CHAPTER 3

LIGHT FROM THE BEGINNING OF TIME

As it was in the beginning, is now, and shall ever be.

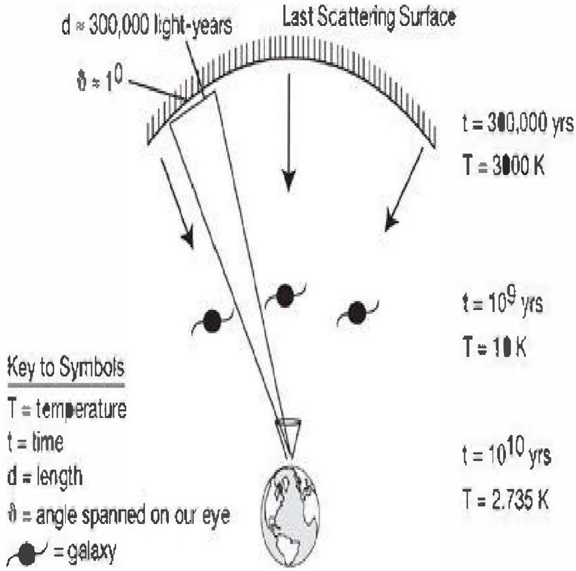
—GLORIA PATRI

If you think about it, trying to determine the net curvature of the universe by measuring the total mass contained within it and then using the equations of general relativity to work backward has huge potential problems. Inevitably, you have to wonder whether matter is hidden in ways that we cannot uncover. For instance, we can only probe for the existence of matter within these systems using the gravitational dynamics of visible systems like galaxies and clusters. If significant mass somehow resided elsewhere, we'd miss it. It would be much better to measure the geometry of the whole visible universe directly.

But how can you measure the three-dimensional geometry of the whole visible universe? It's easier to start with a simpler question: How would you determine if a two-dimensional object like the Earth's surface was curved if you couldn't go around the Earth or couldn't go above it in a satellite and look down?

First, you could ask a high school student, What is the sum of the angles in a triangle? (Choose the high school carefully, however . . . a European one is a good bet.) You would be told 180 degrees, because the student no doubt learned Euclidean geometry—the geometry associated with flat pieces of paper. On a curved two-dimensional surface like a globe, you can draw a triangle, the sum of whose angles is far greater than 180 degrees.

For example, consider drawing a line along the equator, then making a right angle, going up to the North Pole, then another right angle back down to the equator, as shown below. Three times 90 is 270, far greater than 180 degrees. Voilà!



It turns out that this simple, two-dimensional thinking extends directly and identically to three dimensions, because the mathematicians who first proposed non-flat, or so-called non-Euclidean, geometries realized that the same possibilities could exist in three dimensions. In fact, the most famous mathematician of the nineteenth century, Carl Friedrich Gauss, was so fascinated by the possibility that our own universe might be curved that he took data in the 1820s and '30s from geodetic survey maps to measure large triangles between the German mountain peaks of Hoher Hagen, Inselberg, and Brocken to determine if he could detect any curvature of space itself. Of course, the fact that the mountains are on the curved surface of the Earth means that the two-dimensional curvature of the surface of the Earth would have interfered with any measurement he was performing to probe for curvature in the background three-dimensional space in which the Earth is situated, which he must have known. I assume he was planning to subtract any such contribution from his final results to see if any possible leftover curvature might be attributable to a curvature of the background space.

The first person to try to measure the curvature of space definitively was an obscure mathematician, Nikolai Ivanovich Lobachevsky, who lived in remote Kazan in Russia . Unlike Gauss, Lobachevsky was actually one of two mathematicians who had the temerity to propose in print the possibility of so-called hyberbolic curved geometries, where parallel lines could diverge. Remarkably, Lobachevsky published his work on hyperbolic geometry (which we now call "negatively curved" or "open" universes) in 1830.

Shortly thereafter, when considering whether our own three-dimensional universe might be hyperbolic, Lobachevsky suggested that it might be possible to "investigate a stellar triangle for an experimental resolution of the question." He suggested that observations of the bright star Sirius could be taken when the Earth was on either side of its orbit around the Sun, six months apart. From observations, he concluded that any curvature of our universe must be *at least* 166,000 times the radius of the Earth's orbit.

This is a big number, but it is trivially small on cosmic scales. Unfortunately, while Lobachevsky had the right idea, he was limited by the technology of his day. One hundred and fifty years later, however, things have improved, thanks to the most important set of observations in all of cosmology: measurements of the cosmic microwave background radiation, or CMBR.

The CMBR is nothing less than the afterglow of the Big Bang. It provides another piece of direct evidence, in case any is needed, that the Big Bang really happened, because it allows us to look back directly and detect the nature of the very young, hot universe from which all the structures we see today later emerged.

One of the many remarkable things about the cosmic microwave background radiation is that it was discovered in New Jersey, of all places, by two scientists who really didn't have the slightest idea what they were looking for. The other thing is that it existed virtually under all our noses for decades, potentially observable, but was missed entirely. In fact, you may be old enough have seen its effects without realizing it, if you remember the days before cable television, when channels used to end their broadcast days in the wee morning hours and not run infomercials all night. When they went off the air, after showing a test pattern, the screen would revert to static. About 1 percent of that static you saw on the television screen was radiation left over from the Big Bang.

The origin of the cosmic microwave background radiation is relatively straightforward. Since the universe has a finite age (recall it is 13.72 billion years old), and as we look out at ever more distant objects, we are looking further back in time (since the light takes longer to get to us from these objects), you might imagine that if we looked out far enough, we would see the Big Bang itself. In principle this is not impossible, but in practice, between us and that early time lies a wall. Not a physical wall like the walls of the room in which I am writing this, but one that, to a great extent, has the same effect.

I cannot see past the walls in my room because they are opaque. They absorb light. Now, as I look out in the sky back further and further in time, I am looking at the universe as it was younger and younger, and also hotter and hotter, because it has been cooling ever since the Big Bang. If I look back far enough, to a time when the universe was about 300,000 years old, the temperature of the universe was about 3,000 degrees (Kelvin scale) above absolute zero. At this temperature the ambient radiation was so energetic that it was able to break apart the dominant atoms in the universe, hydrogen atoms, into their separate constituents, protons and electrons. Before this time, neutral matter did not exist. Normal matter in the universe, made of atomic nuclei and electrons, consisted of a dense "plasma" of charged particles interacting with radiation.

A plasma, however, can be opaque to radiation. The charged particles within the plasma absorb photons and reemit them so that radiation cannot easily pass through such a material uninterrupted. As a result, if I try to look back in time, I cannot see past the time when matter in the universe was last largely comprised of such a plasma.

Once again, it is like the walls in my room. I can see them only because electrons in atoms on the surface of the wall absorb light from the light in my study and then reemit it, and the air between me and the walls is transparent, so I can see all the way to the surface of the wall that emitted the light. So too with the universe. When I look out, I can see all the way back to that "last scattering surface," which is the point at which the universe became neutral, where protons combined with electrons to form neutral hydrogen atoms. After that point, the universe became largely transparent to radiation, and I can now see the radiation that was absorbed and reemitted by the electrons as matter in the universe became neutral.

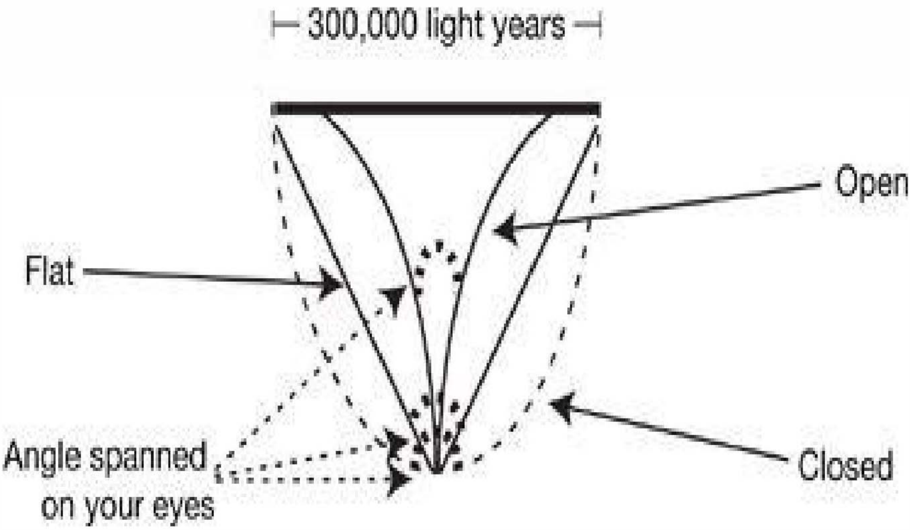
It is therefore a *prediction* of the Big Bang picture of the universe that there should be radiation coming at me from all directions from that "last scattering surface." Since the universe has expanded by a factor of about 1,000 since that time, the radiation has cooled on its way to us and is now approximately 3 degrees above absolute zero. And that is precisely the signal that the two hapless scientists found in New Jersey in 1965, and for whose discovery they were later awarded the Nobel Prize.

Actually a second Nobel Prize was given more recently for observations of the cosmic microwave background radiation, and for good reason. If we could take a photo of the surface of the last scattering surface, we would get a picture of the neonatal universe a mere 300,000 years into its existence. We could see all the structures that would one day collapse to form galaxies, stars, planets, aliens, and all the rest. Most important, these structures would have been unaffected by all the subsequent dynamical evolution that can obscure the underlying nature and origin of the first tiny primordial perturbations in matter and energy which were presumably created by exotic processes in the earliest moments of the Big Bang.

Most important for our purpose, however, on this surface there would be a characteristic scale, which is imprinted by nothing other than time itself. One can understand this as follows: If one considers a distance spanning about 1 degree on the last scattering surface as seen by an observer on Earth, this would correspond to a distance on that surface of about 300,000 light-years. Now, since the last scattering surface reflects a time when the universe itself was about 300,000 years old, and since Einstein tells us that no information can travel through space faster than the speed of light, this means that no signal from one location could travel across this surface at that time by more than about 300,000 light-years.

Now consider a lump of matter smaller than 300,000 light-years across. Such a lump will have begun to collapse due to its own gravity. But a lump larger than 300,000 light-years across won't even begin to collapse, because it doesn't yet even "know" it is a lump. Gravity, which itself propagates at the speed of light, cannot have traveled across the full length of the lump. So just as Wile E. Coyote runs straight off a cliff and hangs suspended in midair in the Road Runner cartoons, the lump will just sit there, waiting to collapse when the universe becomes old enough for it to know what it is supposed to do!

This singles out a special triangle, with one side 300,000 light-years across, a known distance away from us, determined by the distance between us and the last scattering surface, as shown below:



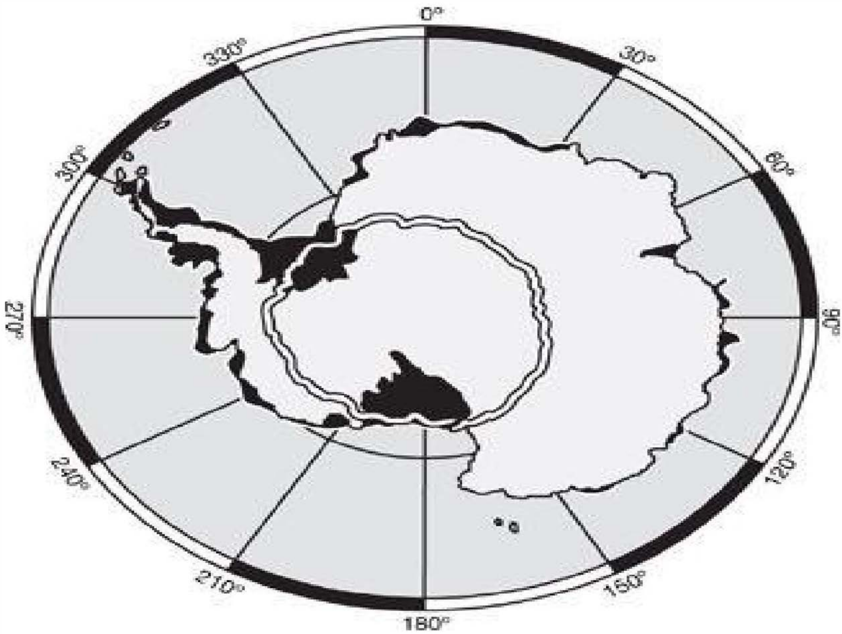
The largest lumps of matter, which will have already begun to collapse and in so doing will produce irregularities on the image of the microwave background surface, will span this angular scale. If we are able to obtain an image of this surface as it looked at that time, we would expect such hot spots to be, on average, the largest significant lumps we see in the image.

However, whether the angle spanned by this distance is precisely 1 degree will in fact be determined by the geometry of the universe. In a flat universe, light rays travel in straight lines. In an open universe, however, light rays bend outward as one follows them back in time. In a closed universe, light rays converge as one follows them backward. Thus, the actual angle spanned on our eyes by a ruler that is 300,000 light-years across, located at a distance associated with the last scattering surface, depends upon the geometry of the universe, as shown below:

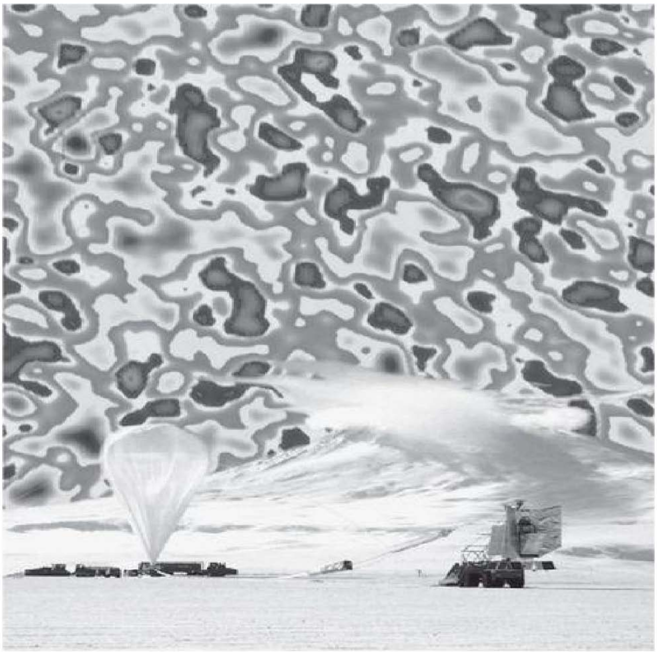
This provides a direct, clean test of the geometry of the universe. Since the size of the largest hot spots or cold spots in the microwave background radiation image depends just upon causality—the fact that gravity can propagate only at the speed of light, and thus the largest region that can have collapsed at that time is simply determined by the farthest distance a light ray can have propagated at that time—and because the angle that we see spanned by a fixed ruler at a fixed distance from us is just determined by the curvature of the universe, a simple picture of the last scattering surface can reveal to us the large-scale geometry of space-time.

The first experiment to attempt such an observation was a ground-launched balloon experiment in Antarctica in 1997 called BOOMERANG. While the acronym stands for *B*alloon *O*bservations *o*f *M*illimetric *E*xtragalactic *R*adiation *an*d

*G*eophysics, the real reason it was called this name is simpler. A microwave radiometer was attached to a high-altitude balloon as shown below:



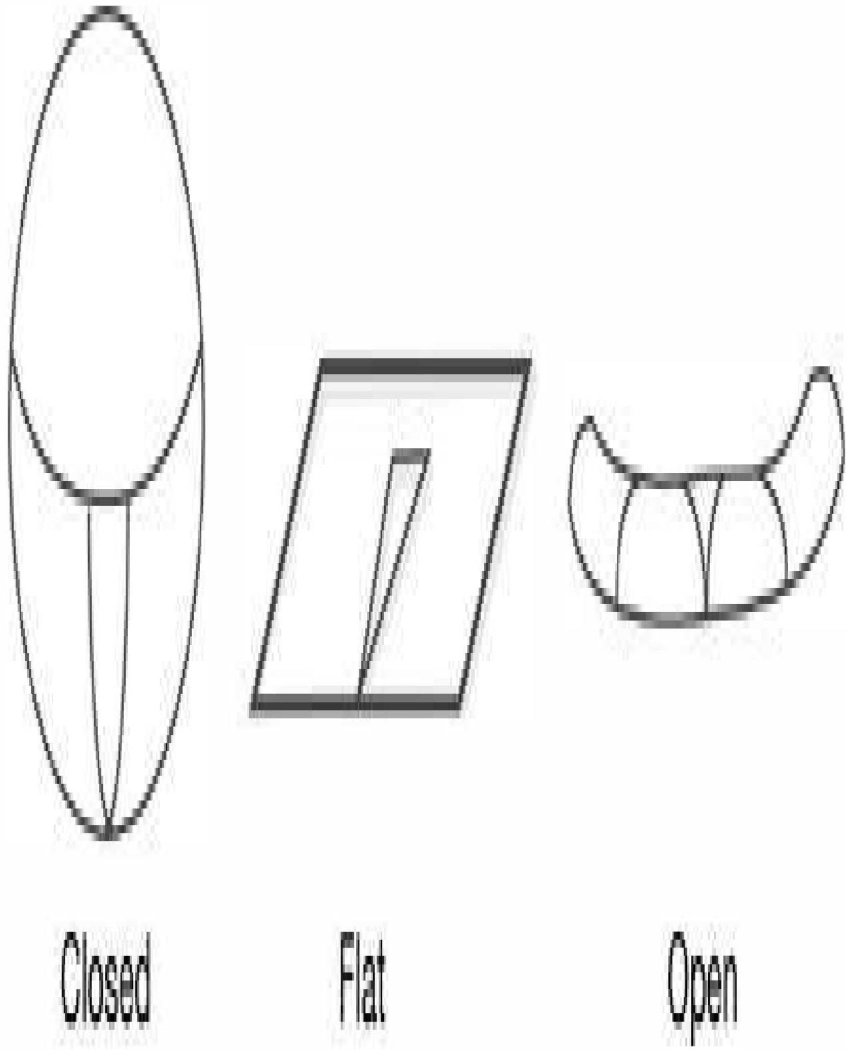
The balloon then went around the world, which is easy to do in Antarctica. Actually, at the South Pole it is really easy to do, since you can just turn around in a circle. However, from McMurdo Station the round trip around the continent, aided by the polar winds, took two weeks, after which the device returned to its starting point, hence the name BOOMERANG.



Boomerang path around Antarctica.

The purpose of the balloon trip was simple. To get a view of the microwave background radiation, reflecting a temperature of 3 degrees above absolute zero (Kelvin scale), which is not contaminated by the far hotter material on Earth (even in Antarctica temperatures are more than two hundred degrees hotter than the temperature of the cosmic microwave background radiation), we want to go as far as possible above the ground, and even above most of the atmosphere of the Earth. Ideally we use satellites for this purpose, but high-altitude balloons can do much of the job for far less money.

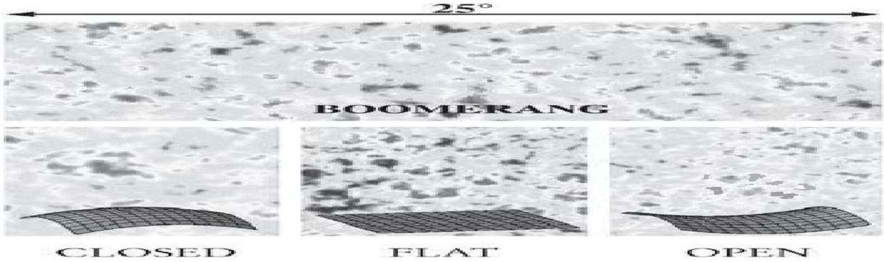
In any case, after two weeks, BOOMERANG returned an image of a small part of the microwave sky displaying hot and cold spots in the radiation pattern coming from the last scattering surface. Shown below is one image of the region the BOOMERANG experiment observed (with “hot spots” and “cold spots” being shaded dark and light respectively), superimposed upon the original photo of the experiment:



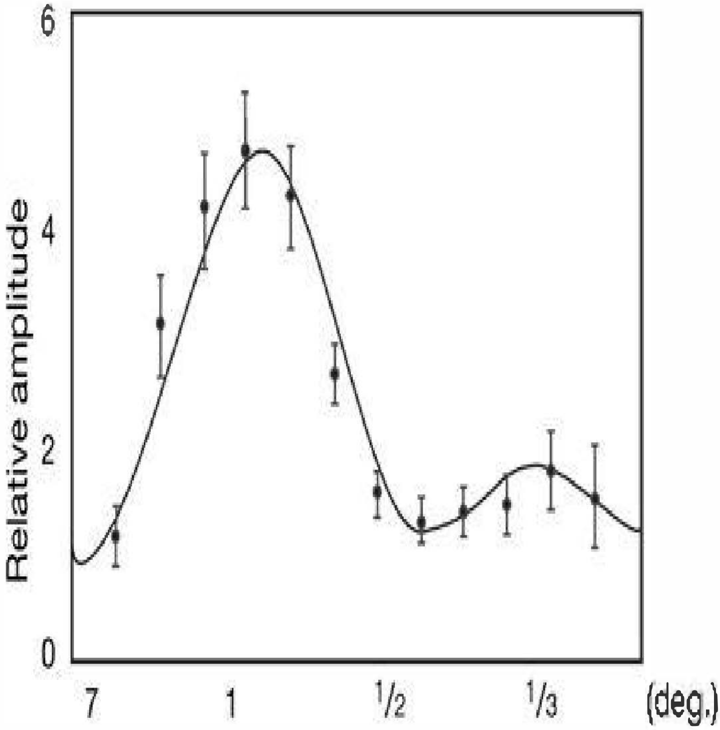
This image serves two purposes as far as I am concerned. First, it displays the actual physical scale of the hot and cold spots as seen in the sky by BOOMERANG, with the foreground images for comparison. But it also illustrates another important aspect of what can only be called our cosmic myopia. When we look up on a sunny day, we see a blue sky, as shown in the previous image of the balloon. But this is because we have evolved to see visible light. We have done so, no doubt, both because the light from the surface of our Sun peaks in the visible region, and also because many other wavelengths of light get absorbed in our atmosphere, so they cannot reach us on the Earth's surface. (This is fortunate for us, since much of this radiation could be harmful.) In any case, if we had instead evolved to "see" microwave radiation, the image of the sky we would see, day or night, as long as we weren't looking directly at the Sun, would take us directly back to an image of the last scattering surface, more than 13 billion light-years away. This is the "image" returned by the BOOMERANG detector.

The first flight of BOOMERANG, which produced this image, was remarkably fortunate. Antarctica is a hostile, unpredictable environment. On a later flight, in 2003, the entire experiment was nearly lost due to a balloon malfunction and subsequent storm. A last-minute decision to cut free from the balloon before it was blown to some inaccessible location saved the day and a search-and-rescue mission located the payload on the Antarctic plain and recovered the pressurized vessel containing the scientific data.

Before interpreting the BOOMERANG image, I want to emphasize one more time that the actual physical size of the hot spots and cold spots recorded on the BOOMERANG image are fixed by simple physics associated with the last scattering surface, while the *measured* sizes of the hot spots and cold spots in the image derive from the geometry of the universe. A simple two-dimensional analogy may help further explain the result: In two dimensions, a **closed geometry** resembles the surface of a sphere, while an **open geometry** resembles the surface of a saddle. If we draw a triangle on these surfaces, we observe the effect I described, as straight lines converge on a sphere, and diverge on a saddle, and, of course, remain straight on a flat plane:

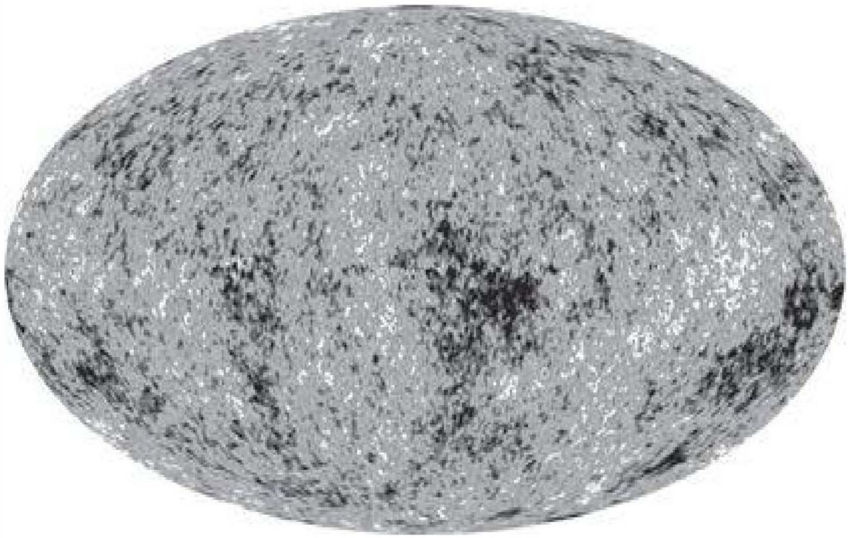


So the million-dollar question now is, How big *are* the hot spots and cold spots in the BOOMERANG image? To answer this, the BOOMERANG collaboration prepared several simulated images on their computer of hot spots and cold spots as would be seen in closed, flat, and open universes, and compared this with (another false color) image of the actual microwave sky.



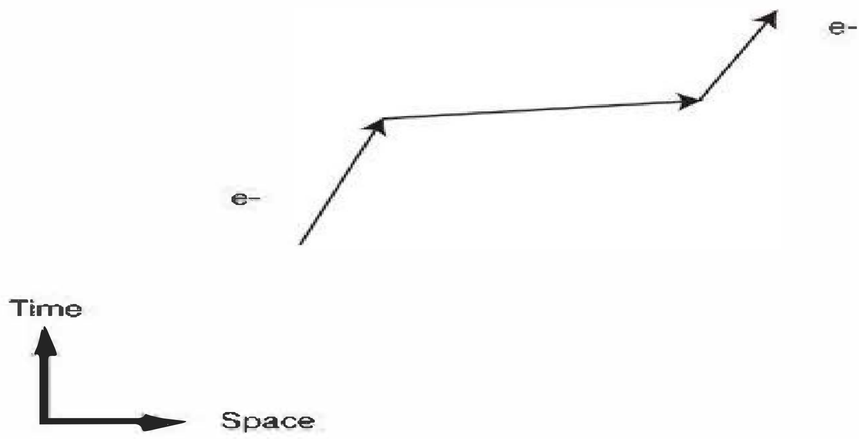
If you examine the image on the lower left, from a simulated closed universe, you will see that the average spots are larger than in the actual universe. On the right, the average spot size is smaller. But, just like Baby Bear's bed in Goldilocks, the image in the middle, corresponding to a simulated flat universe, is "just right." The mathematically beautiful universe hoped for by theorists seemed to be vindicated by this observation, even though it appears to conflict strongly with the estimate made by weighing clusters of galaxies.

In fact, the agreement between the predictions for a flat universe and the image obtained by BOOMERANG is almost embarrassing. Examining the spots and searching for the largest ones that had time to collapse significantly inward at the time reflected in the last scattering surface, the BOOMERANG team produced the following graph:



The data are the points. The solid line gives the prediction for a flat universe, with the largest bump occurring close to 1 degree!

Since the BOOMERANG experiment published its results, a far more sensitive satellite probe of the microwave background radiation was launched by NASA, the Wilkinson Microwave Anisotropy Probe (WMAP). Named after the late Princeton physicist David Wilkinson, who was one of the original Princeton physicists who should have discovered the CMBR had they not been scooped by the Bell Labs scientists, WMAP was launched in June 2001. It was sent out to a distance of one million miles from the Earth, where, on the far side of the Earth from the Sun, it could view the microwave sky without contamination from sunlight. Over a period of seven years it imaged the whole microwave sky (not just a portion of the sky as BOOMERANG did, since BOOMERANG had to contend with the presence of the Earth below it) with unprecedented accuracy.



Here the entire sky is projected on a plane, just as the surface of a globe can be projected on a flat map. The plane of our galaxy would lie along the equator, and 90 degrees above the plane of our galaxy is the North Pole on this map and 90 degrees below the plane of our galaxy is the South Pole. The image of the galaxy, however, has been removed from the map in order to reflect purely the radiation coming from the last scattering surface.

With this kind of exquisite data a much more precise estimate can be made of the geometry of the universe. A WMAP plot that is analogous to the one shown for the BOOMERANG image confirms to an accuracy of 1 percent that we live in a flat universe! The expectations of theorists were correct. Yet once again, we cannot ignore the apparent obvious inconsistency of this result with the result I described in the last chapter. Weighing the universe by measuring the mass of galaxies and clusters yields a value a factor of 3 smaller than the amount needed to result in a flat universe. Something has to give.

While theorists may have been patting themselves on the back for guessing that the universe is flat, almost no one was prepared for the surprise that nature had in store to resolve the contradictory estimates of the geometry of the universe coming from measuring mass versus measuring curvature directly. The missing energy needed to result in a flat universe turned out to be hiding right under our noses, literally.