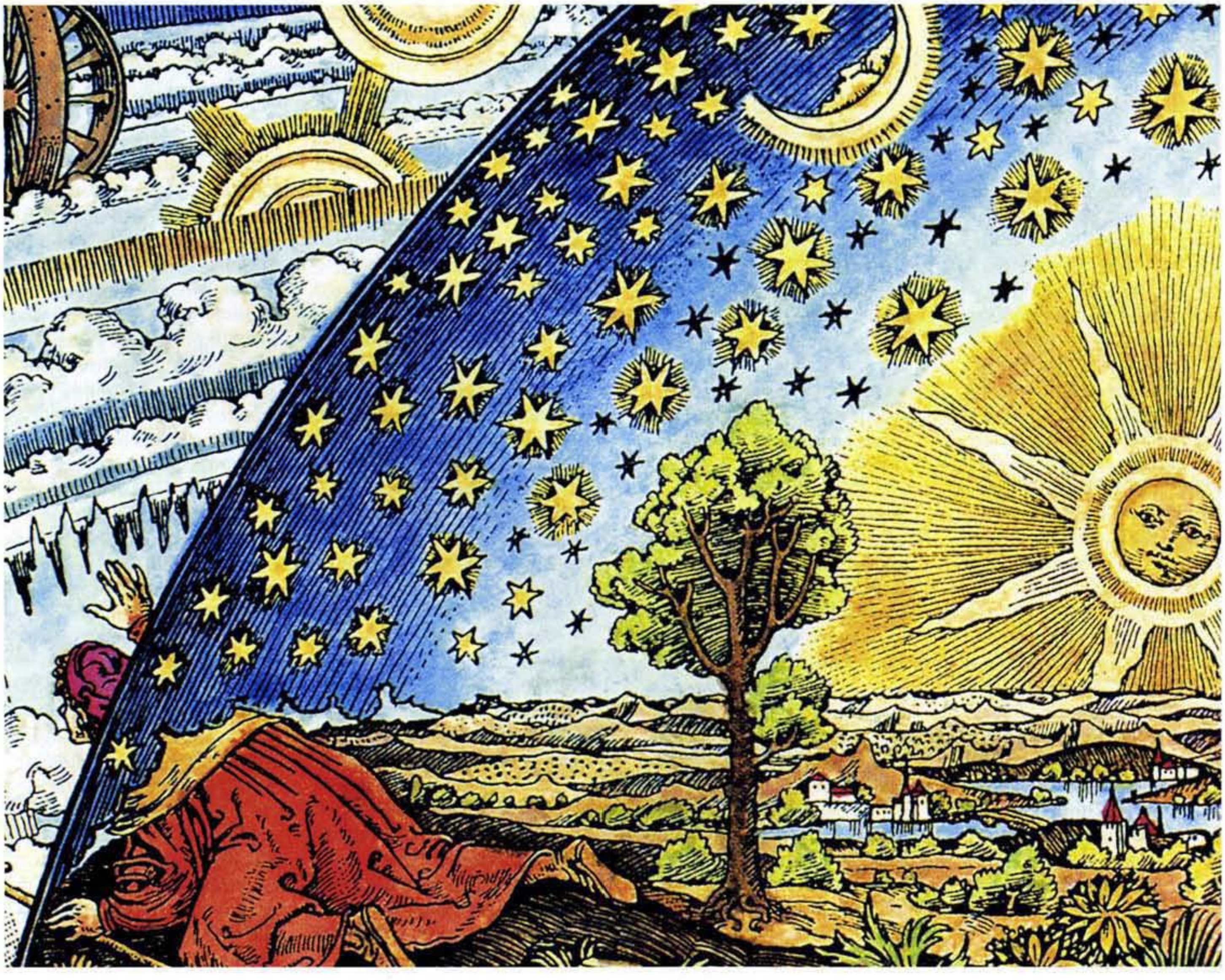
We have a clear view back to that moment in cosmic history when the universe turned transparent. By analogy to a human lifetime, this is about six hours after conception—before the zygote has divided for the first time.



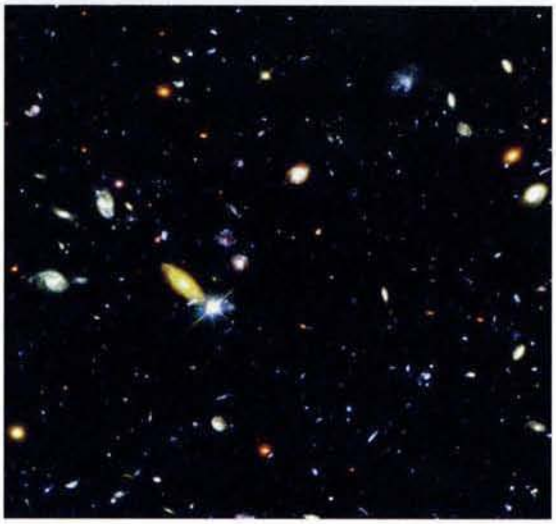
An Ultrasound Portrait of the Embryonic Universe

by Andrew E. Lange

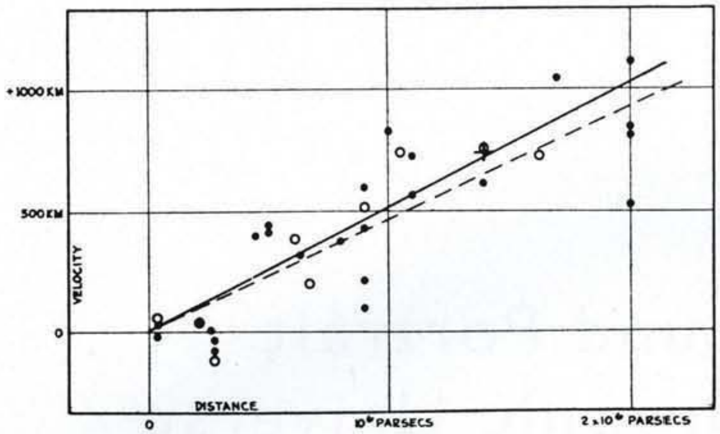
I've been working with telescopes carried aloft by balloons since I was a graduate student. We'd launch them from Palestine, Texas, and my job was to drive like a bat out of hell all night long to Tuscaloosa, Alabama, to set up the downrange station. Then, when the balloon lost radio contact with Texas, I could receive the data in Alabama. And, as will not surprise my wife, I was frequently stopped for speeding—once in Louisiana, which is something you never, ever want to have happen to you. The sheriff, who looked a lot like Jackie Gleason, was actually wearing pearl-handled revolvers. He took me to the sheriff's station, and I was rambling on and on about how we were trying to take pictures of the early universe. He didn't say a word for quite a while. Then he looked me in the eye and said, "Now whadya want to do a thing like that for?" Well, I think that part of being human is a fundamental desire to look beyond the limit of our vision, because another very human instinct tells us that if we do (and this applies to the microscopic scale as well), we're going to find something wonderful. And the project I'm going to tell you about, called BOOMERANG, for Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics, has done just that.

The artist who made the woodcut at left had the same idea—if we could somehow look beyond the stars, there would be some wonderful, magical world "outside." The most powerful equivalent of our eyes these days is the Hubble Space Telescope, which is sensitive to the same wavelengths we see. At right is a piece of the so-called Hubble Deep Field, in which the Hubble stared at a tiny corner of the sky for 10 days straight in order to see as far as it could possibly see. Of all the objects in this image, only two are stars—the rest are galaxies. But our artist would have been deeply disappointed by this picture, because if you look between the galaxies, it's just dark. There's no glowing, otherworldly "beyond" out there.

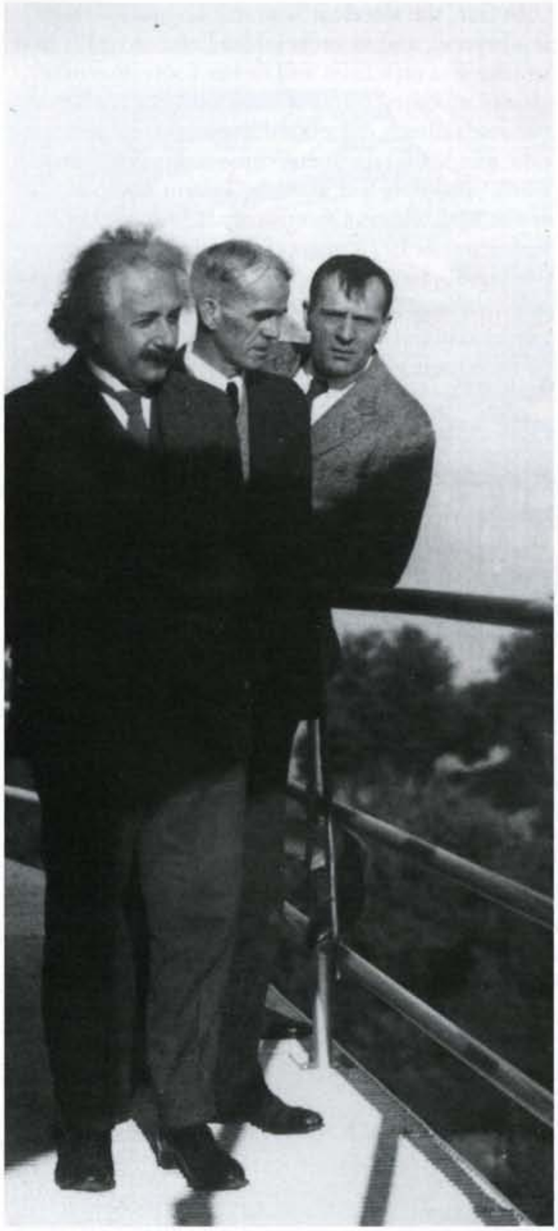
In fact, the woodcut is pretty accurate—there *is* a beyond, and in order to lead you to it, I'll have to take you on a brief and rather Caltech-centric tour of modern cosmology. (That's not hard to do, because Caltech has played a remarkably important role.) I'll talk about three seminal observations. The first was made by Edwin Hubble at the Mt. Wilson Observatory, which overlooks Pasadena, in 1929. Several people, notably Vesto Melvin Slipher, had noticed that the galaxies outside our immediate neighborhood are moving away from us at various speeds, but Hubble plotted their velocities as a function of their distance from us. He found that the farther away they are, the faster they are receding, so he concluded that the universe is expanding. Furthermore, we're not at the center of the expansion—there is no "center." The universe is expanding in all directions from every point. It's much like sitting on one raisin in a raisin bread as it bakes—no matter which raisin you choose, the others are moving away from you. His actual data



Left: What would we see if we could look beyond the visible heavens? Right: The Hubble Deep Field covers a one-arcminute speck of sky—about the size of a dime seen from 75 feet away, or 1/30th the diameter of the full moon—near the handle of the Big Dipper. This region was specifically chosen to exclude bright stars, nearby galaxies and galaxy clusters, and bright radio sources that might obscure the view of dimmer, more distant objects. The dimmest galaxies here are nearly four billion times fainter than the human eye can see.



Hubble's data, as published in the *Proceedings of the National Academy of Sciences* (Volume 15, page 172). Distance equals time in cosmology, because the farther away something is, the longer its light takes to reach us. The oldest, farthest galaxies are also moving away from us the fastest, which implies that the average separation between galaxies—assuming our place in the universe is typical—is increasing over time. In a static universe, where the galaxies remain at fixed distances from one another, the line would be horizontal.



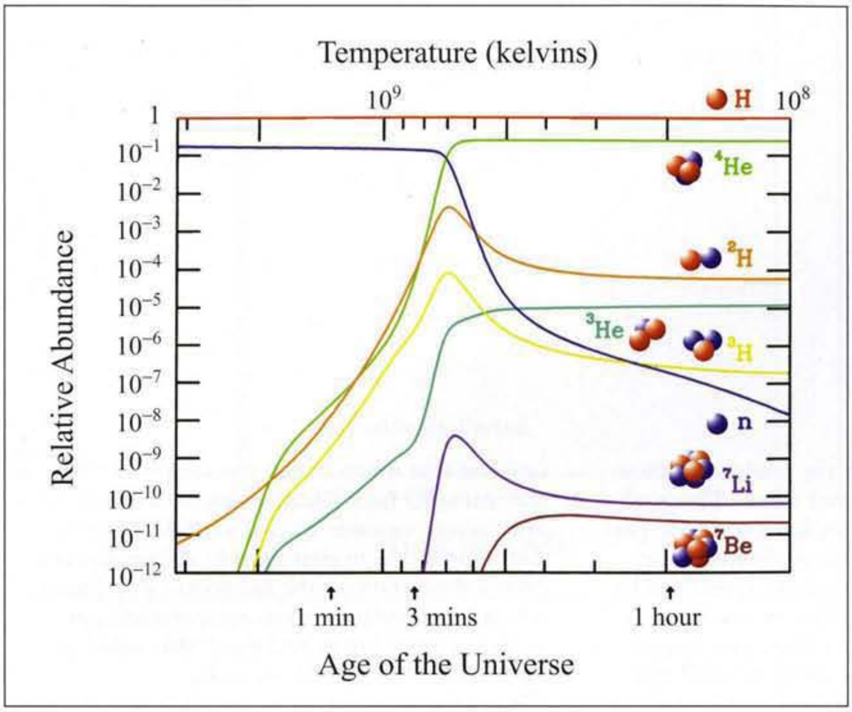
Photograph used with the kind permission of The Hebrew University of Jerusalem and The Roger Richman Agency, Inc.

Einstein (left); Walter Adams, director of the Mt. Wilson Observatory; and Hubble on the catwalk of the observatory's 100-inch Hooker telescope, at the time the world's largest, which Hubble used to measure galactic distances.

is shown above, and in cosmology, the way the points fit that straight line is considered perfect. You rarely get such a good correlation. The slope of that line is now called the Hubble constant, and it tells us the rate at which the universe is expanding. (The numerical value Hubble derived was off by about a factor of 10, but, being cosmology, that was OK too.)

Before moving on to the next discovery, I have to tell you another thing about cosmology: nature is consistently more interesting than we can imagine. When Albert Einstein was working out his field-theory equations for general relativity 12 years before Hubble's discovery, they refused to agree with what Einstein's common sense told him—namely, that the universe had been around forever in pretty much the same form that it is today. He fixed that by sticking in a little thing called the cosmological constant, or Einstein's constant, such that when he plotted the separation between any two galaxies as a function of time, he got a horizontal line. But Hubble showed Einstein that his common sense was wrong. Einstein visited Caltech and met Hubble in 1931, and the campus was abuzz about whether Einstein would disavow his cosmological constant. He stayed mum while he was here, but he later called it the "greatest blunder of my life." More about that later; it's come back to haunt us in the last couple of years.

If the universe is expanding, it follows that it must have been smaller in the past, and that if you play the movie backward all the way to the beginning, it all collapses down to nothing. And now, if you run the movie forward again, you have the so-called Big Bang—the birth of the universe. So people speculated that the universe was much hotter when the matter was all crammed together, because if you let a gas expand, it cools. Our second major discovery was made at Caltech in the 1950s, when the late Nobel Laureate Willie Fowler (PhD '36) and others measured what



Musical chairs in the early universe. The vertical axis shows how many nuclei there are of the other light elements for every nucleus of hydrogen. The lines show how these relative abundances evolve over time. Before the graph begins, there's a seething fog of naked protons (red), which double as hydrogen nuclei; neutrons (blue); and electrons (not shown). The protons and neutrons promptly begin sticking to one another to make heavier nuclei such as deuterium, which has one of each. (Adapted from *The Early Universe*, by Edward Kolb and Michael Turner.)

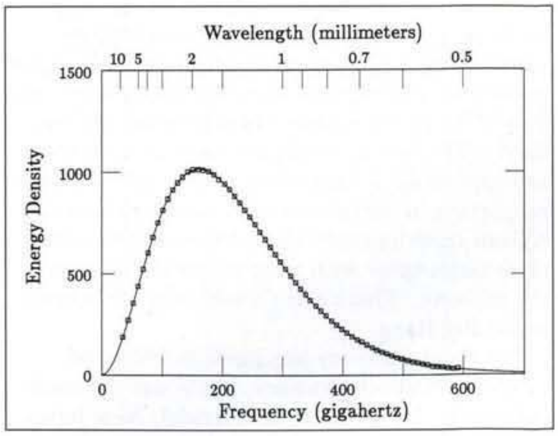
For the next 300,000 years or so, the light and the residual matter were flinging one another around like professional wrestlers.

atomic nuclei do in a very hot, dense environment. I won't go into detail, but at the very high temperatures and densities present in the early universe, protons and neutrons play a strange game of musical chairs from which come the light elements—hydrogen, deuterium, tritium, helium-3, helium, and tiny amounts of lithium and beryllium. (The heavier stuff gets made later, in stars and supernovas.) Each element emerges in a fixed proportion to the others—for example, about one helium atom for every 16 hydrogen atoms—and these ratios agree with what we see throughout the universe. That's a key reason why we believe in the Big Bang.

The third discovery was made in 1964 and involved a Caltech graduate, but it was not made at Caltech. It was made in Holmdel, New Jersey, which had not previously been known as a great astronomical site, at a big radio dish owned by Bell Labs. Nobel Laureates Arno Penzias and Robert Wilson (PhD '62) were working on the Telstar project, which was the first full-fledged communications satellite, and they found that wherever they looked, the sky was aglow with microwaves. This is now called the cosmic microwave background, or CMB, and it's the fossilized primeval fireball. These microwaves are literally the heat left over from the Big Bang. The total amount of energy emitted by all the stars that have ever burned in the whole history of the universe is tiny in comparison to the energy in the CMB.

We've just covered nearly a hundred years of cosmology, so it's okay if you feel a little dizzy. Now let me give you the abridged history of the universe, as told by physicists, that those three observations have led us to. We don't know exactly what happened in the first moments after the Big Bang, but at a time of one second, the observable universe was stuffed full of particles and antiparticles, and its radius was one ten-billionth of what it is today. It was a few light-years in diameter, or about the distance from our solar system to Proxima Centauri, the nearest star. As the universe expanded and cooled, most of that matter and antimatter annihilated each other, turning into energy. One minute after the Big Bang, pretty much everything was gone and all that was left was light. Very biblical. But for every billion antiprotons, there were roughly a billion and one protons, and we should be very, very thankful for that slight imbalance—otherwise we wouldn't be here. So for every proton in our bodies, there are a billion photons of light still echoing around the universe, as Penzias and Wilson discovered. And in the first few minutes after the Big Bang, those billion-and-first protons became Fowler's atomic nuclei.

For the next 300,000 years or so, the light and the residual matter were flinging one another around like professional wrestlers. The matter was an ionized plasma, like a candle flame, so the ions'



The CMB as measured by the Cosmic Background Explorer's Far Infrared Absolute Spectrometer. The data points are many times larger than the actual experimental error. (Adapted from *The Inflationary Universe*, by Alan Guth.)

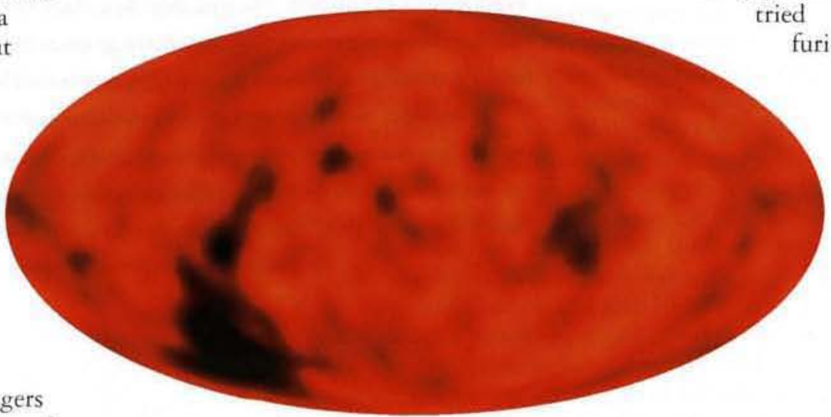
People seem to be fixated on breakfast metaphors—when that beautiful, elliptical COBE map was first published, at least one newspaper proclaimed, "Cosmologists discover early universe shaped like an egg."

electrical charges could grip the photons by their electromagnetic fields, and vice versa. That's why a candle flame is opaque—any light trying to pass through it gets scattered. But as the hot, foggy plasma of loose nuclei and electrons continued to expand and cool, it suddenly (on the cosmic time scale, that is) condensed into electrically neutral, crystal-clear atoms of mostly hydrogen and helium gas. The light finally escaped, and in the 15 billion years or so since, it hasn't interacted with anything. So when it hits our telescopes, we have a clear view back to that moment in cosmic history when the universe turned transparent. By analogy to a human lifetime, this is about six hours after conception—before the zygote has divided for the first time. BOOMERANG literally looks at the embryonic universe, whereas the Hubble Space Telescope typically looks back to the early adolescent universe—a time which, as those of you who have teenagers know, is much more complicated.

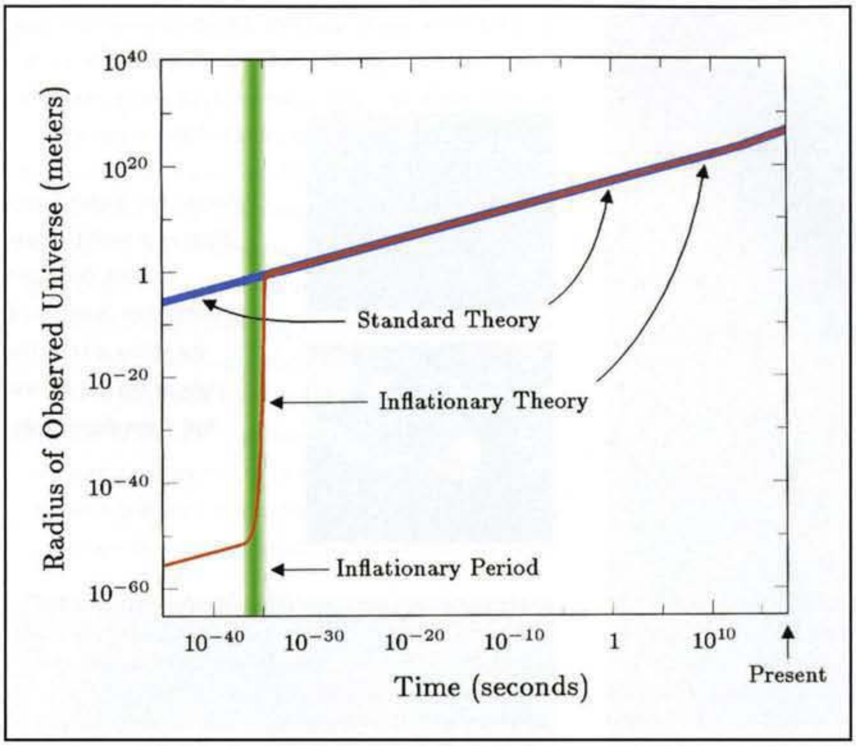
The Big Bang scenario predicts that the cooling universe should radiate a special distribution of colors called a black-body spectrum, which is the same kind of glow a spectrometer would measure from a red-hot stove. Above left is one of the most beautiful measurements ever made in physics—the brightness of the CMB across four orders of magnitude. The line is the theoretical black-body curve, which Max Planck derived in 1900, and the boxes are the data. The two match exactly. The temperature at which the embryonic universe teetered on the brink of transparency was 2,700 kelvins (K) or so, about half the surface temperature of the sun. The entire observable universe that we see today was roughly a thousand times smaller back then—about 30 million light-years across, or some 15 times the distance to Andromeda, the nearest galaxy. As the universe grew a thousandfold, the radiation's wavelength, which is proportional to its temperature, got stretched accordingly, and the CMB cooled to the chilly 2.7 K that we see today.

Any structures we see in the CMB would reflect the plasma's final state, and the hotter, denser regions would be the "seeds" from which galaxies eventually coalesced.

Many people tried furi-



Variations in the CMB were first detected by COBE's DMR (Differential Microwave Radiometers), which operated for four years. This map of the CMB over the entire sky shows what's left once the effects of our own galaxy's motion, interstellar dust, and other confounding factors have been subtracted. But although the DMR was very sensitive to temperature variations, its angular resolution was so broad that there are only 6,144 pixels in the entire map.



The universe gets bigger with time in both the standard and the inflationary model, and the two coincide when inflation ceases. The numbers along the axes are not to be taken as gospel: their exact values depend on the details of the Grand Unified Theory to which you subscribe. (Adapted from *The Inflationary Universe*.)

ously to map it, but success eluded them until the Cosmic Background Explorer, or COBE, satellite in 1992. The reason that it took so long is that there's really not much to see—the difference between the coldest and hottest points is only about one ten-thousandth of a kelvin. In other words, the fireball was exactly the same temperature to within 30 parts per million over the entire sky. But one end of the universe can't phone the other end to find out what it's wearing, because according to Einstein there's no way to send information faster than the speed of light. And the radiation from each end has traveled since the beginning of time and is just now reaching us, so it couldn't possibly have arrived at the other end already. So how do both ends know to be at the same temperature? This may not bother you, but it's the kind of thing that cosmologists lose sleep over.

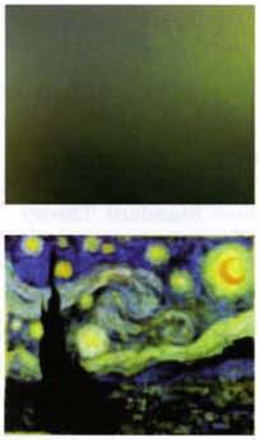
This and other problems have led to an amazing modification to the Big Bang model that solves everything in deus ex machina fashion. Solving so many problems with one idea is great, but the idea is so fantastic (in the sense of outlandish) that if you don't believe it, I don't blame you. Above is a plot of the universe's radius as a function of its age. This so-called log-log plot extends over 40 orders of magnitude on the horizontal axis and 100 on the vertical axis and is the kind of plot physicists love, because if you're right to within a factor of a thousand, you look great. In the standard Big Bang theory, plotted in blue, the universe gets bigger at a constant rate. In the modified theory (red), the universe grew placidly for the first 10^{-30} seconds or so, and then it did something extraordinary—it suddenly exploded in a violent expansion, which cosmologists in their understated way call "inflation." It grew from perhaps a ten-billionth of the size of a proton to about the size of a grapefruit at much faster than the speed of light, and then resumed its nice, gradual expansion. ("Hold on just a minute! Nothing can go faster than light!" you exclaim. Well, if you read the fine print in Einstein's equations, they say that no individual objects in the universe—including photons—can move faster than light in relation to one another. They don't say that the universe as a whole can't expand faster than light, taking all the objects within it with it.) So the microwave background can be the same temperature everywhere because, before the universe inflated, all its parts were in very close contact and would naturally equilibrate to the same temperature.

This has some really interesting implications. Galaxies today form clusters and superclusters—complex distributions of matter on the scale of millions and even billions of light-years. These could have originated as quantum fluctuations in the universe's density, which the inflationary process stretched large on the sky. This fantastic notion is very attractive to physicists, because it connects the largest and smallest scales, but it remains to be borne out. Furthermore, one can speculate that if our entire observable universe sprang from one bit of preinflationary primordial soup, it stands to reason that there could be lots of other bits. So there might be other inflationary bubbles that led to other universes outside our own. But that's perhaps best left (for now!) to the science-fiction writers.

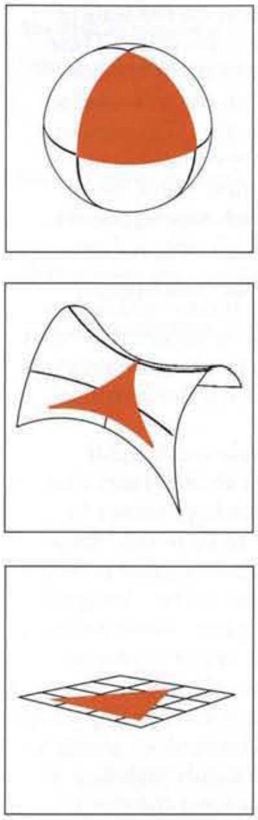
Inflation is not an intuitively comfortable process, and any theory that's so important that the basic observations of cosmology cannot be understood without it needs to be tested. Inflation makes only one really solid, testable prediction, which is that the universe is flat. Imagine standing on the surface of a sphere whose radius suddenly increases by, oh, 27 orders of magnitude—a billion billion billion. You may have been able to see that the sphere was curving underneath you beforehand, but afterward it's going to look real darn flat. You're instantly standing in the middle of Kansas. So whatever the initial geometry of the universe was, the inflationary epoch stretched it flat.

I don't mean that the universe is pancake-shaped, which was the headline in several newspapers when we published BOOMERANG's results. People seem to be fixated on breakfast metaphors—when that beautiful, elliptical COBE map was first published, at least one newspaper proclaimed, "Cosmologists discover early universe shaped like an egg." Here's what "flat" really means: Back in high school you learned that the internal angles of a triangle add up to 180 degrees. But this is only true on a flat surface—if you draw the same triangle on the surface of a sphere, you

Physicists love the early universe. It's uncluttered and easy to work with. Later on, when atoms form, suddenly we get nonlinear physics, chemistry, biology, economics... it all goes to hell in a hurry.



Vincent van Gogh's *Starry Night* as it would appear to COBE (top) and BOOMERANG (bottom), if the yellow star to the right of the tall cypress had a one-degree halo.



Depending on the surface on which you draw it, the three angles of a triangle can add up to more or less than 180 degrees.

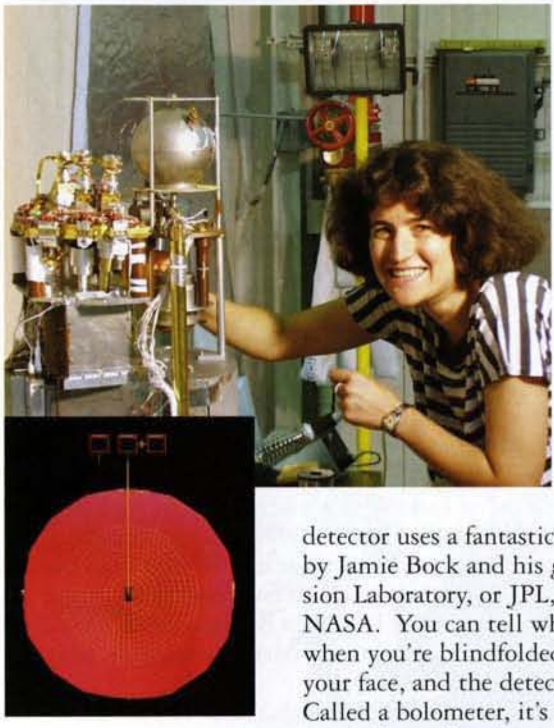
will get a number greater than 180 degrees whose exact value depends on the triangle's area. And if you draw it on a funny, saddle-shaped surface called a hyperbolic surface, you'll get less than 180 degrees. Furthermore, on a flat surface, two parallel lines (or rays of light) never meet. That's what parallel means. But on a sphere, if you send two parallel rays of light due north from different points on the equator, they'll cross each other at the North Pole. Similarly, parallel lines on a hyperbolic surface diverge. The equivalent is also true in three dimensions, and because Einstein showed that matter bends space, only if the amount of matter in the universe is just right will parallel light rays stay "parallel." If there is more or less matter than that magic amount, the rays will either converge or diverge. Cosmologists refer to the average density of matter in the universe as "omega." If omega is greater than one, the universe is closed, like the surface of a sphere, and if I set off in any direction in a straight line, I'll eventually end up back where I started. If omega is less than one, the universe is open and infinite, like the hyperbolic surface. If omega is exactly one, we have a flat universe that is also infinite.

So in order to measure the universe's geometry and calculate its total cargo of matter, while at the same time testing the inflationary model, all we have to do is measure the sum of the angles of a triangle. That sounds pretty simple, but the triangle has to be really big. If we look as far back as we can, all the way to the embryonic universe, and hope that someone way out there is holding up a meter stick, we've made a triangle with two legs that are each 15 billion light-years long. And we don't actually have to measure all three angles, because if we know the length of two legs and the angle between them, we can calculate the rest, using the laws of sines and cosines. If the numbers don't add up, it shows that the universe isn't flat.

There is no meter stick out there, but there is a physical process we can exploit to measure the angle between the legs. The dense plasma of the embryonic universe was trying to collapse on itself due to its incredibly intense gravitation, but the equally intense radiation pressure from all the photons kept it propped up. The slightly denser regions caused by those fluctuations I mentioned earlier—the ones that got writ large on the sky during inflation—would have been collapsing slightly faster, churning up sound waves that propagated through the embryonic universe. These are exactly analogous to the ripples that are seen on the surface of the sun (in fact, the early universe would have looked very much like the sun), except that we're seeing them from within. (The discovery of the solar ripples and subsequent deduction that the sun's interior is resonating like an organ pipe has spawned an entire field called helioseismology, but that's another Caltech-centric story.)

Theorists, including Caltech's Marc Kamionkowski, professor of theoretical physics and astrophysics, have calculated the average size the ripples should have for universes with varying amounts of curvature. Physicists love the early universe. It's uncluttered and easy to work with. Later on, when atoms form, suddenly we get nonlinear physics, chemistry, biology, economics... it all goes to hell in a hurry. Physicists don't even want to try calculating that stuff, but the infant universe is good. It turns out that if the universe is flat, the characteristic diameter of the fluctuations is about one degree, or roughly twice the diameter of the full moon. Unfortunately, COBE couldn't see that sharply. Its angular resolution—the smallest shape it could make out—was seven degrees in diameter, or 14 moons' worth. So BOOMERANG was designed to spot things one-third the size of the full moon. Vincent van Gogh's *Starry Night* also has structures of a characteristic angular scale, so to give you a better idea of what this all means, I've reproduced the painting as COBE and BOOMERANG would

Each bolometer spiderweb (bottom), shown seven times its actual size, is a delicate tracery floating over a cavity from which the silicon has been eaten away. The bolometers are mounted in BOOMERANG's focal-plane assembly (below). The assembly, seen here with Silvia Masi of the University of Rome, is made largely of copper for best heat dissipation. The sphere is the helium-3 reservoir. The assembly, in turn, goes into the bottom of the liquid-nitrogen dewar (right), which one might think was worshipped as a cult object. The devotees are, clockwise, Caltech postdoc Barth Netterfield (seated, wearing black sweater), now at the University of Toronto; Francesco Piacentini of the University of Rome; an anonymous pair of legs; Caltech grad student Brendan Crill; John Ruhl, a professor at UC Santa Barbara; and Armando Iacoangeli, of the University of Rome.



see it. We can't see the brush strokes yet, but the swirls are clearly visible.

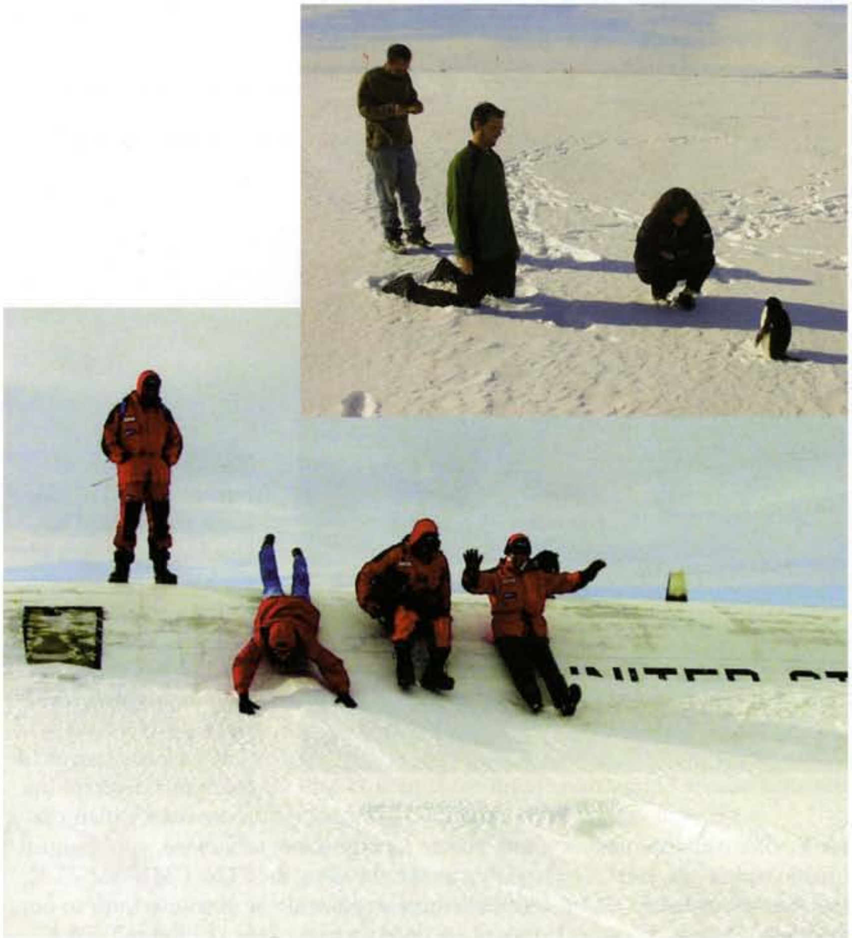
BOOMERANG's detector uses a fantastic new technology developed by Jamie Bock and his group up at the Jet Propulsion Laboratory, or JPL, which Caltech runs for NASA. You can tell whether the sun is shining when you're blindfolded by feeling the heat on your face, and the detector works the same way. Called a bolometer, it's a button-sized, freestanding spider web micromachined on a silicon wafer. The web's mesh is larger than the wavelengths of cosmic rays and other things we aren't interested in, so they fly right through, but it's smaller than the millimeter-sized microwaves from the Big Bang. They get absorbed by the web as if it were a solid surface, and a tiny thermometer in the middle of the web measures how much it heats up with a precision of better than a millionth of a kelvin.

BOOMERANG would not have been possible without the very close contact that exists between Caltech and JPL. Nor would it have been possible without the vision of JPL's Director of Space and Earth Science Programs, Charles Elachi (MS '69, PhD '71). When Jamie and I wandered down from Berkeley some years ago and said, "Hi! You don't know us, but we'd kind of like some money and lab space to build this idea we have," he talked to us for a while and said, "Great! You got it!" And he has supported us in many ways ever since.

It's a basic fact of life that your detector has to be colder than the thing you're trying to see; otherwise, you're mostly going to see the detector. The CMB is 2.73 K, less than three degrees above absolute zero, so our array of 16 detectors was kept chilled to 0.28 K by liquid helium-3. The cryogenic system, which holds 60 liters of helium-4 to cool the helium-3, and 60 liters of liquid nitrogen to cool the helium-4, was developed by Professor Paolo de Bernardis's team at the University of Rome. They also built the 1.2-meter microwave mirror system that focuses the CMB onto the spiderwebs.

Furthermore, measuring a difference of a few millionths K in the presence of our sun's 5,000 K is no mean feat. If the sun, the earth, or even the balloon had gotten near the field of view, they would have cast a glint of light onto the image and ruined it. The mirror and the entire optical path had to be very carefully shielded from stray light, so the telescope was enshrouded in an elaborate system of enormous baffles built from aluminized Mylar.

So what with the dewars and the shielding and the computers and the solar panels and all, the final package wound up weighing 1,400 kilograms. And we needed to get this massive thing above as much of the earth's atmosphere as possible, but the heavier something is, the more it costs to put it in orbit. So we used a poor man's satellite—a balloon that flies about 37 kilometers



What would an Antarctic travelogue be without a few tourist postcards? At top, an Adélie penguin provides a photo op for (from left) Tom Montroy, a grad student at UCSB; Crill; and Masi. In the bottom picture, the wreck of a Pegasus supply plane is now the local jungle gym. From left: de Bernardis; Piacentini; Andrea Boscaleri of IROE (Istituto di Ricerca sulle Onde Elettromagnetiche), Florence; and Francesco Pongetti of ING (Istituto Nazionale di Geofisica), Rome.

high. At that altitude, 99 percent of the atmosphere is below us, and the balloon inflates to about the size of the Rose Bowl. A balloon flight out of Texas typically lasts just a few hours, but about a decade ago, someone discovered that if you launch from the coast of Antarctica at just the right time of year, the winds will carry you around the continent in a big circle. You get a flight time of a week or two before returning to where you took off. Since then, about a dozen balloon flights have been made this way.

The summer of 1998 saw us assembling and testing BOOMERANG back in Palestine, Texas, and by mid-October BOOMERANG had been taken apart again and carefully crated for shipment to NASA's National Scientific Balloon Facility at McMurdo Station, Antarctica. By the first week of November, there were 13 team members down there (including Caltech grad student Brendan Crill, postdoc Barth Netterfield, and Pete Mason (BS '51, MS '52, PhD '62), a retired senior member of the technical staff at JPL) reassembling and retesting the apparatus. I had classes to teach, so I got to stay back in my office in Pasadena and worry. I did manage to get down there on December 11, but was unable to stay long.

Antarctica is a beautiful place, so beautiful that there are very few people who've been there just once. Everyone wants to go back. As Brendan is fond of saying, the weather is "sunny and dry, just like L.A., just 40 degrees Celsius colder." The NASA folks gave us the use of a hangar, which they call a high bay, out at the Williams Field airstrip, which is about six miles from McMurdo. The "road" across the ice shelf to the field is marked by a series of flags on stakes and precious little else, which makes driving interesting when the wind kicks up and the blowing snow cuts your visibility way down. McMurdo is quite plush; Williams Field somewhat less so—our high bay had a canvas door and an outhouse. Phil Farese, a grad student at UC Santa Barbara, cut an insulated toilet-seat liner from a sheet of Styrofoam, which helped enormously.

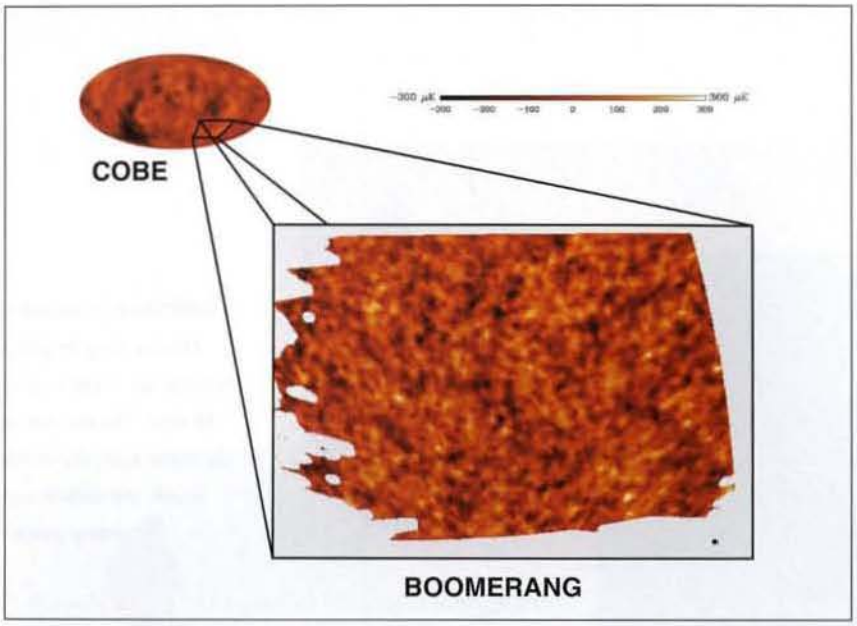
The sun never sets at that time of year, which made it easier to work two shifts, and sometimes around the clock, getting ready for launch. Even so, it took nearly two months. The team got everything back together and operating in a couple of weeks, but the tests and calibrations took a month and a half. It wasn't all grind, grind, grind, though—they worked in a lot of skiing and mountain biking on their off hours, as well as touring the local ice caves, Scott's cabin from his ill-fated polar expedition of 1911, and a nearby plane wreck from the 1960s. We had hoped to launch on Christmas—that would have been the best present ever!—but the launch was scrubbed by high winds.

We lifted off on December 28, 1998, Pasadena time—McMurdo Station is just across the International Date Line, so it was the 29th over there. At the top of the next page is the balloon's actual

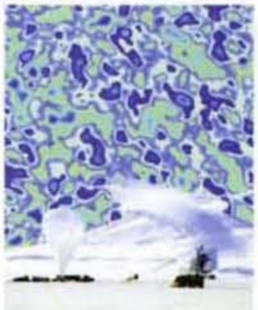
BOOMERANG one-upped Phineas Fogg by going around the world in only 10 days. The red line is the flight path; the arrow marks the takeoff and landing points.

track, which roughly followed 79° south latitude. You don't always get this lucky. When one of my friends at JPL saw this, he said, "Wow! What kind of propulsion system did you use?" In fact, we didn't even tinker with the balloon's altitude to try to steer it. We just let it go, and sat by the computer watching the track as it evolved. We got worried a few times when the balloon started going astray, but it always came back on course, and after an 8,000-kilometer journey, it landed 50 kilometers from the launch site. Most importantly, the landing was 50 kilometers inland across the ice shelf, not 50 kilometers out to sea! The air is so clear down there that the balloon actually came back into view from Williams Field, and the entire landing was visible from the launch site. The landing sequence is radio-controlled (from an airplane—we had assumed we'd have to fly some distance to intercept the balloon), and BOOMERANG parachuted reasonably gently to earth, taking data all the way down. The solar panels crumpled on impact, but as they say, any landing you can walk away from is a good one—the dewar was still under vacuum with helium to spare, and the hard drives were fine. The hard drives were for backup, in case BOOMERANG couldn't transmit the data while

Above: Sun-sensor calibration. In flight, BOOMERANG faces away from the sun. The Mylar wings keep stray light out, as will an inverted Mylar snout. The complete craft looked like a three-story teapot. Right: Launch. Mt. Erebus, behind the balloon, is an active volcano 40 km off.



Above: The BOOMERANG data covers approximately 1,800 square degrees, or 2.5 percent, of the southern sky, as shown in relation to the COBE all-sky map above it. The small black circle in the lower right corner of the BOOMERANG data is the size of the full moon. Below: Although the variations are very faint, they are quite large. Here the CMB, in a more suitably Antarctic color scheme, has been inserted to scale behind the launch preparations.



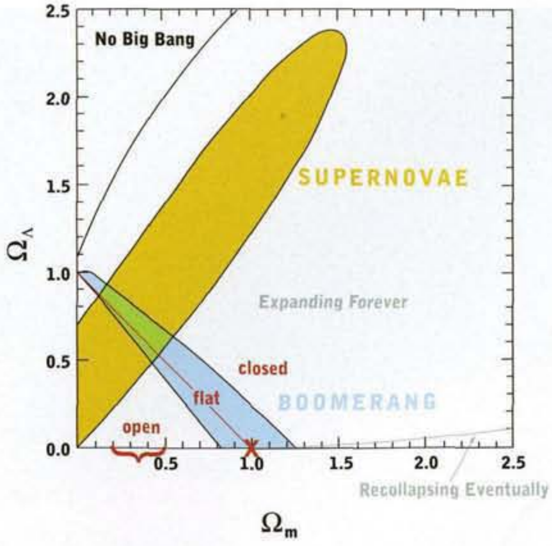
aloft. There's very poor cell-phone coverage in the Antarctic, especially now that the Iridium global wireless network has gone bankrupt. (Iridium was just coming on line back then, and I called them and asked, "How many cell-phone numbers will we have to buy to get all the data down through your system?" The 10-day flight would have cost us $1.5 million in phone charges. No wonder they went out of business.) So BOOMERANG sent all its data to a NASA satellite, which relayed it back to us. And, as it happened, that worked just fine.

The collaboration, including Caltech postdoc Eric Hivon and senior engineer Viktor Hristov, has fully analyzed only 5 percent of the data so far, but here's the punch line. The BOOMERANG map above is different from the COBE map above it in two important respects. First of all, every feature is real. The COBE instrument was operating near the limit of its sensitivity, so there is a lot of noise mixed in with its data. BOOMERANG had much higher sensitivity, and produced a map with relatively little noise in it. We mapped the entire sky once a day for 10 days, and the same structures appeared every day. We observed the microwave background at three different wavelengths, and the same structures appear at all three wavelengths. (We also used a fourth wavelength to look for faint emissions from the dust in our own galaxy.) So we can now put our finger on some point in the sky and say, you know, that really *is* a cold spot. Second, the structures are typically larger than BOOMERANG's angular resolution, so we can, for the first time, get an accurate measure of how big they are. The BOOMERANG map shows structures that are the right size to have evolved into galactic superclusters, so for the first time there's a visible link between the embryonic universe and the present universe. That's very, very exciting.

I failed to mention earlier that if the universe is closed, it becomes more and more closed as it evolves, and if it's open, it becomes more and more open—only if it is exactly flat does it stay flat. But we know from several lines of evidence that the universe is within a factor of 10 of being flat, and why this should be so is a big mystery—it should have gone off in one direction or the other long since. The "baryonic" matter that you and I and planets and stars are made of gives us an omega of a few percent (about 0.03–0.05), and the so-called "dark matter" that cosmologists assume exists—because without it all the galaxies we see would have long since flung themselves apart—brings omega up to between 0.1 and 0.3. As I've said before, being off by a factor of 10 in cosmology is the same as being dead on, so theorists have therefore predicted that the universe must be exactly flat; that is, omega must equal one.

But a couple of years ago, observations of extremely distant supernovae indicated something very unsettling, even to cosmologists—the expansion of the universe is accelerating. To go back to the raisin-bread analogy for a moment (where would we be without our breakfast metaphors?), the loaf of bread is rising at an ever-increasing rate. Nobody knows why. The current thinking is, darn that Einstein, he was right after all. There appears to be a second type of matter-energy density that can be expressed by Einstein's cosmological constant. This idea is so new that we haven't even agreed on a name for it. The favorite so far appears to be "dark energy," which has the potential to be misleading in the popular mind—this stuff is not related to dark matter the way that ordinary matter and energy are related by $E = mc^2$. It's also called "quintessence," but by far the most sophisticated name I've heard is "the 'funny energy' density." Whatever we call it, if we plot it versus various calculated values for the amount of matter in the universe (above right), the supernovae results lie within the yellow region. The BOOMERANG results put us in the blue region. The overlap between the two pins us down squarely in the little green zone. This tells us that there is not enough matter—in all forms, visible and dark—to make the universe flat, but if we add in the dark energy as well, omega comes to within a few percent of being exactly one. This eliminates a lot of theoretical models of the universe that cosmologists have been tossing around. It's also the ultimate Copernican revolution—we've come from not being at the center of the universe to becoming a 10 to 20 percent minority constituent of the dark matter, which has now in turn become a mere one-third of the total matter-energy density in the universe. And we have even less of a clue about what the other two-thirds are than we do about ordinary dark matter. That's great progress, isn't it?

Since our results appeared in *Nature*, there has been a slew of theoretical papers interpreting

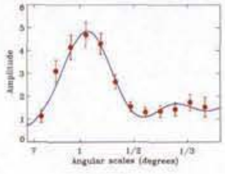


For the last 20 years or so, cosmologists have assumed for a variety of reasons that omega equals one, putting us where the red X is on the graph. Unfortunately, the measurements of all the matter in the universe, including the dark matter, all lie within the red bracket. But if there are really two dimensions to omega, the problem can be resolved. In this graph, Ω_m is the contribution from ordinary matter, and Ω_Λ is the new "dark energy." The sum of the two omegas is one (the red line), and the supernova and the BOOMERANG results intersect above the bracket.

them. People have invoked new neutrino physics, topological defects, leptonic asymmetry, delayed recombination—all kinds of things. We thought our experiment would pin those squirmy theorists down. So far, we've failed badly. It's like the seven blind men and the elephant.

Now at this point, you're thinking, "Sheesh! They went all the way to the Antarctic to make this fuzzy picture?! Cosmologists must be *really* starved for data!" Well, in fact cosmologists *are* really starved for data, but there's more here than meets the eye. Buried in the blotches is a wealth of information, which is extracted mathematically in exactly the way that the graphic equalizer on your stereo system works. As you watch those little lights wiggling up and down, the graphic equalizer is sorting the tones into bass notes and treble notes. In fact, it sorts them into several different bins, or frequency ranges, and the lights tell you how much sound energy is going into each bin. Similarly, you can ask what the distribution in the BOOMERANG data is of large angular scales, corresponding to bass notes, versus small angular scales, which are treble notes. For those of you who are Caltech graduates, we take a Fourier transform of this map to get its power spectrum. This is what I call the music of the spheres, because the sky is ringing with a very characteristic tone—our one-degree angular scale.

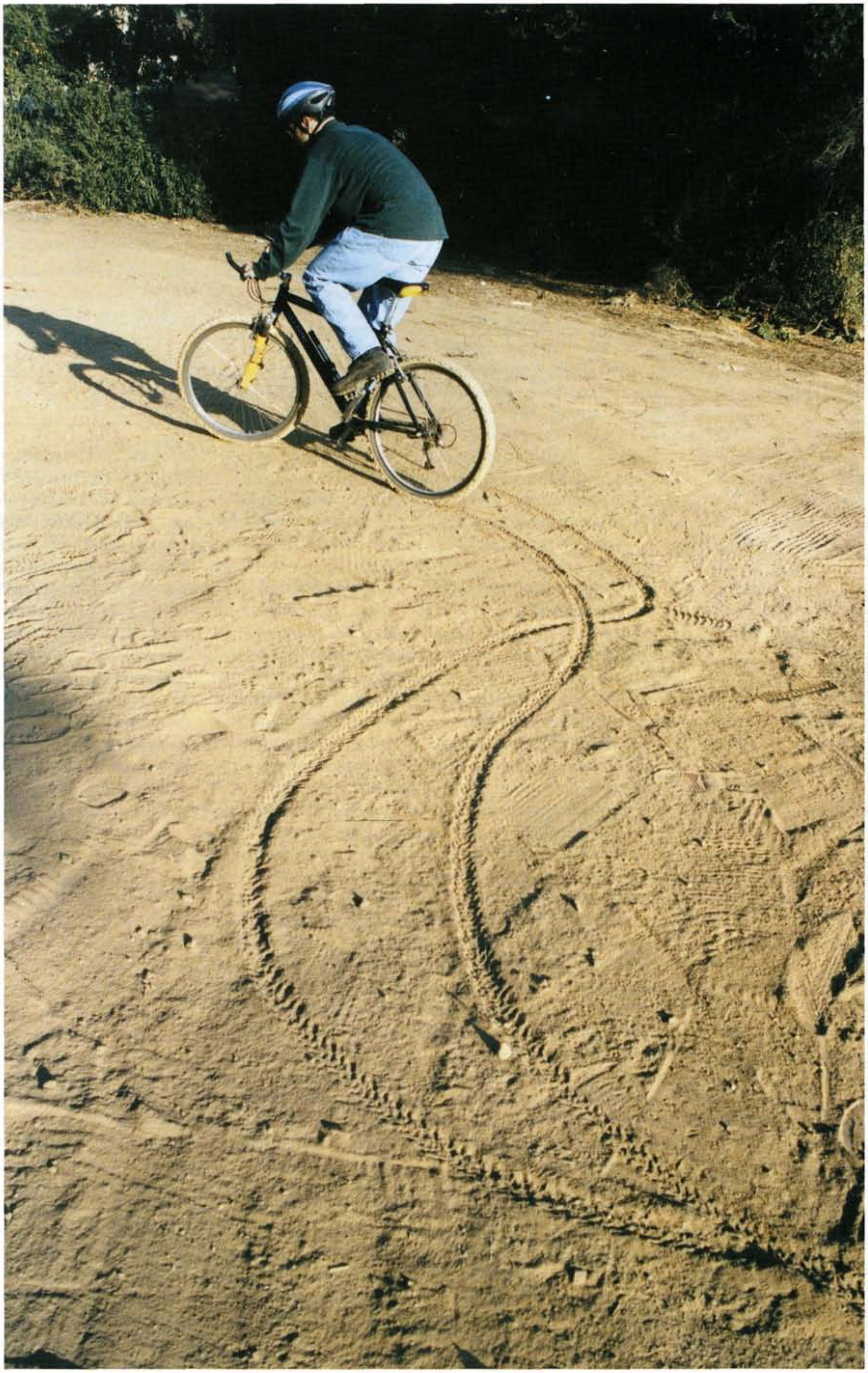
Cosmologists are eager to find out if that tone is being played on a trumpet or a violin. In other words, what are the overtones? The harmonics? The higher frequencies, or in our case the smaller angular scales, are what makes a trumpet sound different from a violin when both are playing the same note. And that's where all the excitement is going to be in the coming months and years. The sound waves that resulted from the pre-inflation fluctuations amplified them and processed them to create a spectrum that will have peaks at higher frequencies, and the hope is that if we can understand that spectrum well enough, we will be able to work backward from it to reveal the original quantum fluctuations through a mathematical process called deconvolution. We hope that we can push BOOMERANG's data out to a little beyond one-third of a degree, which will indicate more precisely what the overtones look like. And Rawn Professor of Astronomy Tony Readhead's group is in Chile with a fantastic machine called the CBI, or Cosmic Background Imager [see *E&S* 1999, No. 3], which was built here at Caltech and will extend our vision out to less than one-tenth of a degree—sufficient to see the seeds of clusters of galaxies as well as superclusters. The combination of these two experiments will really reveal what the music of the spheres sounds like. ☐



In this plot of the CMB's harmonics, the BOOMERANG data and its error bars are shown in red. The blue line is predicted by various cosmological arguments. The BOOMERANG data at scales less than half a degree is consistent with the wavy line, but could fit a straight line just as easily; future observations will tell the tale.

BOOMERANG is a collaboration of 36 scientists at 16 institutions in four nations. Andrew Lange, professor of physics at Caltech, is the leader of the U.S. contingent. This article was adapted from a Watson lecture given by Lange on May 3, six days after BOOMERANG's results made the cover of Nature.

Lange earned his BA and PhD, both in physics, at Princeton in 1980 and Berkeley in 1987, respectively. He came to Caltech as a Visiting Associate in 1993, and stayed on as a professor of physics the following year, having married Frances Arnold, Dickinson Professor of Chemical Engineering and Biochemistry. (An article on Arnold's research appears in E&S *1/2, 1999.)*



You might think you need calculus to determine the area between the tire tracks made by this bike, ridden by Jason McIlhaney, BS 2000. Surprisingly, geometry offers another way of solving it—without formulas.