Cosmologists in Flatland

Searching for the missing energy

By RON COWEN

The second in a two-part series examining alternative views of the shape of the cosmos.

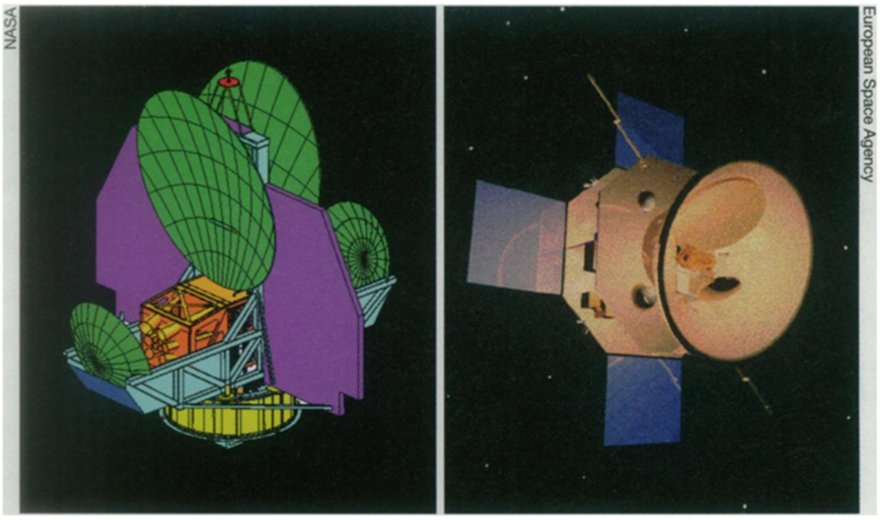
Astronomers accepted centuries ago that the world is round, but many aren't about to give up the idea that the universe is flat.

Even as recent observations have opened fire on the notion, several theorists have developed a panoply of models that protect the cosmos from the slightest hint of curvature. Many researchers gravitate toward the idea of a flat cosmos because it's closely tied to a popular theory of the origin of the universe—inflation.

Inflation theory solves two cosmological conundrums. It posits that the infant universe underwent a tremendous growth spurt just after the Big Bang. In just a tiny fraction of a nanosecond, the cosmos ballooned from a radius much smaller than one-millionth the size of a proton to the size of a dime (SN: 6/7/97, p. 354). This early period of rapid expansion spread out tiny regions that had been in close contact, thus explaining why the universe looks the same in all directions when viewed on a cosmic scale.

Inflation also explains how the universe evolved from a smooth soup of elementary particles into a lumpy collection of galaxies, galaxy clusters, and superclusters. In a cosmos undergoing rapid expansion, any random, subatomic fluctuations in energy are blown up into macroscopic proportions. By preserving and amplifying these fluctuations, inflation produces regions with slight variations in density. Gravity then molds these variations into the starlit structures seen in today's universe.

A flat universe is a natural consequence of inflation. In much the same way that expansion makes a small patch of a hot-air balloon look flat, inflation would stretch the cosmos, smoothing out any curvature it might have had initially.



NASA / European Space Agency

The Microwave Anisotropy Probe, or MAP (left), and the Planck satellite will search for tiny hot and cold spots in the cosmic microwave background, the faint glow left over from the Big Bang. The size of these temperature fluctuations may indicate whether or not the universe is flat.

According to Einstein's theory of general relativity, the total density of the universe determines both its geometry and its fate. A universe with a density greater than a certain critical value has a positive curvature, resembling the surface of a sphere. A universe with less than the critical density has a negative curvature and a shape akin to the seat of a saddle. A flat universe must have neither too much nor too little density—in other words, an amount precisely equal to the critical density.

Therein lies a problem. The universe doesn't seem to have nearly enough matter—the stuff that makes up gas, dust, and stars, as well as the strange, invisible material known as dark matter—to be flat.

Several types of observations, including the brightness of distant supernovas and the amount of mass discerned in galaxies and galaxy clusters, suggest that "the density of matter is less than the critical density," says cosmologist Joshua A. Frieman of the Fermi National Accelerator Laboratory in Batavia, Ill., and the University of Chicago. "More and more of us are getting convinced because the measurements are improving and several independent ways of measuring these [parameters] are starting to converge."

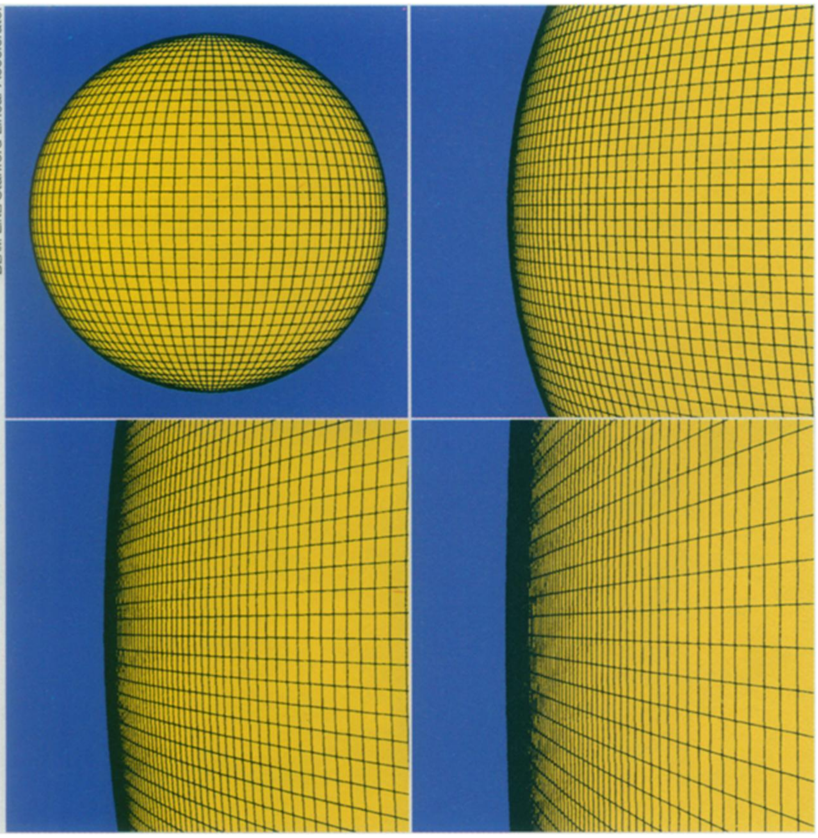
"The fact that the universe appears to have a density of matter less than the critical density is surprising," agrees David N. Spergel of Princeton University. "It contradicts our expectations, and we're really groping around for a way of understanding that."

Theorists face a choice, Frieman notes. "Either we can accede to the astronomers and say, 'Yes, there's only 20 to 30 percent of the critical density available' [hence the universe cannot be flat], or we can ask whether there can be other forms of matter or energy which could make up the difference."

Either we live in a negatively curved universe, or "there is a mysterious missing energy component even stranger than dark matter," says Paul J. Steinhardt of the University of Pennsylvania in Philadelphia. Such a component would drastically alter standard ideas about the fate of the cosmos.

In the traditional view of a flat universe, there exists a delicate balance between the pull of gravity and the expansion that has taken place ever since the Big Bang. If the density of matter is exactly the same as the critical value, the universe will expand indefinitely, though ever more slowly as time goes on.

A low-weight universe does not have sufficient density of matter to be flat. However, it may have enough energy, combined with its mass, to keep it from curving. This energy would also act as an antigravitational force, resulting in a cosmos that not only expands forever but may do so at an ever-increasing rate.


BEAM LINE/Stanford Linear Accelerator

As a sphere grows larger, its surface becomes flatter. Similarly, inflation enlarges space, causing it to flatten. In a flat universe, the total density of mass and energy must equal the critical density.

Necessity is the mother of invention. Although Frieman says he does not favor any particular model of the universe, he and other theoretical astrophysicists are searching for forms of missing energy that would keep the universe flat. The simplest approach, he notes, is to resurrect an idea first proposed by Albert Einstein.

Einstein had noticed that his equations of general relativity predicted that the universe would either expand or contract. In order to make the universe stand still, which he believed it did, Einstein inserted a constant into his equations. Acting as an antigravity term, the so-called cosmological constant exactly balanced the tug of gravity. A few years later, after physicist Edwin P. Hubble showed that the universe was indeed expanding, Einstein called the cosmological constant the biggest blunder of his life.

Astrophysicists have taken a second look at that constant in recent years. When Einstein conceived of the cosmological constant, it had no basis in physics. In the 1960s, however, Russian physicist Yakov B. Zeldovich proposed that the constant could arise from a quantum mechanical source of energy. This is the energy associated with the empty space in the universe. In quantum mechanics, empty space seethes with the creation and annihilation of virtual pairs of particles and antiparticles.

According to Frieman, Zeldovich realized that "it's not up to us to decide whether the cosmological constant is there or not; it could be something that is forced upon us by the properties of the vacuum."

The constant computed from the quantum energy of empty space turns out to be 10^{120} times larger than astronomers' observations allow. If the constant were "humongous, we wouldn't be here; the universe would have done something very different a tiny fraction of a second after the Big Bang, and we know that's not the case," Frieman notes.

"This is the biggest embarrassment of cosmology today," he adds. "We don't know why the cosmological constant . . . isn't a much larger number."

One way around the problem is to change the game plan. Perhaps what Einstein called a cosmological constant isn't a constant after all. In the past, it may have been quite large, Frieman and other researchers speculate, but today, through some as-yet-unknown physical process, it may be only slightly larger than the density of matter. "This would give us some way of trying to understand this big discrepancy between what we expect the cosmological constant to be and what we observe it to be," he adds.

Frieman and his colleagues liken the cosmological constant to a ball rolling down a hill. Early in the universe, the ball rests at the summit and has a high potential energy associated with being there. As it rolls down, its potential energy falls.

Similar changes in potential energy occur in theories that describe elementary particles, Frieman notes. At the moment, he cautions, cosmological models of this sort are not realistic, but they "are a way of thinking how particle physics might work at these energy scales."

Steinhardt's team has shown that a cosmological constant which varies over time cannot have the same value at all points in space. The researchers have devised their own versions of such models, invoking a form of energy that they call quintessence. A key feature of quintessence is that its density decreases as the universe expands, but it declines more slowly than the density of matter. As a result, the two types of density can be similar in the universe today.

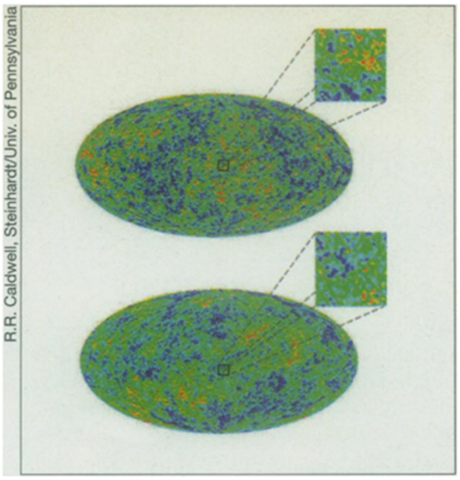
Steinhardt and his colleagues are now attempting to unify this form of energy with another elusive component of the universe—the invisible material known as cold dark matter. In some of the models developed by Steinhardt's team, both the energy density and the cold dark matter are described by the same set of equations.

Steinhardt adds that the declining constant appears to fare at least as well as Einstein's constant in explaining the results of studies that use the brightness of distant supernovas to probe the early universe. These studies suggest that rather than slowing down, the cosmos' rate of expansion may actually be speeding up. One interpretation is that some antigravity force is at work.

"If this is true—and this is a big if—then there is funny matter [or energy] out there, like a cosmological constant," notes Michael S. Turner of Fermilab and the University of Chicago.

Spergel and Ue-Li Pen of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., are investigating another type of model, one in which the missing energy would come from a tangle of lightweight cosmic strings distributed throughout the universe. Unlike the more massive strings that have been proposed (SN: 3/28/92, p. 202), these features would not form the seeds of structure in the universe but they could store energy.

As the cosmos expands, the density of energy in the strings declines. However, that decrease takes place at a slower rate than the decline in the density of matter.



R.R. Caldwell, Steinhardt/Univ. of Pennsylvania

These simulations indicate temperature fluctuations in the cosmic microwave background in two models of a flat universe. Hot spots are shown in red, cold spots in blue. The map at left portrays a universe in which the density of matter equals the critical density, the amount required to keep it flat. The map at right shows a universe in which the density of matter is only 40 percent of the critical density; the rest is provided by a type of energy known as quintessence.

Thus, at some point, the density of energy may equal or even exceed the density of matter. This model could explain why the energy density varies over time and why it becomes more important later. Spergel and Pen summarize their model in the Dec. 20, 1997 ASTROPHYSICAL JOURNAL LETTERS.

It's always possible that the universe isn't flat.

Some recent models of inflation actually predict a negatively curved cosmos. In these hypotheses, "the amount of expansion has to be rather carefully chosen, and it's hard to see how that would fall out naturally," Frieman says. If expansion proceeds unchecked, you still end up with a flat universe. "So purely from an aesthetic view, these models are less compelling."

In a few years, adds Spergel, scientists will have the instruments they need to deduce the universe's true geometry, whether curved or flat, as well as its topology, whether infinite or finite.

To test these ideas, researchers have been examining the cosmic microwave background—that is, the radiation left over from the Big Bang. This effort will get a major boost in 2000, when NASA's MAP (Microwave Anisotropy Experiment) satellite is expected to join the fray.

MAP will record the tiny temperature fluctuations in this whisper of radiation over patches of sky about 1° across. In patches this small, differences between the various models of the cosmos should be apparent. The European Space Agency's Planck satellite, scheduled for launch in about 2005, will scan the microwave background on even finer scales.

In a negatively curved universe, notes Marc Kamionkowski of Columbia University, pronounced temperature fluctuations in the microwave background should occur across smaller patches of sky than in a flat universe.

Models like quintessence, which adds a cosmic energy density that varies both in time and across space, would leave their own imprint on the cosmic microwave background. For example, spatial variations in the energy density would tend to enhance fluctuations already present in the microwave background. As a result, hot and cold spots in the microwave background would most likely be larger.

Temperature fluctuations in the microwave background might also show whether the universe has a simple or complex topology (SN: 2/21/98, p. 123). "What's great is that all this stuff is testable in the next few years," Spergel says.

Although he finds the mathematical richness of a negatively curved universe particularly intriguing, "I view this as not a matter I have much choice on," Spergel chuckles.

"I'm willing to accept whatever the universe turns out to be." □

Letters continued from p. 131

electric currents are distributed within it.
—J. Raloff

In glancing at the table of EMF values, I became curious as to what the author was doing between about 8:00 p.m. and 9:05 p.m. The readings during that span were quite low.

I ask this with some trepidation, for fear that the answer will be "watching TV" and that the cable industry will seize upon such an admission with an ad campaign asserting that "TV is good for you!"

Denny Miller
Columbus, Ohio

According to my log, I was working at my home computer from 8:12 p.m. until 8:59 p.m. I didn't settle down for a little television until 9.
—J. Raloff

It is curious that the ubiquitous electric shaver, which is held at *zero* distance from the skin, is omitted from the table.

Isadore Nicholson
San Diego, Calif.

Electric shavers ranged from 4 to 600 milligauss at 6 inches. —J. Raloff

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