The Greatest Story Ever Told

Is cosmology solved?

By RON COWEN

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Scientists don't often make great debaters. Rather than dealing with absolutes in black and white, they tend to invoke qualifiers and caveats in shades of gray. But cosmologist Michael S. Turner, whose hand-drawn viewgraphs are so colorful that they have adorned the walls of an art gallery, isn't the typical scientist, and 1998 hasn't been the typical year for the study of the universe.

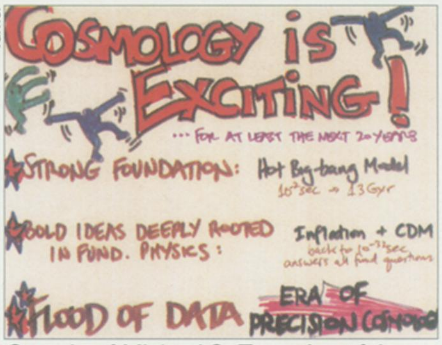
In an October forum—billed as "The Nature of the Universe Debate: Cosmology Solved?"—Turner, who is at the University of Chicago and the Fermi National Accelerator Laboratory in Batavia, Ill., put forth an assertion as bold as his drawings: For the first time in history, cosmologists have developed a consistent framework that integrates the origin, evolution, and current appearance of the universe.

Turner's opponent in the debate, Jim Peebles of Princeton University, took a more conservative view of recent progress in deciphering the cosmos. He prescribed caution in concluding that the key pieces of the cosmic puzzle have all been revealed.

The past year could mark a turning point for cosmology, Turner told a packed auditorium at the Smithsonian Institution's National Museum of Natural History in Washington, D.C.

Clearly, 1998 began with a jolt: Two rival teams studying the titanic explosion of distant, elderly stars overturned the prevailing belief that the cosmos has been slowing down its rate of expansion ever since the Big Bang. In fact, they reported, the universe is actually flying apart faster than ever before (SN: 3/21/98, p. 185; 10/31/98, p. 277).

Although entirely unexpected, that recent finding and others appear to unify elements of a cosmic portrait that have emerged over the past decade, Turner says. Stitching together such disparate concepts as energy associated with empty space, invisible matter in the universe, and the curvature of the cosmos, the new reports may turn out to mark a watershed for cosmology. Their impact could be every bit as important as the discovery more than 3 decades ago of the whisper of radiation left over from the Big Bang.



Turner

Sample of Michael S. Turner's artful viewgraphs.

In 1964, two physicists at Bell Laboratories in Holmdel, N.J., stumbled upon key evidence for the Big Bang. Scanning the sky with a radio receiver, they discovered a faint, uniform crackling. The pervasive nature of the signal and its intensity over a range of frequencies indicated that the radiation could not have come from the universe today. Instead, Arno Penzias and Robert Wilson concluded, it represents the radiation produced by the cosmos when it was young and extremely hot.

This radiation, known as the cosmic microwave background, is one of the cornerstones of the Big Bang theory. Along with measurements of the abundance of light elements forged just after the birth of the universe, the microwave background provides evidence that the universe began with the explosive expansion of a dense, hot soup of subatomic particles and radiation.

A fog of electrons pervaded the infant universe. For thousands of years after the Big Bang, radiation did not stream freely into space but was repeatedly absorbed and scattered by these charged particles.

About 300,000 years after the Big Bang, the universe became cool enough for the

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electrons to combine with nuclei. This lifted the fog, enabling radiation to travel unimpeded. Shifted to longer wavelengths by the expansion of the universe, this relic radiation is today detected as microwaves and far-infrared light. It provides a snapshot of the universe when it was 300,000 years old.

The Big Bang model has been phenomenally successful in explaining the events that took place beginning one-hundredth of a second after the birth of the universe. But by 1980, scientists trying to elucidate even earlier cosmic events were pushing the limits of the theory. The Big Bang model offers no explanation for the explosion itself, notes Turner. The dynamite that produced the Big Bang remains elusive.

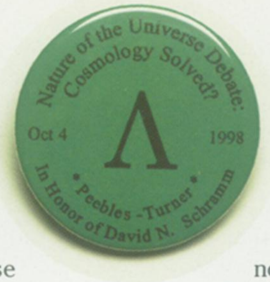
The model has other shortcomings. It does not reveal the nature of the matter that fills the universe. Nor does it explain why the young cosmos was so smooth and uniform and how tiny fluctuations in the density of the early universe could give rise to the lumpy collection of galaxies, clusters of galaxies, and superclusters seen today.

A theory known as inflation, developed and refined during the 1980s, provides a partial answer to these riddles. In this theory, the cosmos undergoes an extremely short but prodigious growth spurt. In just 10^{-32} second, the universe expanded more than it has in the 13 billion years or so that has elapsed since (SN: 6/7/97, p. 354).

This growth spurt captured chance subatomic fluctuations in energy and inflated them to macroscopic proportions. The action transformed the fluctuations into regions of slightly higher and lower density. Over time, gravity molded these variations into the spidery network of galaxies and voids seen in the universe today.

In inflationary cosmology, quantum fluctuations provide the energy for the expansion. According to quantum theory, the vacuum of space is far from empty. It seethes with particles and antiparticles constantly being created and destroyed. Energy from this vacuum can be tapped and is more than sufficient to trigger the era of explosive expansion dubbed the Big Bang.

This scenario gained support from a 1992 discovery: The microwave background does not have a uniform temperature but is full of hot spots and cold spots. The variations, a few ten-thousandths of a kelvin, were detected by the Cosmic Background Explorer (COBE) satellite. They are thought to correspond to slight variations in the distribution of matter at the moment when light and matter parted company, and radiation streamed freely into space. This finding was hailed as proof that microscopic lumps in the infant cosmos, no bigger than about 10^{-23} centimeters across, were the seeds for the galaxies and other large-scale structures we see today.



Buttons showing the mathematical symbol for the cosmological constant, the simplest form of the "funny energy" that may pervade the universe, were given out during the debate.

Inflation also explains the overall uniformity of the universe. Conventional Big Bang cosmology cannot account for how regions of the universe separated by distances so large that they have never even exchanged light signals can look so similar to each other. According to inflation theory, the universe began with regions so tiny that they were homogeneous. These regions then expanded into volumes vastly bigger than astronomers can ever observe.

Inflation makes the cosmos not only uniform but also flat. Any curvature to space-time is stretched out by the expansion, like a cosmic version of a balloon stretched to enormous proportions.

Over the past 4 years, nearly 20 ground-based and balloon-borne telescopes began measuring variations in the temperature of the cosmic microwave background over small spatial scales. The pattern of variations is known to be sensitive to the shape of the cosmos (SN: 2/21/98, p. 123). The measurements are not yet conclusive, but they suggest that the geometry of the universe is indeed as flat as the inflation theory would predict.

For the universe to be flat, astronomers calculate that it must contain a critical density of material. A variety of observations, however, including measurements taken over the past year, has revealed that the universe comes up short: It doesn't have nearly enough matter to be flat.

Of the four types of lightweight nuclei forged in the Big Bang, deuterium is the most sensitive indicator of the density of ordinary matter, which is made of protons, neutrons, and electrons. The greater the density of deuterium, the lower the density of ordinary matter (SN: 5/18/96, p. 309).

Because stars burn deuterium, the amount present today is not a good indicator of the primordial abundance, Turner notes. By measuring deuterium in very distant, essentially starless, hydrogen clouds, which hail from a time when the universe was very young, David R. Tytler of the University of California, San Diego and Scott Burles of the University of Chicago this year pinned down the amount of deuterium made in the Big Bang. Their measurements indicate that the density of ordinary matter contributes only 5 percent of the density needed for the universe to be flat.

Astronomers set their sights on clus-

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ters of galaxies to estimate the total density of matter in the cosmos, including exotic kinds of matter that would reveal their presence only through their gravitational influence. To weigh these behemoth clusters, the scientists use several methods. They measure the temperature of the X rays the clusters emit, and they determine the random motion of galaxies within a cluster.

With these methods, researchers recently found that the total density of matter is about 40 percent of the critical density.

This result has two profound implications, Turner notes. First, it suggests that most of the matter in the universe is not the familiar stuff that rocks and people are made of. Rather, it's some unseen, exotic material.

This dark matter could be remnants from the earliest, fiery moments of the universe, when high temperatures would have set the stage for the creation of a vast zoo of elementary particles. Slow-moving particles, generically known as cold dark matter, are the best candidates for this exotic material, Turner says. These particles would allow for the pattern of structures seen in the universe today, which indicates that it evolved from the bottom up, forming galaxies, then clusters of galaxies, and so on. Other theories had suggested that the large structures formed first, then fragmented.

The other consequence of the new measurements of matter density is even more startling. If the universe is flat, then there must be something else—a special form of matter or energy (the two are equivalent according to Einstein) that makes up the missing 60 percent of the critical density. Turner dubs this component "funny energy."

This special energy resists the gravitational pull of galaxies, so it distributes itself uniformly throughout the cosmos.

Funny energy "leads to a striking prediction," notes Turner. "The expansion of the universe should be speeding up, rather than slowing down."

How so? According to Einstein's theory of general relativity, gravity derives both from energy and matter and from pressure. The funny energy manifests itself as a negative pressure. If the universe contains a large enough component of funny energy, the net effect of gravity is to exert a repulsive, rather than an attractive, force. The expansion of the universe then accelerates rather than slows down.

In 1998, this bizarre state of affairs received tentative confirmation. Two teams of scientists, including researchers at the University of California, Berkeley and Lawrence Berkeley (Calif.) National Laboratory, examined a distinct type of exploding star, or supernova. Previous studies have suggested that this type, known as a supernova Ia, has the same intrinsic luminosity in both nearby and distant galaxies.

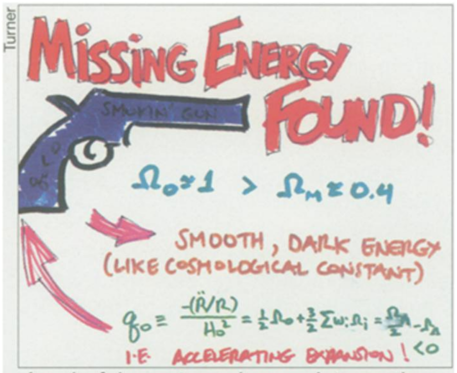
Because the light from a faraway galaxy takes several billion years to reach Earth, telescopes see such a galaxy as it appeared when the universe was younger. If cosmic expansion had recently slowed, then there should be less distance between Earth and a faraway galaxy—and a shorter travel time for light—than if the expansion had maintained its speed. A supernova in a distant galaxy would look slightly brighter in the case of the slowed expansion.

The researchers this year found exactly the opposite. Distant supernovas looked dimmer than expected, indicating that the universe has increased its rate of expansion.

Measurements of the geometry of the cosmos and the gravity within it finally add up, says Turner. "For the very first time, we have a complete and plausible accounting of matter and energy in the universe."

The avalanche of data now and expected over the next few years will go a long way toward explaining the basic features of the universe with a theory rooted in fundamental physics, Turner concludes. "What I want to argue is that in 1998, we had the first key evidence for a theory that takes us well beyond the hot Big Bang cosmology."

Turner



A colorful way to make a point: another cosmological cartoon from Turner.

Turner's debate opponent, Peebles, argues that nothing is settled until the proverbial fat lady sings—and as far as Peebles is concerned, she hasn't sung yet. Cautioning his colleagues not to go overboard in their enthusiasm, Peebles recalled the words of a cosmologist of an earlier era, Willem de Sitter, who admonished in 1931 that "it should not be forgotten that all this talk about the universe involves a tremendous extrapolation, which is a very dangerous operation."

"Observational advances since then have greatly reduced the danger," says Peebles, "but I think [they] should leave us with a sense of wonder at the successes in probing the large-scale nature of the physical universe and caution in deciding just how well we understand the situation."

"The basic tenets of inflation plus cold dark matter have not yet been confirmed definitively," Turner admits. He contends, however, that a survey under way to map the location of 1 million nearby galaxies and the planned launch of two NASA missions to record the cosmic microwave background in unprecedented detail "could make the case soon."

Peebles raises another criticism, which Turner acknowledges: The existence of an accelerating universe implies that we live during a very special time in the history of the cosmos. This circumstance harks back to the different behavior of the two components—matter and energy—that contribute to the critical density. The amount of mass per unit volume declines as the universe expands, but the energy density, at least in its simplest form, remains the same. Indeed, it is sometimes referred to as the cosmological constant.

Observations suggest that right now, the densities of matter and funny energy are roughly equal. The energy density is just beginning to take over from matter density as the factor controlling cosmic expansion. At an earlier time, when the mass density was higher, the global effect of gravity would have been attractive, and we would not have observed the universe to be accelerating.

The big question, quips Turner, "is the Nancy Kerrigan question: 'Why me, Why now?'" There's only one period when matter and energy densities are comparable, he notes, "and that's today, and we happen to be around."

Although he finds that seeming coincidence "bothersome," Turner doesn't see it undermining the model of an accelerating universe. He says, "Often in science as you answer one question, a new question is raised."

At the end of the debate between Turner and Peebles, moderator Margaret J. Geller of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., took a straw poll. She asked the listeners if they thought that a century from now, the basic concepts exciting astronomers this year would be cornerstones of understanding. Most of the audience thought the concepts would be substantially different.

Even if today's models endure, "solving cosmology does not mean the end of the study of the universe, nor even the beginning of a less exciting period of inquiry," Turner says in a monograph that accompanied his talk.

"A list of today's puzzles is long enough and challenging enough to occupy astrophysicists for decades: What are the objects that make gamma-ray bursts, and how do they work? How do galaxies form stars and light up the sky? How are stars born? . . . Is there life elsewhere in the cosmos? . . .

"With the flood of data coming, the list will only grow longer and more interesting," Turner concludes. "I am confident that there will be plenty of challenges for next century's astrophysicists." □