corresponds to the distance of several large agglomerations of galaxies, including the so-called Great Wall, discovered in the 1980s by Margaret Geller and John Huchra of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts. Zehavi, Riess, and Dekel, along with CfA's Robert Kirshner, think the gravitational pull of the mass concentrated at the borders of our cosmic neighborhood might help speed up cosmic expansion locally by tugging galaxies outward toward the Great Wall, resulting in a more tenuous region in which our own galaxy sits.

The group's paper, to be published in the *Astrophysical Journal*, should be regarded as "a preliminary discovery paper," says Dekel. "It may still be a statistical fluke." But if the 6% bubble doesn't burst, says Edwin Turner of Princeton University, then techniques that measure the Hubble constant using nearby objects, such as variable stars, "might be giving the right value but not the true, global value." That might help explain what some astronomers regard as a persistent, nagging discrepancy between those techniques and ones that measure the constant from distant beacons like supernovae. Wendy Freedman of the Carnegie Observatories in Pasadena, California, who specializes in measuring the Hubble constant, isn't yet persuaded that the Hubble bubble can explain the differences but is still intrigued. "There are very few methods that have the kind of promise this does for attacking the problem," she says.

Peter Garnavich of CfA and his colleagues on the High-z team are looking much farther out along a Hubble diagram based on 16 supernovae recently analyzed by Riess and others. The exact shape of the curve in the diagram should reflect just what kind of energy is at work on large scales, giving a boost to the expansion. Garnavich and his colleagues are comparing the data to the curves expected from the cosmological constant—an effect first postulated by Einstein—and from other forms of background energy, which theorists have named quintessence or X-matter. Although no one knows just what physical processes might produce these forms of energy, they would behave differently. The cosmological constant would deliver an unchanging push, while quintessence and X-matter could have varied over time, and energy from quintessence could actually flow and bunch up, affecting different parts of the universe differently.

So far, says Garnavich, the unrelenting push of the cosmological constant fits the data best. But the handful of distant supernovae



Hubble bubble. A graph of distance versus expansion rate suggests a surge in expansion out to a few hundred million light-years.

SOURCE: ZEHAVI *ET AL.*

observed so far "certainly doesn't do much in restricting what exactly the [form of the] quintessence is." The most that can be said, he explains, is that one form of quintessence seems to be ruled out: defects in the fabric of space, called light nonabelian strings, that might have been left over from the big bang. The Perlmutter group is now analyzing 40 supernovae, which could give a clearer picture of the mysterious energy.

But whatever form the acceleration energy takes, there appears to be just enough of it to combine with matter and give the critical density of mass and energy that is predicted by leading theories of the big bang. To gauge the total, Garnavich, with CfA's Saurabh Jha and others, added the supernovae data to observations of the cosmic microwave background radiation, often referred to as the big bang's afterglow. Slight ripples in the background reflect conditions in the early universe and yield clues to basic cosmic parameters. The result is just the right density to make the universe geometrically "flat"—the kind of universe predicted by the simplest versions of inflation, the theory of how a sort of spark in the primordial nothingness could have set off the big bang.

Everything that researchers have concluded so far from these distant beacons rests on a crucial assumption: that the redshifts actually are caused by universal expansion. Most cosmologists don't question this assumption, but a few mavericks have proposed alternative explanations for the reddening of distant objects—for example, a sapping of the photons' energies as they traverse great distances.

Type Ia's offer a way to distinguish among these possibilities, because the physics of the explosions force them to brighten and dim on a predictable schedule. That "light curve" should appear to be stretched out for supernovae rushing away from Earth, because the light carrying news of later and later events would have to travel longer and longer distances.

By examining the light curves of about 40 supernovae, Berkeley's Gerson Goldhaber and others in the Perlmutter group found spectacular confirmation that they really are speeding away from Earth: Events that actually take a month on Earth were stretched to almost 7 weeks for the most distant of the supernovae. Although no one was surprised by the result, says Goldhaber, it's one more example of the light a standard candle can shed on the cosmos.

–James Glanz

ATOMIC PHYSICS

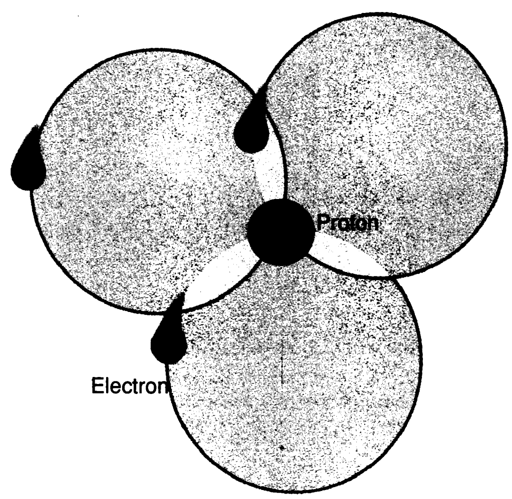
On the Trail of Supercharged Hydrogen

Hunters of exotic atoms usually make their forays to the furthest reaches of the periodic table, where they hope to bag big game by creating heavier and heavier elements. But a trophy may await physicists at the other end of the table, near ordinary hydrogen. New calculations suggest that with a laser's light touch, physicists may be able to create a hydrogen atom carrying two or more extra negative charges. If the feat can be done, it would open up new research avenues for using light to manipulate atoms.

As any chemistry student could tell you, hydrogen, the simplest atom, consists of an electron orbiting a one-proton nucleus. Researchers can vary hydrogen's charge by stripping the lone electron to leave a positively charged nucleus or by adding an electron to give the atom a negative charge. A hydrogen atom with two electrons repels additional electrons; that's why one would not expect to stumble across a hydrogen ion sporting any more than two. "Such ions don't exist in nature," says Harm Geert Muller of the Institute of Atomic and Molecular Physics in Amsterdam. Indeed, in a recent experiment, Lars Andersen at Aarhus University in Denmark shot free electrons at hydrogen ions with two electrons (H^-) but was unable to forge a beast bearing three. "We simply couldn't create such an ion," says Andersen.

Muller and colleague Ernst van Duijn, however, may have found a new way to foist two or even three extra electrons onto a hydrogen atom, to create H^{2-} or H^{3-}. The trick is to use intense laser beams, which contain powerful electric fields, to steer the extra electrons into wide orbits, essentially spreading out their charge. The electrons then "are able to take turns in occupying positions near the nucleus," says Muller.

It took some fancy computational footwork to arrive at that conclusion. In calculations compiled in Van Duijn's Ph.D. thesis, published by the institute last month, the Dutch duo developed a new way to calculate the diffuse shape of a hypothetical multielectron hydrogen ion. "We developed a computation method that specifically could deal with the shapes such an ion would take," says Muller. Their formulas showed that polarized laser light, whose photons vibrate in a preferred plane, could push the electrons into wider orbits. Such orbits would minimize the repulsive forces between electrons, allowing more than two to orbit the same proton. Some experts, however, are skeptical that this electron swarm would stick around a proton long enough for researchers to detect exotic hydrogen as an integral ion. "It could turn out to be an unrealizable phenomenon," says Chris Greene of the University of Colorado, Boulder.



SOURCE: E. VAN DUIJN / IAMP

Three's a crowd. Calculations suggest that a laser can force three electrons to orbit a single proton.

Muller and Van Duijn are plotting a strategy to prove their calculations right. The required lasers are available, says Van Duijn, but the challenge "is to get electrons and protons together in a laser beam." Lasers powerful enough to forge the ion only deliver ultrashort pulses, lasting up to 10^{-12} seconds. The brief illumination rules out the possibility of shooting free electrons at negative hydrogen ions. "Because of the short laser pulses, you have a very low probability for collisions," says Muller.

A way to skirt this problem may be to start out with a larger molecule, such as methane, and use a laser like a sniper to remove its electrons. This would trigger a "Coulomb explosion" in which repulsive forces rip apart the stripped-down, positively charged methane. "The trick will be to choose a laser of such an intensity that it allows three electrons to end up around one of the ejected protons," says Muller. One might then look for H^{2-} or H^{3-} with a photoelectron spectroscope, which could shoot photons into the ions and measure specific energies of electrons ejected by multielectron hydrogen. "This experiment is definitely on our Christmas list," says Muller. If they succeed, he adds, exotic hydrogen ions may be useful for, among other things, generating soft x-rays for probing molecular structure.

–Alexander Hellemans

Alexander Hellemans is a science writer in Naples.