system might also be more stable than that of a satellite sounder, because the receiver could be calibrated every time it views a transmitter unobstructed by the atmosphere.

In the troposphere, GPS might seem to be getting in over its head. The troposphere contains so much water vapor that humidity and temperature both have great effects on the signal. Disentangling the two might prove difficult, though feasible, Hardy thinks, in the coldest and the warmest regions of the atmosphere—the tropics and the wintertime arctic, for example. And even when moisture and temperature variations can't be teased apart, the combination might provide a useful long-term measure of the state of the atmosphere that could anchor other less comprehensive measurements, Bretherton thinks.

As appealing as GPS looks for monitoring the lower and middle atmosphere, it isn't the only proposal for fine-scale, global probing. A satellite-borne infrared instrument now in the late stages of design could equal the temperature accuracy of GPS while measuring 10 trace gases, including ozone and water vapor, according to its U.S. principal investigator, John Gille of the National Center for Atmospheric Research in Boulder. Called the High-Resolution Dynamics Limb Sounder, the instrument would surpass the resolution of vertical-sounding satellites by looking toward Earth's edge rather than straight down, and it would have a low-noise design for greater accuracy. Launch is scheduled for 2002, if not sooner, as part of NASA's Earth Observing System.

But Hardy and Kursinski think the long-term stability of a GPS monitoring system might give it an edge. And considering the low cost involved, they think it deserves a try. Only $10 million would be needed for the trial mission they hope to propose, and a full 24-satellite system would probably cost less than $100 million to deploy. If the concept works, atmospheric researchers might share the use of GPS receivers on future commercial satellites for the cost of a bit of additional electronics. A small price to pay, they say, to harness a machine of war for the battle against global change.

–Richard A. Kerr

Cosmologists Search the Universe For a Dubious Panacea

Einstein was wrong once. In 1917, to keep the universe from collapsing under its own gravity, Einstein added to his equations of general relativity a constant that countered the inward pull of gravity with a universal outward push. The result was a universe that was unchanging in all directions, for all time—a universe that just sat there. A few years later, though, theorists and observers found that the universe does change—it expands. And it does this, they concluded, apparently without needing any extra push. To everyone's relief, the master quickly killed off his cosmological constant. But lately cosmologists have suspected that Einstein may have been wrong when he killed the constant, not when he created it. The extra push, they think, might have a role even in an expanding universe. And yet, cosmologists by necessity being among the subtlest of theorists, virtually none of them wants it.

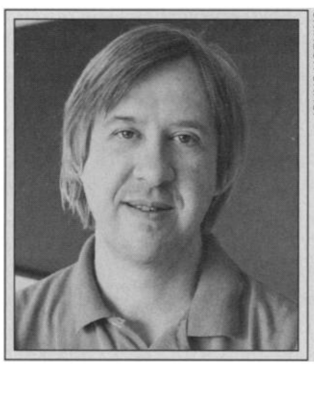
Why not? "It's ugly," says Princeton University theorist James Peebles. "It's an addition. If I were building a universe, I would not put in a cosmological constant." The simplest universe cosmologists can envision doesn't need this extra cog, which would act to infuse "empty space" with extra energy. But theorists may not get their way: The cosmological constant, like one of those late-night movie characters, won't stay dead.

In its latest incarnation, starting about 2 years ago, cosmologists realized that the constant could come in handy in ways that could never have been envisioned in 1917. Specifically, it might solve several of the field's worst embarrassments at once: the seeming shortfall of mass in the universe, the mysterious large-scale clumping of galaxies, and the mounting evidence suggesting that the universe might be younger than its oldest stars. A cosmological adjustment that could solve all those problems at once, though perhaps too good to be true, is surely too good to ignore. And that is spurring several groups to conduct the largest of large-scale measurements, scanning the farthest galaxies and quasars for signs of the constant.

The search is necessary because theorists alone can't set a value for the constant. General relativity, Einstein's theory of gravity, offers no clues about its value, says Michael Turner, a physicist at the University of Chicago and Fermilab, though the theory gives the constant "every right to be there." The so-called standard model of particle physics, which describes forces and particles operating at the smallest scales, does predict a value for the constant—but a patently improbable one. In the late 1980s, physicists using the laws of quantum physics to calculate how much energy would be dumped into empty space by the random quantum fluctuations of matter and energy came up with an astoundingly high value. The cosmological constant was so large, they found, that it would have blown the universe apart before gravity could collect matter into galaxies or planets. The very fact that cosmologists are around to debate the constant means that its value is close to, if not exactly, 0. And that poses a major problem for particle physicists, says William Press, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics. Solving it, he says, will take "either a miracle or an unexplained principle."

"It's unnatural. It would be nice to get rid of it."

—Alex Szalay


JOHNS HOPKINS

A neat fit. While particle physicists wrestle with the question of where their theory went wrong, cosmologists have realized that just the tiniest fraction of the value from particle physics would solve three of their most pressing problems "with one fell swoop," as Michael Turner puts it. Princeton cosmologist Edwin Turner (no relation) agrees: "It could balance all the books at once." Just to keep things complicated, though, the cosmological constant would solve different problems in different ways.

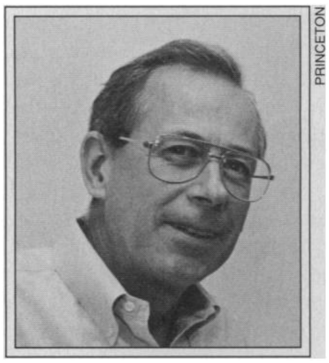
Besides giving a push—adding "an extra springiness to the universe," as Edwin Turner puts it—the extra energy density would also have a gravitational effect. In the language of Einstein's theory of relativity, it would affect the curvature of the universe. That could solve one major problem in cosmology. Since the 1980s, for what Peebles calls "theoretical but nonetheless plausible reasons," theorists have more or less agreed that the universe is flat. But the gravitational effect of observable matter is at most 20% of what is needed for a flat universe. A nonzero cosmological constant could add the other 80%, substituting for the missing mass.

As for the second conundrum, maps drawn up in the last 2 years show galaxies clustered into ropes and sheets on scales of tens of millions of light years. Cosmologists assume that the clustering grew by gravity from tiny fluctuations in the smooth ocean of matter and radiation created by the Big Bang. But theorists have a hard time explaining how the biggest structures could have taken shape in the limited time since the birth of the universe. Enter that springiness imparted by a nonzero cosmological constant. It could have helped sweep matter into the large-scale structures, accelerating their growth.

And cosmic springiness might solve a deepening mystery related to the Hubble constant (the rate of expansion of the universe).

"Considering the observations, I think the universe might have put in a cosmological constant."

—James Peebles



Measurements of the Hubble constant remain indirect and highly controversial (see article on p. 321). But lately, says Peebles, "the young Turks are going for a high value," by which he means that based on such benchmarks of distance as galaxies and stars of standard brightness, cosmologists are arguing that the expansion rate is high. Under standard assumptions, a high rate implies that the universe got started relatively recently, perhaps 11 billion years ago. But other observers studying the clumps of stars called globular clusters have pegged their age at 15 billion to 18 billion years—apparently older than the universe.

A nonzero cosmological constant could reconcile the two ages by changing the early expansion rate of the universe. To account for the observed expansion without a cosmological constant, theorists have to assume that the initial rate was fast, because gravity has been slowing the expansion since then. "The normal Big Bang is an explosion," explains Edwin Turner, "and since then everything has been coasting—the push is gone." But with the steady push contributed by the cosmological constant, the expansion could have started out slower and then accelerated to its current rate. A universe expanding more slowly in the past could have been expanding longer, and could thus be old enough to contain its oldest stars.

A cosmological constant of 0.8, or the equivalent of 80% of the mass needed to close the universe, could simultaneously solve all three puzzles—missing mass, large-scale structure, and the age of the universe. Nevertheless, cosmologists don't regard that neat fit as decisive evidence in favor of the constant. Even those who are intrigued admit it's an easy out. "The cosmological constant is the last refuge of scoundrel cosmologists," says Michael Turner, "beginning with Einstein." Theorists have proposed other, less arcane ways of solving each problem. What's more, says Edwin Turner, "none of these problems is clear and hard and certain." All three are rife with assumptions and uncertain measurements. The only reason to believe a value for the cosmological constant would be to observe one.

Observers are now trying to track down the cosmological constant by looking for its effects on the history of the universe. Since a universe with a cosmological constant can have been growing for longer than an ordinary universe, it can also have reached a larger size. And a bigger universe should contain more galaxies and other objects. Look in any direction in a universe shaped by a cosmological constant, and more objects should lie along your line of sight.

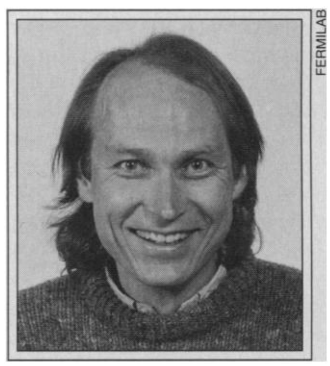
A constant quest. One search strategy has already ruled out a constant higher than 0.8. Cosmologists have been hunting for gravitational lensing of quasars, the most distant objects known. Gravitational lensing results when the quasar's light, traveling through space toward Earth, encounters the gravitational pit of a galaxy and is bent, resulting in a multiple image (*Science*, 3 April, p. 30). The logic behind the quest is that the bigger the universe is, and the more galaxies and quasars it contains, the more often such chance alignments should occur. A universe with a cosmological constant of 1.0 should have 10 to 100 times more gravitational lenses than one with a constant of zero. But the most recent survey, led by astrophysicist John Bahcall of Princeton's Institute for Advanced Study, found only one gravitational lens in a sample of hundreds of quasars observed with the Hubble Space Telescope. "The cosmological constant should have a big effect," says Edwin Turner, who did the original calculations, "and we don't see it."

But gravitational lenses are scarce under any circumstances, which makes them an uncertain probe of the cosmological constant. For better resolution, researchers are turning to galaxies. The larger the universe, the more galaxies it should harbor within a given fraction of its volume. A few earlier galaxy counts gave contradictory results. So astronomers led by David Koo and Garth Illingworth of the University of California at Santa Cruz have proposed a large-scale assault on the problem. Their project, called the Deep Extragalactic Evolutionary Probe (DEEP), would use the new Keck Telescope on Mauna Kea to map 12,000 galaxies, counting the number that lie at the same relative distance from Earth. If the cosmological constant is 1.0, two to three times more galaxies should be found the same fraction of the way to the edge of the universe than if the constant is zero. With its vast sample, DEEP could find a constant as small as 0.1, says Koo.

Until more results come in, the cosmological constant's value seems to come down to bets. They're mostly on zero. William Press asks rhetorically, "Do we need it to explain what we know? Are there direct observational bounds on it? My personal bet is on zero." Says Alex Szalay, a cosmologist at Johns Hopkins University and a participant in DEEP: "It's unnatural. It would be nice to get rid of it." So it's zero? Szalay: "Oh, sure." Edwin Turner: "It's not necessary and it's zero." Michael Turner: "In my heart of hearts, it's zero." Koo comes close to disagreeing: "I bet it's nonzero, maybe .001. Though we'd never find that [observationally]."

"In my heart of hearts, it's zero."

—Michael Turner



Peebles thinks most of these bets are emotional—deeply felt rejections of unnecessary intricacy. "We want nature to work in a simple way," he says. "No bells and whistles." But maybe cosmology can't be guided by aesthetics, and maybe the universe isn't so elegant after all. "Considering the observations, I think the universe might have put in bells and whistles, a cosmological constant," Peebles says. "I'd put money on both sides, but more on the constant."

–Ann Finkbeiner

Ann Finkbeiner is a free-lance science writer based in Baltimore.