Research News

In Search of a New Cosmic Blueprint

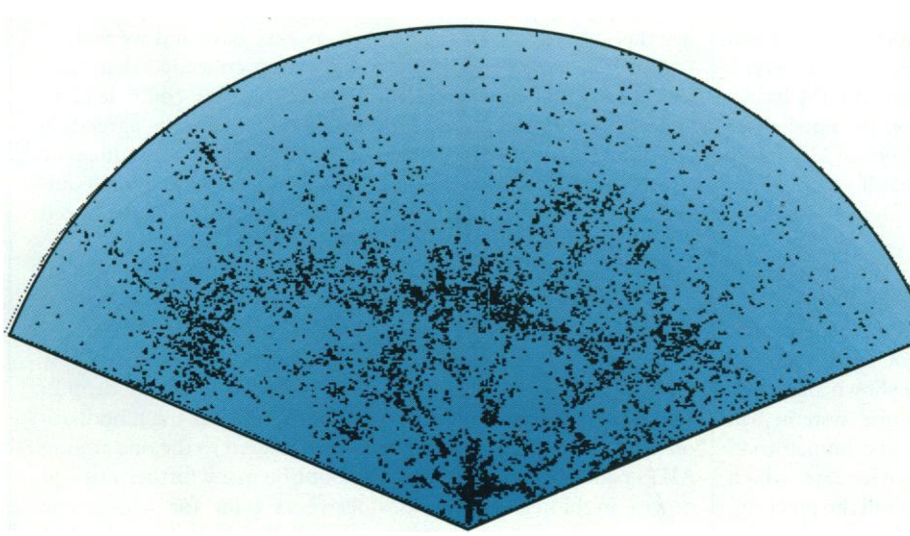
As doubts build about a once-favored model explaining how structures formed in the universe, new theories are jockeying in a cosmological free-for-all

COSMOLOGIST MICHAEL TURNER OF THE University of Chicago recently coined the rule that, in a cosmological theory, you can't invoke the tooth fairy twice. His tooth fairy is not a mythical being who replaces lost teeth with quarters, but any wild, whimsical assumption dreamed up to answer some problem. In a field like cosmology, where the questions are vast and data scarce, you would expect to have to summon a tooth fairy from time to time. But today, to hear many cosmologists talk, the population of tooth fairies is exploding. "In some of the newer theories, we are inventing a new physical principle for every new observational fact," complains astronomer Marc Davis of the University of California, Berkeley.

Spurring the proliferation of fairies are recent reports of unimaginably vast clumps and sheets of galaxies. The bigger those structures get, the harder it becomes for cosmologists to figure out how they could have coalesced in the limited time since the Big Bang. And things apparently didn't start out clumpy—matter in the early universe left a record of its uncanny smoothness in the perfectly even "background" radiation that still permeates the cosmos. Those clashing measurements of smooth radiation and clumpy galaxies are reopening some of cosmology's biggest questions.

For much of the 1980s, one scenario dominated the gallery of models explaining how cosmic structures came to be: the cold-dark-matter-model, in which relatively slow-moving ("cold"), invisible ("dark") particles clumped around tiny wrinkles in the fabric of the early universe and eventually gathered all the remaining matter around them. But the cold-dark-matter model doesn't have what it takes to amass the ever larger clusters of clusters that observers have seen throughout the last 10 years. And while cosmologists maintain their old theory isn't dead yet, they concede that the recent observations are stretching the model to the breaking point.

While one camp is trying to salvage the original model, others are busy searching for alternative stories of the early universe. Some propose that huge defects in the fabric of space—larger but sparser than the small wrinkles—seeded the coalescence of galaxies and clusters of galaxies. Others speculate about an as-yet-unseen force—a very weak one that might act only on neutrinos, drawing them together over distances of hundreds of millions of light-years into a scaffolding for other matter. Though accusations of tooth fairies are flying, these theorists are undaunted, arguing that there's no longer a strong alternative. The field of cosmic structure is opening up to creative speculation.



JOHN HUCHRA AND MARGARET GELLER

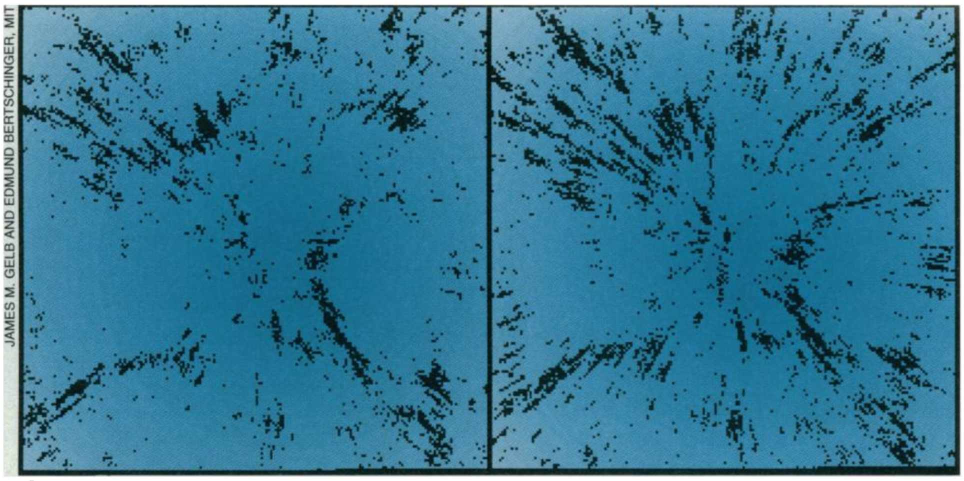
Bubbles, walls, and sheets. *A wide-angle view shows how galaxies are distributed in a slice of the universe stretching to a distance of 450 million light-years.*

Whatever form that speculation takes, it's likely to include some role for dark matter, which cosmologists have been theorizing about since the early 1980s. That was when astronomers noticed that both the stars in spiral galaxies and the galaxies in clusters were zipping around too fast to avoid flying apart unless they were held together by the gravitational pull of much more mass—as much as 10 times more—than telescopes could reveal. That exotic material would have to be still more prevalent if, as many cosmologists assume, the universe contains enough mass to "close" it: to keep it from either collapsing or expanding to infinite size.

Later work showed that at least some of that extra mass had to be made up of something other than the protons and neutrons of ordinary matter. Based on the relative abundance of hydrogen, helium, and other light elements in the universe, physicist David Schramm of the University of Chicago and his colleagues set a limit on how many protons and neutrons the universe could contain—and that limit fell short of the amount of mass that was needed to close the universe.

Theoretical particle physics provided plenty of candidates for the role of dark matter, though only one had actually been detected: the neutrino. Neutrinos might fit the bill if there are enough of them and they have some mass, something that's still uncertain. Moving at close to the speed of light, neutrinos would be classed as "hot" dark matter; anything else, traveling slower, falls under the heading of "cold." Cold dark matter, like the blank spaces on an old map, is the domain of fanciful entities, so far undetected, with names like "axions," "photinos," and "winos and zinos."

Theorists, including James Peebles of Princeton University, Sandra Faber and George Blumenthal of Lick Observatory, and Joel Primack of the University of California, Santa Cruz, were quick to see that these exotic particles provided a way of explaining how tiny inhomogeneities—the forerunners of today's structures—could have existed in the early universe in spite of the observed smoothness of the background radiation. Unlike ordinary matter, whose



JAMES M. GELB AND EDMUND BERTSCHINGER, MIT

Cold dark matter falls short. *A simulated cold-dark-matter universe* (right) *looks smoother than the real thing, approximated by a computer-generated pattern* (left).

early lumps and bumps would have left bright spots in the radiation, neutrinos or cold-dark-matter particles could have organized themselves into clumps secretly, without leaving a ruffle. Then, 100,000 years after the Big Bang, when nuclei pulled electrons into atoms and set radiation free to traverse space, ordinary matter would have begun joining the clumps.

To get the whole process started, the theorists envisioned “seeds”: tiny wrinkles in the fabric of the universe, which would have originated during the first fraction of a second after the Big Bang, explains Chicago's Schramm. Their source, the theory held, was the quantum-mechanical uncertainty principle, which could have imprinted small ripples, or “quantum fluctuations,” onto the smooth fabric of the infant universe, he says. Such seeds would have been best at gathering up cold rather than hot dark matter, which is why the structure theorists of the early 1980s called their scenario the cold-dark-matter model.

But then came the sky surveys done through the mid- and late 1980s, which showed that clusters of galaxies were grouped into larger clusters, which in turn were clumped into even larger clusters stretching across much of the observable universe. The cold-dark-matter model, relying on such puny seeds, just couldn't keep up. As University of Pennsylvania cosmologist Paul Steinhardt puts it, “There wasn't enough time in the history of the universe for gravity to pull together these structures.” Just a year after he proposed the model, Peebles says, he saw the writing on the wall and abandoned it.

Steinhardt and many of his colleagues nevertheless hold out hope for the cold-dark-matter model because it works so well for building smaller structures, such as galaxies and small clusters of galaxies. And some researchers even go so far as to discount the observational challenge to the model. “A lot of the observations challenging the theory are actually just wrong,” says Berkeley's Davis. Lacking hard, quantitative measurements, he says, the eye can often be fooled into seeing false patterns in maps of galaxies and clusters. Also, most earlier surveys don't take a big enough sample to show if the “structures” they reveal are statistically significant.

But Schramm is ready to try other kinds of seeds, hoping to find one that organizes matter efficiently enough to explain the structures now being mapped. A change of seed, in turn, can mean a different kind of dark matter as well, since some kinds of alternative seeds might grow best in hot dark matter rather than cold, he says. “The choice of dark matter—hot or cold—is wide open.”

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—Paul Steinhardt

As alternative seeds, Schramm and his colleagues are intrigued by “topological defects”—flaws in space itself induced as the universe expanded and cooled during its first fraction of a second. First proposed by Thomas Kibble of London's Imperial College, the defects would have originated as the single unified force operating in the newborn universe split into the four forces we now know. Each splitting constituted a phase change—analogous to the more familiar kind of phase change as a liquid freezes or boils. Those transitions would have left the entire cosmos riddled with defects, explains Neil Turok of Imperial College, rather like the flaws that are visible in an ice cube.

The cosmic flaws go by various names depending on their shapes, including monopoles, strings, walls, and “textures,” which can be thought of as twists in three-dimensional space. Turok first tried building a scenario of structure formation around strings, which, being larger than the small quantum seeds, could have pulled large amounts of matter into them fast. But in the last 2 years, says Turok, his string scenarios ran into trouble: The predicted network of string defect was too sparse to account for the observed density of structures. Now Turok's attention is on textures.

Turok says he pictures a texture as behaving something like a tangle in a rubber band. As the rubber is stretched, the tangle straightens out with a snap. Similarly, an “untangling” texture creates a pocket of energy that acts as if it were a massive object, pulling in any matter within its gravitational grasp.

Computer models of the process, says Turok, show that the textures can organize big chunks of matter much more efficiently than the quantum seeds of the cold-dark-matter model. “The most exciting thing about our texture theory is that when we put all the ingredients—matter, dark and light, as well as radiation—into a computer, we get out the right distribution of galaxies,” he says. “This is the only theory that's done that.”

Some theorists are equally enthusiastic. But Chicago's Turner thinks the concept is too vague to be tested against observations. “Topological defects haven't been able to make any sharp predictions the way we can with the cold-dark-matter model.” Other researchers are skeptical because Turok's model requires scrapping a well-accepted idea known as inflation, in which the infant universe underwent an extra-rapid growth spurt. While inflation theory neatly predicts the quantum seeds of the cold-dark-matter model, the brief ballooning would have flattened out the textures. But Turok is happy to see inflation theory deflate. “With the wave of a wand it was going to solve all the problems of the early universe,” he says.

One group of theorists ignores the infant universe altogether in searching for the seeds of structure. According to a scenario once considered outlandish but now gaining interest, the seeds of big starry structures originated not in the first fraction of a second but 30 million years after the birth of the universe. In this scheme, developed by Fermilab's Christopher Hill and his colleagues, including Schramm, the seeds were sowed in a “late-time phase transition,” much like the earlier ones that give the forces of nature their separate identities. Because they appeared so long after the origin of the cosmic background radiation, explains Hill, these seeds could have been as large as needed without ruffling the background radiation at all.

Unlike other scenarios, Hill's doesn't rely on gravity alone to gather matter around the seeds. In the proposed late phase transition, Hill says, a new force of nature would appear, one that is so discriminating in its effects that we haven't yet detected it. The force might affect only neutrinos and show its strength only at distances of several hundred million light-years—about the scale of the biggest structures yet seen in the universe. Perhaps, he and colleagues speculate, neutrinos responding to this force could have rounded up particles into the vast structures we see.

That's a little much for some of his colleagues to swallow. "The late-time phase transitions are what is called in the trade now the invocation of the tooth fairy," says Davis. Even so, Hill and his colleagues are encouraged by a recent observation. A survey published last year, measuring the distribution of galaxies along thin but very long "pencil beams" extending into the far reaches of space, appeared to reveal clumps every 400 million light-years. "It's as though we are living in a cage with walls every 400 million light-years or so," says Hill—just the scale on which his force would act. But other cosmologists are skeptical of such galaxy surveys, arguing that current knowledge of cosmic structure is far too sketchy to favor any particular scenario of structure formation.

Peebles hopes the 1990s will improve the situation. The 1980s was a decade of theory, as particle physicists joined the cosmology game armed with "a slew of exciting and clever concepts," he recalls. "On the other had, they didn't bring with them any particular knowledge of what it was they were trying to explain."

In the next decade, he looks forward to an observational push that would bring bigger surveys of galaxies, as well as an analysis of the clumping of quasars, which lie at such large distances that they may point to yet another level of structure that needs explaining. At the same time, increasingly precise satellite and balloon measurements may turn up the first bumps in the cosmic background radiation, which could help theorists choose among scenarios. Maybe then some of the tooth fairies will take flight. "After you know what is happening really well," says Peebles, "maybe you will get some hints as to why."

■ FAYE FLAM

Neuroscience Meets in the Big Easy

New Orleans—*While all of Louisiana—and much of the nation—waited with bated breath for the vote that would decide whether an ex-Klansman and Nazi sympathizer would be elected governor of a U.S. state (he wasn't), more than 15,000 neuroscientists who had gathered here for the annual meeting of the Society for Neuroscience learned the results of another vote: Society members chose by a margin of 2 to 1 not to return to this popular convention mecca in 1996—not because so many in the state seem to sympathize with David Duke, but as a response to Louisiana's restrictive anti-abortion law, one of the toughest in the nation. Then, with the results of their vote behind them, the focus of the researchers at the meeting shifted from politics to science. Among the highpoints of the science at the meeting were new ways of recording nerve impulses from intact brains, skepticism about an experimental Huntington's treatment, and a promising new twist on eye development.*

Patch Clamping au Naturel

Patch clamping, the revolutionary technique for recording electrical currents in cells, whose developers—Bert Sakmann and Erwin Neher—were honored last month with a Nobel Prize, has been taken one important step further by David Ferster of Northwestern University. In the 1980s, patch clamping revolutionized electrical recording from cultured neurons. Then 2 years ago Sakmann found a way to use the technique in slices of brain tissue. And now, in New Orleans, Ferster reported the first use of patch electrodes to record electrically from neurons in the intact brains of living animals.

Ferster's work represents a breakthrough in what Sakmann calls "a mental barrier" to trying the technique in whole, living brains. "People said it would never work," the developer of the technique told *Science*, because researchers thought the tiny patch pipettes would clog in the messy milieu of a living brain and not form an effective seal on an individual cell. But Ferster wasn't daunted, and he found that he could in fact get the seals he needed to record from neurons in the visual cortex of cats.

Ferster's accomplishment was more than a mere technical breakthrough. He and graduate student Bharathi Jagadeesh used the method to address a long-standing debate about how certain neurons in the visual cortex are able to respond selectively to lines with a specific spatial orientation. Some researchers have hypothesized that inhibiting signals from neighboring neurons help tune that specificity, but Ferster and Jagadeesh used the patch electrode to add up the electrical signals coming into the neurons while the cats looked at patterns on a screen, and found no evidence of the proposed inhibition.

Sakmann notes that Ferster has answered a question that Sakmann himself tackled and failed to answer 25 years ago, using the old method of impaling neurons with sharp electrodes. But that's not the only progress made possible by Ferster's work. The patch-clamp advance opens the door to many experiments that have previously been impossible in living animals—such as recording the activity of tiny neurons in the brain stem and elsewhere in the brain that are too small to impale, and doing the kind of detailed analysis of ion currents into and out of cells that only patch clamping can achieve. Concludes Sakmann, "It's marvelous."

Grafts for Huntington's—Too Much Too Soon?

Mexico city neurosurgeon Ignacio Madrazo may not have enjoyed the Big Easy as much as the average meeting attendee last week. Madrazo is one of a small group of pioneers who have used brain grafts as therapy for Parkinson's disease. For a decade or more, the concept of attacking neurodegenerative diseases with brain grafts—especially with grafts of fetal tissues—has exerted an intellectual appeal. After all, it makes a certain intuitive sense to replace tissue that has degenerated with, say, fresh fetal tissue. But while this tack has been tried on 100 or so Parkinson's patients at various research hospitals around the world during the past 4 years, progress has been slower than people had hoped: Only recently have a handful of patients shown improvement. Which is why Madrazo met with sharp criticism from his