

COPYRIGHT NOTICE:

Michael D. Lemonick: Echo of the Big Bang

is published by Princeton University Press and copyrighted, © 2003, by Princeton University Press. All rights reserved. No part of this book may be reproduced in any form by any electronic or mechanical means (including photocopying, recording, or information storage and retrieval) without permission in writing from the publisher, except for reading and browsing via the World Wide Web. Users are not permitted to mount this file on any network servers.

For COURSE PACK and other PERMISSIONS, refer to entry on previous page. For more information, send e-mail to permissions@pupress.princeton.edu

CHAPTER 1

Is Something Amiss in the Universe?

Spring does not come subtly to Princeton University. It's early April 2002, and even after a mild winter, the brilliance of the campus in full bloom is almost overwhelming. The air is still uncomfortably cool, but vivid color is visible no matter where you look. Daffodils and hyacinths cover the ground; forsythia bushes burst with yellow flowers at eye level; cherry and magnolia trees are clouds of pink and white overhead. David Spergel doesn't notice any of this. He's much too distracted. A few weeks ago, he discovered evidence of something surprising and unsettling about the universe, evidence suggesting that its fundamental character is not what astrophysicists have believed for the past two decades or so. Papers published by other astrophysicists over recent months have declared that the cosmos is, at last, well understood. Modern cosmology, they say—the branch of astronomy that dares to address the ultimate questions about the birth and death of the universe—is essentially solved, only eighty years or so after it was founded. All that remains is to

tidy up the last few decimal points. Newspapers and magazines have dutifully reported this comfortable conclusion, much as they reported a strangely similar comment made by the American physicist Albert Michelson in 1894: “While it is never safe to say that the future of Physical Science has no marvels even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice.” Within a few years after that declaration, physicists would discover such previously unsuspected phenomena as radioactivity, subatomic particles, relativity, and quantum mechanics.

But David Spergel has reason to believe that cosmology is not solved. For a few hours he was the only one on Earth who had evidence to support this doubt. He may even have been the only one in the universe who had it. Now a small group of colleagues, fewer than twenty in all, have seen the evidence as well. They’ll tell the rest of the world early the following year, most likely at a press conference at NASA headquarters. Their announcement will almost certainly be accompanied by the sort of public-relations blitz NASA has perfected in more than forty years of space exploration and discovery. The space agency puts on press conferences at different levels of breathlessness, from mild to hyperventilation, depending on what’s being announced. The discovery of a new isotope of tin in the dust that floats between the stars doesn’t generate much enthusiasm. The claim of evidence of life in a Martian meteorite gets the full treatment.

But for now, Spergel is focused on convincing himself and the others that what he’s found is real rather than some glitch in the satellite that has been scanning deep space for the past nine

months, or a bug in the computer code he uses to analyze its observations. Either of these is possible, for no matter how careful Spergel and his colleagues at Princeton and a handful of other institutions have been, the chance of a mechanical or electronic or software flaw, either new or too subtle to have been noticed over the past six years of careful work, may be making its presence known now, at the worst possible moment. The last thing these astronomers, physicists, and engineers want to do is make the shocking claim that much of the work of cosmology over the past two decades has been based on a faulty theoretical foundation—and then, a few months later to say, “Never mind.”

This is looking increasingly unlikely, though. At first, when he told the others about what he’d found, they were appropriately skeptical. Spergel is one of the smartest, most talented theoretical astrophysicists around. That’s why he was recruited for this project in the first place, and why, in the fall of 2001, the forty-year-old scientist had won a MacArthur Foundation “genius” grant. But even geniuses can make a mistake when they’re writing hundreds of thousands of lines of computer code. Even geniuses can think they see patterns in data when the patterns aren’t really there. Even geniuses are human enough to leap to world-shaking conclusions while overlooking a mundane explanation for what they’ve evidently found. Besides, the others on the team—all of them extraordinarily bright, even if the MacArthur committee hasn’t formally certified them as such—have also looked at the data, and they can’t think of any mundane explanation, either. The computer code is working fine. The satellite is performing as close to perfectly as anyone could wish. And it’s simply not telling the story everyone expected.

In principle, of course, scientists aren’t supposed to expect anything when they go into an experiment. They’re simply sup-

posed to observe, as objectively as if they were robots, aware of, but unprejudiced by, what their predecessors have seen. But they aren't robots. Science is an intensely human enterprise. Observers go into a new experiment with both expectation and hope. Unless it's the first time an experiment is being done, they generally expect that existing theories or assumptions are probably correct, that this latest attempt to observe and measure will expand or refine what we already know. This is true often enough that it can prove dangerous: people tend to see what they're expecting to see. When that happens, says Tod Lauer, an astronomer at Kitt Peak National Observatory in Arizona, "you're not likely to double-check it very carefully. Whereas if you see something unexpected, you recheck it over and over to figure out where you might have been fooling yourself." Yet the "correct" observation could be equally wrong. An observer can be too quick, in other words, to dismiss a crucial, telltale anomaly as nothing more than experimental error.

Scientists can also be tempted to err in precisely the opposite direction. It's important and satisfying to confirm or refine an existing theory with higher precision than anyone's ever achieved before. But most scientists agree that it's even more satisfying to prove the conventional wisdom utterly wrong. Showing yet again that Einstein's general theory of relativity is correct is certainly a good thing; refuting it would be a much bigger deal (that's one reason Einstein refutations are the number-one choice of cranks who send their handwritten "manuscripts" to physicists and science journalists).

So if a scientist discovers something dramatically new and important—cold fusion, say, or the first evidence of a planet orbiting a star other than the sun—it can be tempting to shout the news before you've thought it through. In the former case, two

chemists from the University of Utah coined a new shorthand for “discovery that really isn’t.” But even when you have thought it through, you can overlook something. In 1991, a radio astronomer named Andrew Lyne thought he’d discovered planets orbiting a pulsar, the dense, burned-out remnant of an exploded star. He knew this was an audacious, even a preposterous claim, so he did every test he could think of to explain it away as a glitch. Eventually, he went public, only to realize to his horror that he’d failed to think of the one test that actually could—and in fact did—prove that the planets weren’t there after all. Lyne’s public apology to the astronomical community was deemed by John Bahcall, then president of the American Astronomical Society, to be “the most honorable act I’ve ever witnessed.” But that didn’t make Lyne feel much better.

Finally, there’s a more subtle source of confusion in presenting new data. It’s common that the first studies or experiments to explore a scientific question are inconclusive, but suggestive. The instruments in question—the telescopes, or particle detectors, or seismographs—are pushed to their limits of sensitivity, and find evidence that’s not quite definitive. Depending on their confidence, researchers might play up or play down what they’ve found—label it a tentative discovery, or merely an interesting result. A long-sought particle known as the Higgs boson may have turned up in 2000, for example, in experiments at the Large Electron-Positron Collider in Europe. Or it may not; because of a scheduled major upgrade of the equipment, the experiment couldn’t be run long enough to make a definitive measurement—although the physicists pleaded for a few more months. These scientists opted for caution, and didn’t claim a discovery.

In medicine, by contrast, the public demands to hear about every result, preliminary or not, and often acts on it. When doc-

tors found a relationship between fresh vegetables and reduced risk of cancer, they deduced that beta carotene, a chemical found in many vegetables, was a likely reason. Beta carotene supplements, they said, might be a good idea. So people began swallowing beta carotene pills by the handful. Later studies showed that taking these supplements actually raised the risk of cancer in some people. Something similar happened when doctors first established a link between saturated fats and heart disease. They suggested it might be wise to switch from butter to margarine. Then, a few years later, they discovered that the processed, or hydrogenated, vegetable oil in margarine was actually worse for the heart than ordinary saturated fat. So the recommendation swung back. People were indignant and assumed that medical scientists didn't know what they were talking about. But the earlier recommendations were as good as the data permitted them to be. The mistake, largely the fault of health experts and journalists, was that the provisional nature of the research was downplayed in the interest of making a good story.

Among the sciences, cosmology is especially prone to the danger of premature conclusions. One reason is that it's not an experimental science. There is only one universe, and it's physically inaccessible. You can't deduce its underlying structure or behavior or laws by taking one apart in the lab, or by varying the growth medium and cultivating a new one to see what happens. It's hard, moreover, to gather information about the cosmos; the photons of electromagnetic radiation that carry information about the stars and galaxies are sparse, and they overlap with each other in a tangle of data that must be untangled. As a result, astronomers have always been forced to build their models of the universe, initially at least, on meager information. A century ago it wasn't even clear that a universe existed beyond the Milky

Way. Eighty years ago, nobody imagined that the universe was expanding. Forty years ago, the Big Bang was a somewhat crackpot theory.

Time after time, astronomers have been startled to realize how much less they understood about the universe than they'd thought. Confident statements about its basic nature have been proven not just wrong, but deeply, profoundly and sometimes embarrassingly wrong. In almost every case, the mistakes have been based on incomplete information, which in turn has been the fault not of sloppy observers but of primitive technology. In the 1920s, when the modern picture of the cosmos began to emerge, the largest and most powerful telescope on Earth had a light-gathering mirror just 100 inches across; the largest today spans nearly 400. The most sensitive medium for recording that light was the photographic plate, which was much better than the human eye but still very inefficient and inconsistent; today's charge-coupled devices, or CCDs, are a hundred times better.

And that just covers visible light. Nobody suspected a century ago that it would be useful to explore the full range of the electromagnetic spectrum, of which visible light is only a small subset. As the wavelength of light becomes shorter and shorter, visible light shades into ultraviolet, which humans can't detect (but which causes sunburn nonetheless). As the wavelength shrinks further, ultraviolet gives way to X-rays, then gamma rays. All three are part of the electromagnetic concerto broadcast by the universe, by individual stars and black holes and knots of superheated gases; all three carry telltale messages about the nature of these phenomena; yet none of them was part of astronomers' observing programs, nor even contemplated.

The same applied to the region of the spectrum with wavelengths longer than those of visible light. If short-wavelength

radiation corresponds to the right-hand keys, the high-pitched notes, on a cosmic piano, then infrared radiation, microwaves, and radio waves are the bass notes to the left. By the 1920s, physicists understood something about radio waves, and broadcasters had begun to exploit them, first to send Morse code across the oceans and then to send news, and music, and jingles for selling detergent. In the early part of the twentieth century, Guglielmo Marconi even aimed his primitive wireless antenna toward the planet Mars, to try and pick up any broadcasts the Martians might be directing toward their sister planet.

But Marconi never tried to listen for natural radio emissions from the heavens. Nobody did. And so the deepest tones of the cosmic electromagnetic concerto, like the high notes, went unheard. Astronomers tuned in only to the few notes they could get to at the center of the keyboard. What they learned was true, as far as it went. But the bass and treble notes they couldn't hear would, time and again, alter the melody beyond recognition. Quasars, black holes, neutron stars, dark clouds of organic chemicals between the stars were all invisible, and in many cases unimagined, until astronomers learned to probe the high- and low-pitched frequencies of light.

So it was as well with the experiment David Spergel and his colleagues are now engaged in. Anyone who watched television before the days of cable, or who still gets a TV signal out of the air, remembers "snow"—the salt-and-peppery visual static that filled the screen when a set was tuned to a weak or nonbroadcasting channel. Nobody ever gave it much thought, except to curse at it; those who did figured it was some electronic noise in the picture tube, or maybe a distant station, coming through so feebly that the picture had disintegrated.

But at least some of those electronic crackles were and are something much more important than that. They're a message from the birth of the universe—a detailed record of the beginnings of space and time, and of the subsequent evolution of the cosmos. Every minute of every day, the Earth is bombarded with a barrage of photons, the particle-like building blocks of electromagnetic radiation. Most of these come from the Sun and the stars; they were emitted anywhere from today to a few thousand years ago. The photons that help wash out the *Today Show* and *Sesame Street*, though, are thousands of times older. They are by far the oldest radiation in the universe—the electromagnetic echo of the Big Bang itself. These photons began their journey through intergalactic space about 14 billion years ago. At that time, they carried an intensity as bright as that of the Sun. If we'd been around to see them, we'd have been blinded by a yellow-white brilliance bombarding us from all directions at once. Now, enfeebled during their long journey, they've cooled from about 6000° Celsius to -270°—a bit less than three degrees above absolute zero, the coldest temperature possible. Their nature has shifted too, down from visible light to near infrared and finally into the microwave part of the spectrum—a bass note in the electromagnetic keyboard, not quite as deep as a radio wave, but much lower than the middle octave of ordinary light.

Ever since Einstein founded the science of theoretical cosmology by treating the universe of space and time as a distinct object with distinct attributes, and especially since Edwin Hubble discovered the expanding universe in 1927, physicists and astronomers have tried to divine the origin and fate of the universe. Stars, planets, and even galaxies come and go, but they do so on a grand stage that has its own, independent history. But it wasn't

until the 1940s that theorists realized that the expanding universe must have loosed a burst of hot photons, and it wasn't until 1965—an astonishingly long interlude, in retrospect—that observers first identified them. When John F. Kennedy was assassinated—an event that seems to tens of millions of Americans as though it happened yesterday—the Big Bang model of the universe was still considered a long shot, and rightly so.

The fact that this background glow of cosmic microwaves existed at all was powerful evidence that the Big Bang had taken place—an unmistakable announcement that the universe had a birth date. But theorists quickly realized that it could also be used as a powerful diagnostic tool. The modern universe, they knew, is lumpy—mostly empty space, punctuated, at varying levels of organization, by stars, galaxies, clusters, and superclusters of galaxies. These lumps must have started as variations in density in the newborn universe, which grew, under gravity, into their present form. But since the newly found glow of microwaves was emitted when the universe was a mere 300,000 or so years old, any density variations present at the time should have left their imprint on it. A slightly overdense region would have been very slightly hotter than average, while a slightly underdense region would have been cooler. And these temperature differences should still be detectable, even after 14 billion years.

The hot and cold spots, moreover, should be a direct consequence of the physical conditions present at the time—of the temperature and pressure and composition and previous history of the young universe. If you could see them sharply enough, you could figure out how big they were, and how much hotter the hot was than the cold, and the ratio of big hot spots to medium to small to tiny. And using standard physics, that informa-

tion would in turn tell you what the young universe was made of (a bowl of Jell-O vibrates differently from a bowl of oatmeal, after all), and how dense it was, and what forces were in play at the time. By comparing maps of the microwave background radiation with maps of the present-day cosmos, astronomers could also piece together the story of how we got from there to here—exactly how the galaxies formed, and how the Earth and its inhabitants ultimately came to be.

With all this information hidden within it, the cosmic microwave background radiation, or CMB, was the astronomical equivalent of the human genome. Just as the genome bears all of the data required to manufacture and operate a human being, the microwave background encodes all of the information—all the initial conditions and physical laws—for making and operating a universe.

The major difference is that the genome has been relatively simple, if laborious, to read, but so complex that geneticists don't expect to understand it fully for decades. The genome of the universe, by contrast, would be simple to understand if only astrophysicists could read it. It's so faint, though, and so badly contaminated with other sorts of radiation from our own planet and the solar system and the galaxy that only in the 1990s could astronomers finally see the hot and cold spots for the first time. It took a satellite, the Cosmic Background Explorer (COBE), to do so. Seeing anything at all after so many years of searching was so exciting that astrophysicist George Smoot, the principal investigator on one of COBE's key instruments, declared at the time that "it's like seeing God." He could have said more accurately that it's like seeing God through Coke-bottle eyeglasses that haven't been cleaned for a year. The satellite showed for the first time that the spots were there, which came as a relief to

cosmologists who were beginning to wonder. But the images were much too crude to say much more than that.

Still, COBE did help solidify the so-called Standard Model of the universe, a model that had begun taking shape in the 1920s with the discovery of the expanding universe. Over the years it had been modified to accommodate a number of theories and discoveries—that the early universe was hot and dense, that the cosmos is suffused with mysterious “dark matter,” probably in the form of a yet-undiscovered particle; that spacetime underwent a brief but dizzying period of hyperexpansion known as inflation. But just as was the case forty or fifty or eighty years ago, suggesting that these elements of the Standard Model are “known” is an intellectually dangerous concept. Now, as then, some of what’s known is almost certainly wrong, perhaps subtly, perhaps egregiously. The best way to put the Standard Model on a firm footing, or, alternatively, to expose its unsuspected weaknesses, is to take a harder, sharper look at the CMB; to see the details the COBE satellite couldn’t; to read the genome of the universe with high precision.

In the aftermath of the COBE satellite, that’s just what cosmologists proposed to do. They would build another satellite to take the next step. This time, they wouldn’t be satisfied just with detecting the cosmic ripples: they’d also measure their intensity and distribution and characteristic sizes. They’d try do it faster, and for less money than COBE had used up; Daniel Goldin, the NASA administrator, proclaimed in the early 1990s that henceforth his agency would be doing everything “better, faster, cheaper.” COBE, which had cost \$500 million and taken an agonizing fifteen years from concept to launch, was a good illustration of what he wanted not to repeat. Even under the best of circumstances, though, it would take years to decide precisely

what the design of the new satellite should be and who would build it, and then to construct and launch such a complex, delicate piece of machinery.

One team of cosmologists would be selected among several applicants to design and build the new satellite, which would ultimately be named MAP, the Microwave Anisotropy Probe. But others would try to make the measurements from the ground or from balloons floating in the stratosphere. Their measurements would be contaminated with microwave emissions from the air and the ground, and would thus be harder to decipher. They would be able to scan only a small part of the sky. As with a public opinion poll, it might be possible to get a good idea of the overall situation by surveying only a fraction of the available data. But it also might be highly misleading; if you'd polled voters only in New York City prior to the 2000 presidential election, you'd have predicted a landslide for Al Gore.

These limited experiments might, in other words, answer some of the great open questions in cosmology before the satellite could, but it would be hard to know for sure that they'd really done it. Sometimes the marginal experiments that precede a definitive one are wrong or misleading. Sometimes they're right but are ignored because someone failed to make a crucial connection between theory and observation, or because the field is not yet mature enough to put things into their proper context. The expanding universe was officially discovered in 1927, but the evidence was already there in 1920. The CMB was arguably first detected in 1939, a quarter-century before the formal discovery, but it went unrecognized. The experiment that was finally credited with seeing the CMB in 1965 had first taken place in 1961 and been analyzed—incorrectly—in 1962. The scientists who did it decided there was nothing there. Only when a second

team of observers tried again did they make the discovery. And while COBE's detection of ripples in the CMB made headlines, the ripples were actually seen a few months earlier by microwave detectors in several other experiments—but the physicists who saw them weren't confident enough of their results to report them.

Mindful that they might be able to find at least some of the answers MAP would be seeking before the satellite could be launched, ground-based observers would be working harder than ever through most of the 1990s. Given the drawbacks of their experiments, they would have to weigh carefully just how early and how definitively to present whatever results they might get; it would be professionally delicious to scoop MAP, but it would be embarrassing to be first but wrong. Nevertheless, it would be easier and quicker to take measurements from the ground than from space. In the decade that would ultimately elapse between COBE and MAP, plenty of other groups would make discoveries about the cosmic microwave background. Some might say “margarine” when the real answer would turn out to be “butter.”

But MAP, when it finally reported in, would end much of the debate. When great questions about the universe are first asked, the relevant observations are almost always too sparse and too unreliable to give solid answers. The data eventually become good enough to change that, the questions are laid to rest—and sometimes, unsuspected questions are newly posed. Thanks to its sensitivity and extraordinary performance, David Spergel knows that MAP will do the former, and he hopes for the latter as well. He just needs to make sure that he understands what MAP is telling him before he tells it to the world.