COBE Confronts Cosmic Conundrums

Now measuring the microwave background, the new satellite ultimately could help us understand how the galaxies formed

IT'S NOT OFTEN that a simple data plot inspires a scientific gathering to spontaneous applause. But then, the information pouring down from the National Aeronautics and Space Administration's new Cosmic Background Explorer (COBE) satellite is not just any data set.

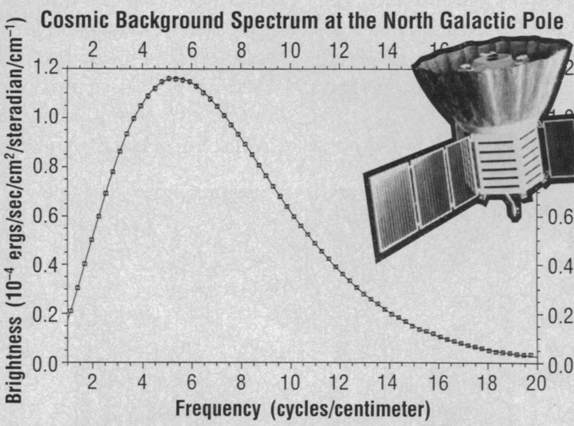
In the 2 months between its launch on 18 November and the January announcement of its preliminary findings before an enthusiastic gathering of the American Astronomical Society,* COBE has used its liquid helium–cooled detectors to make stunningly accurate measurements of the Big Bang's "afterglow"—the microwave background radiation that bathes every object in the universe with a cool wash of photons at 2.7 K. It has sent a wave of relief through the cosmological community by disproving a recent finding that seemed unexplainable by known physics. And it has confirmed that the Big Bang was a remarkably smooth and homogeneous event—so smooth, in fact, that the theorists are more baffled than ever: how could the Big Bang have possibly given rise to the galaxies and clusters of galaxies that so obviously exist around us today?

"We haven't ruled out our own existence yet," quipped COBE project scientist John Mather of NASA's Goddard Space Flight Center. "But I'm completely mystified as to how the present-day structure exists without having left some signature on the background radiation."

It was Mather who made the most dramatic announcement at the astronomical society, and the one that drew the audience into an extended ovation: COBE's measurement of the background radiation's precise spectrum and temperature.

Many of the astronomers had been waiting for the moment with a keen anticipation. In the quarter-century since the radiation was discovered in 1965, data from ground-based instruments at a variety of microwave wavelengths have consistently pegged its temperature at about 2.7 K. This consistency is just what is predicted by the standard Big Bang model, which holds that the radiation was emitted from the cosmic fireball just a few hundred thousand years after the Big Bang itself and has been cooling off ever since.

This happy conjunction of theory and observation got a jolt in 1987, however, when researchers from the University of California, Berkeley, and Nagoya University in Japan flew a sounding rocket to examine the radiation at infrared wavelengths inaccessible from the ground. They found what seemed to be a distinct warming trend at those wavelengths—a finding that left the theorists astonished. The Berkeley-Nagoya team was quick to caution against the possibility of systematic error, particularly since the results had not been replicated. (A follow-up rocket flight this past September failed to produce usable data.) But still, if the warming trend were real it implied that the cooling cosmic plasma had been roiled by massive energy outbursts, upheavals more powerful than could be accounted for by any known process. "You'd need the tooth fairy" to explain that much energy, says theorist David N. Schramm of the University of Chicago.



Applause line. *Measurements of the background radiation made by COBE (inset) fit a 2.735 K spectrum to 1%.*

Thus the astronomers' eagerness to hear definitive results from COBE. And thus the drama as Mather put up the viewgraph: in a plot of radiation intensity versus wavelength, the data points fell along the theoretical curve predicted by the standard model of the Big Bang like beads along a string. COBE's value for the cosmic background temperature was 2.735 ± 0.06 K, with no point deviating its predicted value by more than 1%. The Berkeley-Nagoya excess simply was not there.

"Most of us," says Schramm, "were very relieved."

The other COBE results reported at the astronomy meeting were less dramatic, but showed the promise of what is to come as the spacecraft continues on its 2-year mission. To take just one example, Berkeley's George Smoot and his colleagues are using the Differential Microwave Radiometer to look for "anisotropies": variations in the brightness of the radiation from point to point on the sky. Finding and measuring these anisotropies has emerged as one of the most critical issues in cosmology, says Smoot. They would presumably correspond to density variations in the cosmic plasma shortly after the Big Bang. And these variations, in turn, are presumably the clumps of matter that contracted by gravity to form the galaxies and clusters we see today.

The problem is that the anisotropies, if they exist at all, are so weak that it's hard to see how they could have contracted into much of anything. Any clump that is going to form a galaxy needs to be hefty enough to fight cosmic expansion, which tends to pull the material apart almost as fast as gravity can pull it together. And yet, says Smoot, with preliminary measurements now completed over about 75% of the sky, COBE shows no anisotropies at all to an accuracy of one part in 10^4. By the end of its mission, moreover, COBE should improve its accuracy by a factor of 10, to one part in 10^5. Ground-based measurements on smaller segments of the sky have already done almost that well without finding any anisotropies; if COBE confirms that result over the entire sky, then the theorists are going to be in trouble.

They may be in trouble anyway, even if COBE does find the anisotropies. The most popular explanation for how these weak fluctuations grew into galaxies is that they had outside help from the "dark matter"—an invisible ectoplasm that is thought to make up 90 to 99% of the mass in the universe, and that could have swept the ordinary matter along as it formed gravitationally bound clumps at an enormously accelerated rate. Judging from the observed motions of the visible galaxies, in fact, dark matter is all that is holding them together

*The 175th meeting of the American Astronomical Society, 9 to 13 January 1990, Washington, D.C.

today. The presumption is that the dark matter consists of some kind of massive, but weakly interacting elementary particles produced in the Big Bang. And indeed, with the additional assumption that the dark matter particles are slow-moving, or "cold," the theory explains the observed properties of galaxies and clusters quite well.

What the cold dark matter theory cannot easily account for, however, are the structures that astronomers have begun to find on extremely large scales. In that context, two findings discussed at the meeting independent of COBE were especially noteworthy:

■ **The Great Attractor.** The existence of this structure has been a matter of continued controversy since 1986, when a redshift survey conducted by a team of seven astronomers—"the Seven Samurai"—seemed to reveal that our galaxy and every other galaxy for hundreds of millions of light-years in every direction were streaming toward a region of the southern sky at hundreds of kilometers per second. Their conclusion was that something was pulling at us, a diffuse concentration of mass centered some 150 million light-years away and containing several quadrillion times as much mass as the sun, or about ten times the mass of a typical supercluster of galaxies. The trick has been to convince other astronomers: It's very hard to understand how cold dark matter or

Looking Forward to Hubble

After years of delay and frustration, astronomers and NASA officials alike are beginning to feel like children looking forward to Christmas: on 19 April, if all goes according to schedule, the space shuttle Discovery will at last climb from its launch pad, bearing the $1.6-billion Hubble Space Telescope.

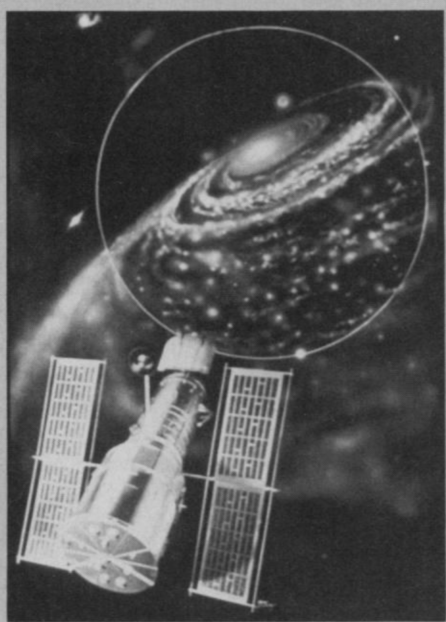
Indeed, as the launch approaches, the software problems and scheduling headaches that have dogged the instrument's development (*Science*, 17 March 1989, p. 1437; 22 December 1989, p. 1551) have receded into the background, and science is coming to the fore. At a prelaunch press briefing on 8 and 9 January, scientists at the Space Telescope Science Institute in Baltimore gave a tour d'horizon of some of the cosmic features that may soon be visible for the first time, and they explained the telescope's three major advantages over ground-based instruments—high angular resolution, broad wavelength coverage, and the ability to see very faint objects.

■ **High angular resolution.** Space Telescope's workhorse imaging instrument, the Wide Field/Planetary Camera, should be able to resolve objects on a scale of 0.1 arc seconds. That's about ten times better clarity than telescopes can typically attain on the ground through the murk of the atmosphere and about 600 times better than the unaided eye. The institute's public affairs director, Eric Chaisson, who is himself an astronomer, points out that this will be the biggest single jump in astronomical resolving power since Galileo turned his first handmade telescope to the heavens in 1610.

Within our own solar system, for example, the telescope will provide Voyager-quality images of the cloudscapes on Jupiter and will show us Pluto—the only outer planet not visited by Voyager—almost as well as we can see the face of the moon with the unaided eye. Further out, the telescope should be able to image gas and dust shells ejected from Supernova 1987A, about 170,000 light-years from Earth. It will peer into the heart of our galaxy's globular clusters to see if these star-rich systems contain massive black holes. It will try to image material falling into a supermassive black hole that many astronomers believe lies about 2 million light-years away in the core of our nearest cosmic neighbor, the Andromeda galaxy. And at cosmological distances, it should provide the first clear images of newborn galaxies forming, colliding, and evolving in the aftermath of the Big Bang.

■ **Imaging very faint objects.** When it comes to analyzing the spectra of very faint objects, where the name of the game is sheer size and light-gathering power, the instruments of choice will still be the ground-based behemoths such as the 5-meter Hale telescope on Palomar Mountain, or the 10-meter Keck Telescope soon to be completed on Mauna Kea. Space Telescope's 2.4-meter primary mirror is decidedly modest in comparison.

However, when it comes to making *images* of the faintest stars and quasars, Space Telescope will be unsurpassed: the absence of atmospheric background light in space should allow it to see compact sources down to the 28th or 29th magnitude, or about 50 times fainter than is possible from the ground. Among other things, this should allow the telescope to image individual stars in distant galaxies. And that, in turn, should allow astronomers to calibrate the size and age of the universe—which is today uncertain by a factor of 2—to better than 10%.


D. Berry

Coming into focus. *This artist's conception gives an indication of what Space Telescope's clarity will mean for astronomy.*

■ **Large wavelength range.** Fortunately for human life and health, Earth's atmosphere provides a very effective shield against ultraviolet light. Unfortunately for astronomers, however, the atmosphere also screens out a rich array of atomic absorption and emission lines in the ultraviolet, the most notable being the intense Lyman alpha line of hydrogen. Space Telescope's two spectrographs will therefore be breaking new ground almost everywhere they look.

A prime example is the spectra of the quasars, which sprang to life only a billion years or so after the Big Bang, and which shine like searchlights through galaxies and primordial gas clouds along the line of sight. Spectra taken from the ground in visible light have already revealed the most distant of these intervening objects as a "forest" of highly redshifted Lyman alpha absorption lines. Ultraviolet spectra taken by Space Telescope should likewise show absorption lines from the closer, more recent objects. The result should be a complete record of how galaxies formed, evolved, and clustered as the universe expanded.

■ M. Mitchell Waldrop

anything else could have produced mass concentrations of this magnitude.

At this meeting, however, the controversy was notably absent. Two of the original Seven Samurai, Alan Dressler of the Mount Wilson and Las Campanas Observatories, and Sandra Faber of Lick Observatory presented a survey showing that galaxies on the far side of the purported Great Attractor are falling back inwards, thus demonstrating that there really is a mass concentration there. At the same session, moreover, Robert A. Schommer of Rutgers University presented the results of an independent survey that showed the same thing.

In short, the Great Attractor is real. Now, where did it come from?

■ **The Great Wall(s).** Just last fall, Margaret J. Geller and John P. Huchra of the Harvard-Smithsonian Center for Astrophysics announced their discovery of "the Great Wall"—a system of thousands of galaxies arrayed across the cosmos in the form of a vast, crumpled membrane (*Science*, 17 November 1989, pp. 885 and 897). With a width of at least 500 million light-years, it seemed to be the largest coherent structure ever seen in the universe. The question was whether it was anything more than a statistical fluke, a chance superposition of smaller structures. If so, then the Great Wall would be at least as hard to understand as the Great Attractor.

Now the answer is in, and it seems to be "Yes." At the meeting, Alex S. Szalay of Johns Hopkins University and David C. Koo of Lick Observatory presented a compilation of four galaxy surveys at the north and south galactic poles—the two opposing points on the sky where the interference from stars and dust in our own galaxy is least. Each survey covers a very narrow patch of sky, but compensates by including galaxies that are very faint and very distant. In effect, the combined survey yields a core sample through the universe. And when Szalay and company plot the number of galaxies as a function of redshift, it becomes very apparent that the Great Wall is not alone: other concentrations of galaxies occur with a nearly periodic spacing of about 400 million light-years.

Whatever this repeating structure means, says Szalay—he prefers to call it a "characteristic distance" rather than a periodicity—it is telling us something profound about how the large-scale structure of the universe came into being. The question is what?

It is also telling us what many other astronomers at the meeting were saying: the cold dark matter model is dead. The question is what will replace it? No one yet seems to have an answer.

■ M. MITCHELL WALDROP

Understanding the Simplest Reaction

Sixty years after its initial development, quantum mechanics has finally succeeded in completely describing the simplest possible chemical reaction. A team headed by Richard Zare at Stanford University has shown that the reaction $H + H_2 \rightarrow H_2 + H$ proceeds almost exactly as predicted by two separate groups of theoreticians, one led by William Miller at the University of California at Berkeley and the other by Donald Truhlar at the University of Minnesota in Minneapolis.

Although this might seem like a small step to those outside the field of chemical dynamics, Miller says, "We're all jumping up and down." Long ago, the equations of quantum mechanics were solved to give the precise behavior of individual atoms, but the dynamics of chemical reactions—interactions involving at least three atoms and the exchange of one or more atoms—had defied exact description.

The transfer of a single hydrogen atom in $H + H_2 \rightarrow H_2 + H$ may look simple, but it was not easy for either theorists or experimental scientists to get a good look at it. For experimentalists, Zare says, the problems include producing hydrogen atoms that move fast enough to overcome the electrical repulsion from H_2 molecules and measuring how many product molecules are in a given quantum state.

In his work, Zare actually performed the reaction $D + H_2 \rightarrow HD + H$, where D is deuterium, a heavy isotope of hydrogen with one proton and one neutron. The theoretical calculations for this reaction are almost identical to the ones involving only hydrogen atoms, and the substitution of deuterium makes it easier to identify the end products. Zare used a laser to split DBr molecules, creating D atoms with enough energy to react with molecules of H_2. After the reaction, the same laser ionized the HD molecules so that they could be detected and analyzed by a mass spectrometer.

Zare measured how many HD molecules were produced in the reaction with a given rotation, or spin, and compared this distribution with those predicted by Miller and Truhlar. Within experimental error, "there is nearly perfect agreement between theory and experiment," Zare says. He also compared his results with calculations made using the quasi-classical trajectory approximation—a technique that omits some of the quantum effects—and found its estimates to be slightly but consistently off.

For theorists, the problems in calculating the reaction arise from the need to solve quantum mechanical equations for three atoms—with six or more individual particles—with the atoms moving relative to each other. Just a few years ago, theorists first computed the total reaction rate of $H + H_2 \rightarrow H_2 + H$ as a function of how energetically the H atom and H_2 molecule come together. At the time, however, they still were unable to calculate the fine details, such as the probability that the product H_2 molecule would be in a given vibrational and rotational quantum state.

The technical difficulties, Truhlar says, centered on the boundary conditions—the mathematical descriptions of the system before and after the reaction. The exchange of atoms makes it difficult to match up the before and after boundary conditions. Truhlar sidestepped the difficulty by transforming the problem of solving differential equations with boundary conditions into a problem in linear algebra.

Miller says he and John Zhang discovered a subtlety about the boundary conditions that had hampered calculations. "Once we realized this subtlety, there were lots of simplifications that were obvious," he says. Those simplifications made computing the reaction's dynamics "straightforward, although not trivial," he says.

Earlier experiments by Richard Bersohn at Columbia University showed that the total reaction rate of $H + D_2 \rightarrow HD + D$, where the initial and final quantum states were not taken into account, was predicted quite well by the quasi-classical trajectory method. Now Zare's work shows that although quasi-classical methods may be good enough to predict the broad outlines of the reaction, quantum mechanics is needed to provide the details. "The world really is quantum mechanical on the molecular level, not classical," Zare says.

■ ROBERT POOL

ADDITIONAL READING

N. C. Blais, M. Zhao, D. G. Truhlar, D. W. Schwenke, D. J. Kouri, "Quantum mechanical calculations and quasi-classical trajectories for comparison to stimulated Raman pumping measurements of the high-energy state-to-state reaction dynamics of $D + H_2 \rightarrow HD + H$," *Chem. Phys. Lett.*, in press.

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J. Z. H. Zhang and W. H. Miller, "Quantum reactive scattering via the Kohn Variational Principle; differential and integral cross sections for $D + H_2 \rightarrow HD + H$," *J. Chem. Phys.* **91**, 1528 (1989).