Weighing the Universe

Astronomers are making inventories of the unseen mass in the universe to learn its composition and fate. They also want to test an elegant theory of its origin

The universe has been putting on weight lately, and astronomers, like anxious parents, are pleased to see it filling out. They have been searching for the unseen matter that seems to control the motions and organization of galaxies and will also determine the universe's fate—whether it will continue expanding to infinity or will ultimately recollapse. And in recent years, they have had an aesthetic reason for seeking extra mass: an elegant theory of the universe's first moments implying that it contains enough heft to poise it exactly on the borderline between a closed big-crunch universe and an open ever-expanding one. In short, astronomers these days want to weigh the universe to find out whether it is beautiful.

Armed with new techniques—from charting the motions of galaxies across vast tracts of sky to looking through gravitational lenses far out in the cosmos—astronomers are now finding at least some of the mass they have sought. They do not know the fate of the universe yet, but they are optimistic about finding an answer. "We can stop thinking about cosmological parameters as *gedanken*," says Saul Perlmutter of the Lawrence Berkeley National Laboratory, "and go out and measure them." Or, as Marc Davis of the University of California, Berkeley, puts it, "We're getting close to having an answer. That is kind of neat."

But to date, the answer is not as beautiful as many cosmologists had wished. Inflation, a theory that has been the backbone of big-bang theorizing ever since Alan Guth of the Massachusetts Institute of Technology (MIT) invented it in 1980, holds that the universe underwent a massive growth spurt just after the big bang and is now "flat." In the simplest model of the universe, that means the ratio of the universe's actual mass density to the borderline density between big crunch and infinite expansion—which astronomers designate as omega—is exactly one. But while cosmologists have been detecting more and more mass as they survey the universe on larger scales, with few exceptions they are not finding more than about a third to half of the critical amount, which leaves cosmologists, like the optimist or the pessimist staring at a glass of water, wondering if the universe is half full or half empty.

While some cosmologists remain confident that more dark matter will be found, a growing number are beginning to suspect that the universe will remain half empty. "Maybe we should stop insisting that the universe is a higher density when there is no evidence for it," says Davis. To save inflation, the theorists among them are tinkering with it, proposing new low-omega versions of the theory and even reintroducing one of the most notorious ideas in the history of cosmology: Albert Einstein's cosmological constant, which would flesh out the universe with energy instead of mass.

The problem begins at home, with the most familiar kind of cosmic stuff. Even with the 40 billion new galaxies implied by recent Hubble Space Telescope observations of the distant universe, luminous matter only amounts to about 1% of the mass needed to reach the critical density suggested by Guth's inflation theory. Calculations of how much matter must have been forged in the big bang suggest that the total amount of baryonic, or ordinary, matter could be several times larger than this paltry amount (see p. 1429), and some of the missing mass is turning up. For example, several teams of astronomers recently announced that about half of the Milky Way's dark halo—which is estimated to contain five or 10 times more mass than the visible part of the galaxy—might be accounted for by dim stars, giant planets, and other cosmic riffraff collectively known as MACHOS. And this has led some astronomers to conclude that the halo is probably made entirely of ordinary matter.

Matter deficit

But that's far from enough to fill the cosmologists' glass. And no matter how much ordinary matter turns up, the nucleosynthesis calculations imply that the total can be no more than between 5% and 15% of the critical density. That leaves the fate of the universe in the hands of whatever nonbaryonic dark matter may exist in the form of clouds of exotic elementary particles left over from the big bang. The larger the scale on which the universe is surveyed, the more of this elusive stuff there seems to be.

The Early Universe

The early universe isn't an empty canvas anymore. Not long ago, cosmologists could tick off on the fingers of one hand their certainties about how the universe began and evolved. They knew it had started with the big bang, they knew its age within a factor of 2, and they knew that at least some dark matter had influenced its architecture and motions. Most of the rest was the domain of theory. As cosmologist Craig Hogan of the University of Washington—himself a theorist—puts it, "theory was in such good shape 10 years ago because there were no observations."


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No longer. A battery of new telescopes, led by the Hubble Space Telescope and the 10-meter Keck Telescope—which has just been joined by a twin—together with new detectors and techniques, are filling in that canvas. By looking back to the most remote times or turning a keener eye on our own neighborhood, astronomers are getting the details about cosmic origins. Theorists must now contend with real measurements of its overall mass, its complements of ordinary and dark matter, and the structures, large and small, that took shape in its early years. There's much more to come. And as the stories in this Special Report show, reality can be bewildering.

–Tim Appenzeller

TONY TYSON

Darkness visible. Dark matter is one component of the mass in this gravitational lens, which refracts multiple images of a blue galaxy behind it.

Looking not at single galaxies but at rich clusters of them, astrophysicists see a haze of hot, x-ray emitting gas. Recent observations by the German ROSAT spacecraft have made it clear that this gas outweighs the stars in a cluster by a large factor, says Simon White at the Max Planck Institute for Astrophysics in Garching, Germany, who has been analyzing ROSAT data. And when astronomers calculate the total amount of mass that must be holding the gas in place, they find evidence of still more. These calculations typically point to an omega of 0.2 if clusters are representative of the cosmos as a whole, which would require at least some exotic, nonbaryonic dark matter.

These calculations may underestimate the amount of mass in clusters, however. For one thing, they assume that the clusters are in equilibrium, so that the gas is a good tracer of gravity, but many of them look irregular, as if they are still coming together. Moreover, the hot gas can only be seen at their cores, leaving much of their mass uncharted.

A more recent technique for weighing clusters, which doesn't depend on measuring the gas, may offer a way around these problems. It has its roots in 1990, when Tony Tyson of AT&T invented a way to determine the distribution of the matter in a cluster from the lensing effect of its gravity on light from faint galaxies that lie behind it. Two years ago theorist Nick Kaiser and his graduate student Gordon Squires at the University of Toronto added a twist to Tyson's scheme that allows astronomers to determine the total mass, and not just its distribution, in a cluster. The result has been an explosion of activity and a race to build large-format cameras that can take in the large expanse of sky a typical cluster fills. "We hope to push off into the suburbs of the clusters and stumble into a giant overdensity of dark matter not associated with galaxies," says Tyson, who dreams of a dedicated "dark-matter telescope."

Tyson has surveyed about 30 clusters of galaxies so far. Like his x-ray counterparts, he is finding that clusters contain a bigger fraction of dark matter than galaxies do, but not that much bigger. At large distances from the cluster cores, Tyson reports, the dark matter seems to be truncated. "We find less dark matter than we had thought," Tyson concludes. "Clusters have big halos, galaxies have big halos, but not enough to close the universe."

Advocates of an omega of one are not discouraged, however, for yet more dark matter may be hiding in structures that are even larger than clusters, which are typically 5 megaparsecs in diameter (about 16 million light-years). "Is there a more diffuse component of dark matter?" asks Carnegie Observatories astronomer Alan Dressler. "Only on scales of 10 megaparsecs or more would you see it. If you don't see it there, you're cooked."

The largest scale on which the universe has yet been weighed is some 100 megaparsecs. The region in question tilts slightly southward from twin conglomerations of galaxies in the constellations Perseus and Pisces, across a great void in Sculptor past our own Local Group of galaxies at the center, and through the nearby Virgo and Coma clusters to another great chain of galaxies in Hydra and Centaurus on the opposite side of the sky. This entire swath of sky, with its tens of thousands of galaxies, is on the move, sliding southward at an average speed—a "peculiar velocity," calculated by subtracting out the expansion of the universe—of 500 kilometers per second toward a gigantic and poorly mapped accumulation of galaxies hiding beyond the Hydra-Centaurus cluster.

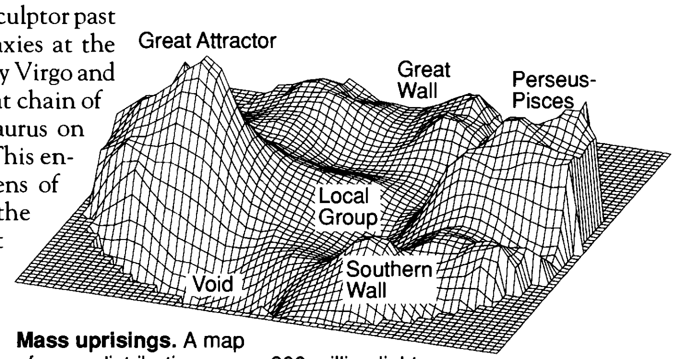
Dressler, one of a group called the Seven Samurai who discovered this cosmic migration 10 years ago, has dubbed this concentration the Great Attractor. Since then the flow's ebbs and surges have been mapped in detail by a varied assortment of observers who have among them compiled a catalog of distances and peculiar velocities for more than 3000 galaxies within the 100-megaparsec neighborhood. This river in the sky yields yet another means of weighing the universe.

As Avishai Dekel of the Hebrew University in Jerusalem points out, the Great Attractor itself is only one factor in the flow, which should be seen as the sum total of the smaller tugs that result from the uneven distribution of mass in this vast region of space. Dekel is the driving force in a shifting and expanding army of collaborators at a range of institutions attempting to use this insight to "weigh" the entire 100-megaparsec expanse.

Mapping mountains

One of their main weapons is a computer program called POTENT, invented by Dekel and Ed Bertschinger of MIT in 1989, which averages the velocities of individual galaxies in 12-megaparsec bins and replaces them with a continuous field, as if the galaxies were a kind of fluid flowing under the pressure of gravity. By a series of integrations and differentiations this flow can be transformed into a map of the mass density. "Velocities," explains Dekel, "are honest tracers of mass." The end result, now in its third incarnation, is a map of mountains and valleys of mass density that bears an encouraging resemblance to the clusters and voids in the distribution of galaxies themselves.

POTENT, however, can only measure the relative heights and depths of those hills and valleys; the whole cosmic mountain range could still be sitting on a plateau or in a depression of mass. To calculate absolute elevations—and thus measure omega—Dekel and his collaborators have to fit their map to the observed distribution of galaxies. The first time they did this, using a galaxy map derived from an all-sky survey done by the IRAS satellite, they got results consistent with values of omega near the magical unity, giving the flat universe a major boost. When these results were announced in 1991, David Schramm of the University of Chicago said, "This is the first evidence that omega really is one." Dekel is now in the midst of a new comparison of the density maps, using an improved third-



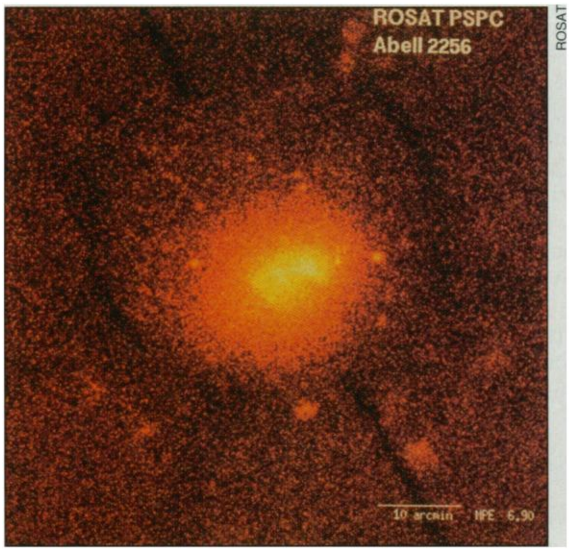
AVISHAI DEKEL

Mass uprisings. A map of mass distribution over a 300 million light-year region, compiled from galaxy motions, points to a high omega.

generation peculiar velocity catalog and a newer version of POTENT. He and his collaborators still get a high value for omega.

But there are many ways to play the omega game with cosmic flows. In a recent review Dekel listed about 20. Naturally they give conflicting results, ranging from an omega of 1.0 all the way down to 0.15. The last figure comes from outside Dekel's group, but "even in our own group there is disagreement," says Jeffrey Willick of Stanford University. For example, when Willick, Michael Strauss of Princeton University, and Dekel used an algorithm called VELMOD, which produces a finer scale velocity field than POTENT, to analyze a smaller, 30-megaparsec region of the flow, they got an omega of 0.3 to 0.55. "The dust has not settled," concludes Dekel.

The disagreements, Dekel says, may reflect a flaw in the assumption underlying most of these methods: that there is a simple relationship between the visible galaxies and the underlying, invisible mass, and that this relationship is the same everywhere in the universe. But the way in which light traces mass, the so-called bias factor, could vary by scale or environment. Some conceivable forms of dark matter—massive neutrinos, for example—would cluster on larger scales than do galaxies themselves, in which case they would not show up in small-scale motions. "Omega can change a lot if we have reason to believe the bias is different," says Willick.



Hot and hazy. X-ray–emitting gas that swathes a galaxy cluster traces the unseen mass holding the gas in place.

The one thing the results from POTENT and its descendants have in common is that they point to a greater mass density than do surveys done on smaller scales. "Everybody looking in one way or another gets 0.3 to 0.5, all very much higher than you get from the galaxy halos," summarizes Davis.

All but one, that is. A separate collaboration consisting of James Peebles of Princeton, Brent Tully of the University of Hawaii, and Ed Shaya of the University of Maryland used a slightly different data set of peculiar velocities and treated the galaxies as discrete point masses rather than as a fluid. They calculated the trajectories of "tracer" galaxies in a 30-megaparsec volume, jiggling omega until the predicted and actual positions of these galaxies statistically coincided to get 0.15 for omega. "If the measurements are right," says Peebles, "we have to get used to living in a low-density universe."

In spite of their success at finding more mass density as they take an ever wider view of the universe, more and more cosmologists are coming to agree with him. "I've been persuaded that omega probably is 0.2 or 0.3," says Dressler. Peebles recalls that people used to think he was being silly when he advocated a low-density universe. "Now I hear a lot of talk of low omega. Fashions move around; otherwise they wouldn't be fashions."

Einstein's blunder

Some flat-universe cosmologists are hedging their bets by adding a complication to their equations that was first introduced by Albert Einstein: the cosmological constant, denoted by the Greek letter lambda. Einstein inserted the constant—the most famous "fudge factor" in the history of science—into his cosmological field equations in 1917 as a long-range repulsive force to keep the universe from collapsing under gravity. He rejected it a decade later, calling it his greatest blunder, after learning that the universe was in fact expanding.

Einstein's blunder is now back in vogue for several reasons. First of all, modern quantum physics provides a basis for this repulsive force by predicting that empty space should be teeming with energy. Second, the boost that this repulsive force would impart to the cosmic expansion would allow the universe to be older than it appears from the expansion rate today, thus resolving a potential conflict between some measurements of the expansion and the age of the oldest stars. Finally, the vacuum energy density, like any other form of mass-energy, would increase omega to make the universe flat, as required by the latest versions of inflation theory. "Six years ago I gave a talk in which I said the best fit was a universe with a cosmological constant. I apologized up one wall and down the other," says Michael Turner of the University of Chicago and the Fermi National Accelerator Laboratory. "Six years later I gave a talk and said it was still the best fit, and nobody said it was a dumb idea."

Turner and the others emphasize that this time the cosmological constant is not a fudge factor, but rather a prediction that can be tested. In a universe with a substantial cosmological constant, the expansion would actually be speeding up instead of slowing down, as expected from mass alone. That effect can be detected by measuring yet another cosmic number known as the deceleration parameter, q_0. In principle the deceleration parameter can easily be measured by comparing the redshifts of distant objects—an indicator of velocity—with their distances. If the universe is expanding at an unchanging rate, the ratio of redshift to distance should be constant no matter how far off, and hence how far back in time, an object lies. In practice measuring the deceleration parameter is devilishly difficult, because it requires the use of a "standard candle" whose distance can be accurately gauged from its apparent magnitude.

In recent years two groups, one led by Robert Kirshner at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, and the other by Perlmutter, have pursued this quest using what has become the favored standard candle, Type Ia supernovae—believed to be the explosions of white dwarf stars. And in February, Perlmutter announced the first, tentative results of the analysis of his first batch of seven supernovae. Perlmutter declined to quote a specific number for q_0 lest someone take it too seriously. But he was willing to say that the outlook is not bright for a substantial cosmological constant. "We do want to say it is very difficult to have an accelerating universe," Perlmutter said in February. "We live in a decelerating universe."

"This could be a lambda killer," Peebles said when told the result. "Lambda killer?" said Perlmutter when Peebles's comment was related to him. "That's what we were after: Get lambda out of the way so it won't be a spoiler anymore."

Whether or not the universe is decelerating fast enough to come to rest given infinite time, as an omega of one requires, is a question that will be answered, at the earliest, only when Perlmutter, Kirshner, Dekel, Tyson, and the rest of the apostles of dark matter finish their work. But Dekel already sees signs of progress. "In the last 5 years there has been a revolution," he says. "All this field of large-scale dynamics became more quantitative, a premature science becoming a science."

In time, cosmologists may find out just how beautiful the universe is. "I think everyone agrees that if we are going to build a universe it would be [flat]," says Peebles, "but maybe we have some things to learn yet."

–Dennis Overbye

Dennis Overbye is the author of Lonely Hearts of the Cosmos.