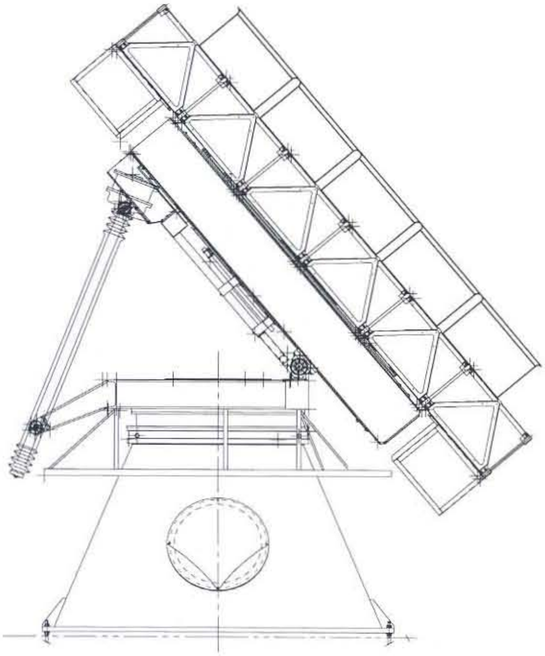
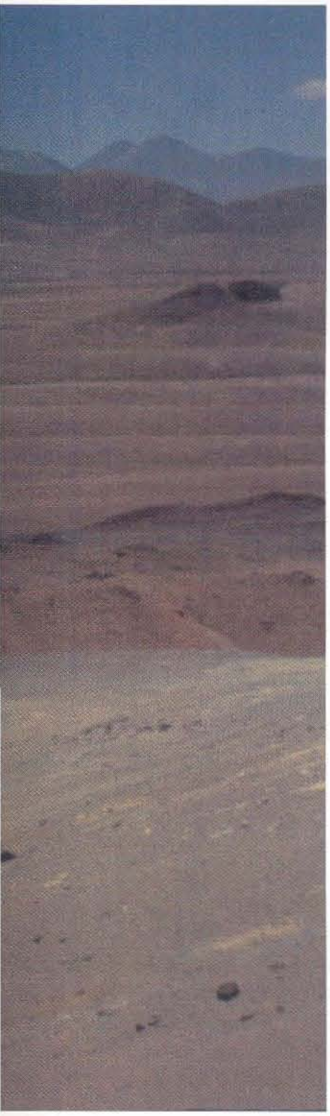


The Cosmic Background Imager (CBI) being designed and built at Caltech will make real images of the universe as it was 15 billion years ago and reveal structures that gave rise to galaxies and clusters of galaxies. The CBI's radio interferometric array consists of 13 one-meter radio telescopes mounted on a 6.5-meter platform. The diagram at left shows a side elevation view of the CBI. In addition to the usual two axes of rotation that point it at the field of interest, the array will be able to rotate about its optical axis in order to eliminate spurious instrumental signals.

Below: One of the prime sites under consideration for the CBI is at 16,000 feet (to minimize the effects of atmosphere) in the Andes Mountains in northern Chile. (Photo by Steve Padin)

Observing the Embryonic Universe

by Anthony C. S. Readhead



What did the universe look like 15 billion years ago? A new instrument we are building here at Caltech should be able to show us. Called the Cosmic Background Imager, or CBI, it will provide real images of what the universe actually looked like 300,000 years after the Big Bang. This is equivalent, when compared to a human life span of 70 years, to imaging a human embryo just a few hours after conception. The images will record the "microwave background radiation," which has been traveling through space for the last 15 billion years and presents an accurate picture of the universe during this embryonic period.

The CBI is designed to reveal minute variations—of down to one part in a million—in the background temperature of the universe as seen in different directions. These variations in temperature are believed to hold the key to understanding one of the central mysteries of modern cosmology—the formation of galaxies and hence of all the structures in the universe, including stars and planets. The temperature variations that we will see in the microwave background radiation are produced by tiny fluctuations in the density, temperature, and velocity of the universe's matter at this early period, and these tiny fluctuations are the seeds that eventually produced galaxies. A region that was slightly denser than its surroundings would slowly accrete mass by gravitational attraction of the surrounding material, and eventually become a galaxy or a cluster of galaxies.

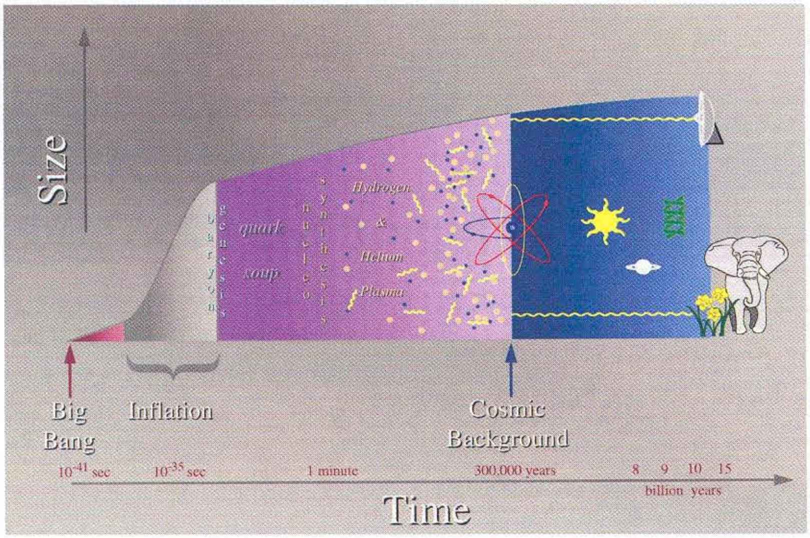
At present we are woefully ignorant about how galaxies form, but there is no shortage of interesting and often bizarre theoretical speculation.

If we could image the microwave background radiation with sufficient precision, we would be able to measure those tiny differences in temperature and density. The physics of how those seed fluctuations grew with time in those early epochs is simple, so the only real problem is the actual measurement itself. With the measurement as a starting point it would be possible to develop a real theory of galaxy formation based on solid observations. At present we are woefully ignorant—as we will see shortly—about how galaxies form, but there is no shortage of interesting and often bizarre theoretical speculation.

In the illustration on the following page, I have taken great liberties with the time axis in order to focus on the most important cosmological events in

These tiny quantum fluctuations would then also be responsible for everything, from galaxies down to stars and planets.

The theoretical history of the universe in a nutshell (time is clearly not to scale). After the hot Big Bang about 15 billion years ago, the universe cooled and the first atoms formed. When the universe was about 300,000 years old, the "decoupling" of light from matter allowed the microwave background radiation to travel freely through the universe, where today it provides us a picture of what went on in that early epoch.



the history of the universe. I will assume, for the sake of clarity, that the universe is 15 billion years old (although estimates of the age vary between about 10 and 15 billion years). The epoch that we will image with the CBI—just 300,000 years after the Big Bang—is marked with an atom. Before this epoch the universe was so hot that the material in it was ionized; that is, the electrons were not bound to the atoms and thus there were lots of free electrons. These free electrons absorbed and scattered photons readily, so that a photon couldn't travel very far before interacting with an electron. The universe was therefore "optically thick"—any light ray could travel only a short distance before being absorbed. It's rather like being in a dense fog, where one can only see a very short distance. It's impossible, therefore, to make direct images of the universe when it was less than 300,000 years old.

However, as the universe expanded it cooled (just as the air escaping from a tire cools as it expands through a valve), and about 300,000 years after the Big Bang the temperature of the universe dropped below 4000 K. The electrons then combined with hydrogen and helium nuclei to form the first atoms. Once atoms had formed, there were no longer free electrons to absorb and scatter light, and photons could travel freely through the universe. We call this epoch—when the universe was 300,000 years old— the epoch of "decoupling." (Before this time light could not travel far without interacting with matter, and light and matter were therefore strongly coupled. However, after this time light could travel across the universe without interacting with matter, so light and matter were no longer coupled together.) Since the epoch of decoupling, the universe has been optically thin. Observations of the microwave background radiation therefore provide a direct picture of the universe at the epoch of decoupling, since these photons were present then, were stamped by the early universe's imprint, and have been unaffected by matter ever since, until they reached our telescopes.

Most of astronomy and astrophysics concentrates on events after the epoch of decoupling, since all of the structures that we are familiar with were formed later. I shall be concentrating primarily on these later epochs in this article. However, some important events from before the decoupling epoch have a bearing on this tale, so I will discuss them briefly now.

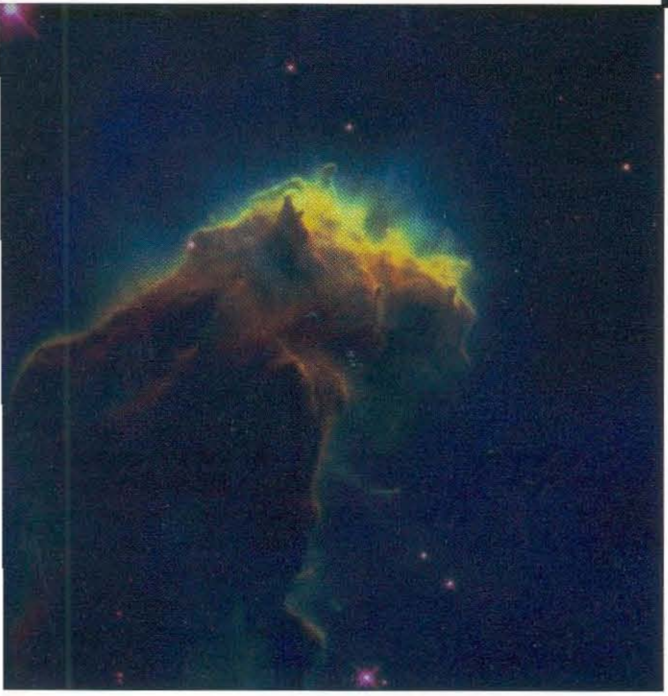
We now know that the universe began with the Big Bang, about 15 billion years ago. Our understanding of the universe's earliest moments is extremely primitive, because when the universe was about 10^{-43} seconds old, gravitational and quantum effects were comparable. At that point, the universe was so dense that gravity, which is usually much weaker than the strong nuclear force, was on an equal footing with it. In order to understand the physics of this period, we need to have a combined theory of gravity and quantum mechanics. (This has eluded theoretical physicists for the last 80 years, although significant progress is now being made.) Many cosmologists think that the universe went through a period of very rapid (exponential) expansion shortly after the Big Bang, when the universe was some 10^{-32} seconds old. This is referred to as the epoch of "inflation."

I will not discuss this epoch in any detail, except to mention that there are a number of puzzles in the standard Big Bang picture that are nicely explained by inflation. After the epoch of inflation, the universe settled down into the standard, much slower expansion that is still going on today.

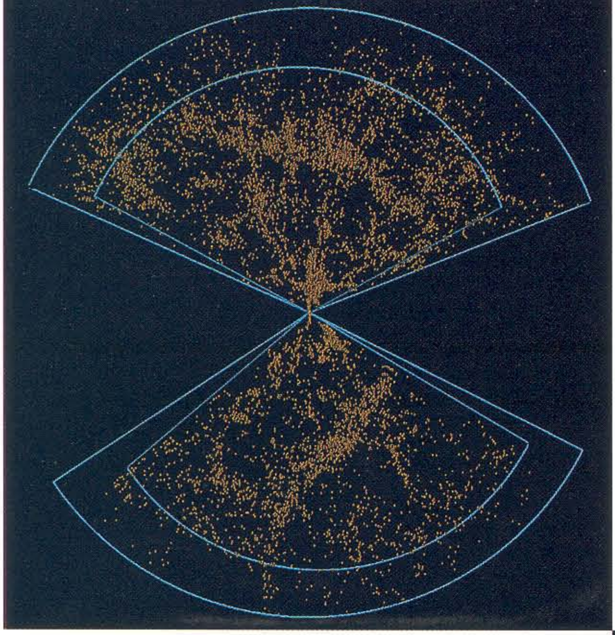
Continuing with the illustration, the next important milestone occurred when the universe was between one second and a few minutes old. During this epoch the universe cooled to a temperature of a few billion degrees, allowing the nuclear reactions that built up the light elements to take place. Deuterium, helium-3, helium-4, and lithium were created out of the primordial neutrons, protons, and electrons. One of the major strengths of the Big Bang cosmology, and one of the reasons that we accept it, is that it gets the ratio of these light elements right—the abundances calculated from the Big Bang theory correspond to those we see today.

The next important epoch is the one we have already considered in some detail, namely the epoch of decoupling. This occurred, as we have seen, when the universe was about 300,000 years old. This is when the microwave background radiation that we observe today was produced. Imprinted on this radiation are tiny variations in temperature between one line of sight and another, caused by the small fluctuations in the primordial matter's density, temperature, and velocity. These were the seeds that eventually gave rise, through the effects of gravity, to galaxies. These fluctuations must have been caused by something that happened even earlier, and if we can study the microwave background radiation in enough detail, we may even be able to figure out what that something was. The most popular theory is that quantum fluctuations during the inflationary epoch were responsible. This would be very remarkable if true, since it would mean that small-scale quantum fluctuations in the very early universe gave rise to the largest structures that we see in the universe today. These tiny quantum fluctuations would then also be responsible for everything, from galaxies down to stars and planets.

I now want to review briefly the structures that any successful cosmological theory must explain. These range from planets and stars to galaxies, clusters of galaxies, superclusters, and voids. All of these structures appeared after the decoupling epoch. It should be clear that the formation of galaxies is an essential step in the formation of both stars and planets, since it is in galaxies that the matter density gets high enough to produce these smaller objects under the influence of gravity. A beautiful image, at left, of the star formation process was recently obtained by the Hubble Space Telescope. On larger scales we see clusters of galaxies like the one pictured above. This is an image of the galaxy cluster named Abell 2218, after the late George Abell [BS '51, MS '52, PhD '57], who worked on this cluster as a graduate student at Caltech. The deepest high-resolu-



Both of these images were captured by the Hubble Space Telescope (using the second Wide Field/Planetary Camera built at JPL). Below is a star-forming region in our own galaxy and, at right, a cluster of galaxies named Abell 2218. All of these structures originated in tiny fluctuations in primordial matter.



Until the beginning of this century, only one cosmological fact was known—that the sky is dark at night.

tion optical image of the sky to date is the Hubble Space Telescope image shown at right. Here we see galaxies that span a very large range of distances—from 2 billion light-years away to about 14 billion light-years away. One of the most astonishing discoveries in modern cosmology has been that of gigantic sheets of galaxies, separated by enormous "voids" in which there are fewer galaxies than average. The most famous of these is the "Great Wall," illustrated above, discovered by Margaret Geller and John Huchra [PhD '77]. It lies at a distance of about 500 million light-years from us, and is about 500 million light-years long. Looking at images such as this, one can't help but wonder how such structures were produced by the small fluctuations that existed in the embryonic universe.

As a result of a remarkable discovery in 1963 by Maarten Schmidt (now the Francis L. Moseley Professor of Astronomy, Emeritus), we know that some of the familiar objects in the universe formed in the first billion years. Radio astronomers had discovered objects in the sky that seemed to be unresolved (that is, compact) radio sources, and they had managed to measure accurate positions of these objects. Optical astronomers found starlike objects at these positions, and hence they were called "quasars," short for "quasi-stellar objects." Both Schmidt and Jesse Greenstein (now the Lee A. DuBridge Professor of Astrophysics, Emeritus) were trying to identify the lines seen in quasar spectra when Schmidt had the brilliant insight that the lines might have been shifted far toward the red, toward longer wavelengths, and so were not appearing anywhere near where they were expected. (These lines, which are emitted by the various chemical elements in the source object, lie at characteristic wavelengths that can be used to identify those elements. That's how we know what distant stars are made of.) The redshift, caused by the Doppler effect, indicated that the quasars were moving rapidly away from us. We shall see shortly that measuring the speed of a celestial object

Shown above is the Hubble Space Telescope Deep Field image of a small region near the north celestial pole. This is the deepest high-resolution image made to date. It shows galaxies ranging from 2 billion light-years to about 14 billion light-years away.

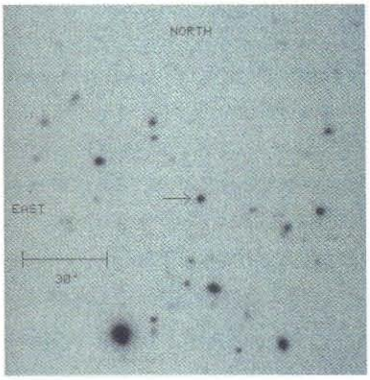
Above, left: The "Great Wall" is a sheet of clustered galaxies with voids in between. It's about 500 million light-years away and 500 million light-years across. (Courtesy of Margaret Geller and John Huchra of the Smithsonian Astrophysical Observatory.)

enables us to estimate its distance, and Schmidt concluded that the object—3C 273—was about two billion light-years away. But 3C 273 is one of the brightest radio sources in the sky, implying that similar, fainter radio sources must be even more distant—which turns out to be true.

Schmidt has continued in this line of research, and he and his collaborators hold the record for the most distant object now known: a quasar called 1247+3406, which is about 14 billion light-years away (right). This object formed just one billion years after the Big Bang. When we look at the spectrum of this distant quasar and compare it with the spectra of intervening galaxies, we find that they all show evidence of the familiar heavy chemical elements that we see in the nearby universe. You need stars to create all the elements heavier than lithium, so this tells us that when the universe was one billion years old, it had already gone through quite a bit of star formation and had already been forging the heavy elements. How the tiny fluctuations from the decoupling epoch could have given rise to stars and quasars in only one billion years is a major problem of astrophysics. We will discuss this in some detail later.

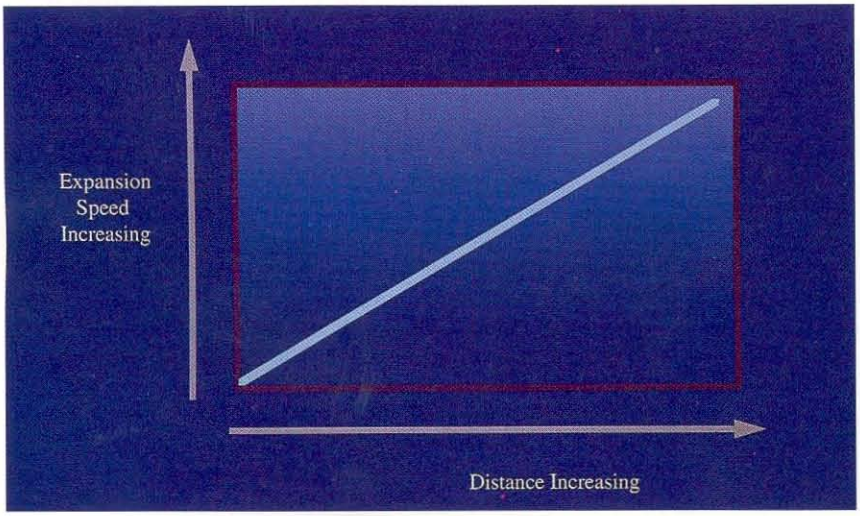
Edwin Hubble discovered that there's a linear relationship between the speed and distance of galaxies (graph at bottom), evidence that the universe is expanding.

For now, I'd like to step back and talk a bit about the science of cosmology, which deals with the origin and structure of the universe. This is only now becoming a real science, because we're beginning to get enough observational data to make testable predictions.



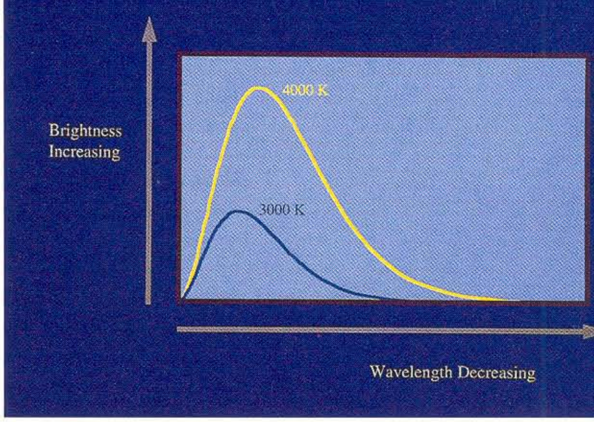
The arrow points to the most distant object known—a quasar 14 billion light-years away.

Until the beginning of this century, only one cosmological fact was known—that the sky is dark at night. In one sense this may sound trivial, but in another sense it's actually very profound. The peculiar aspect of this phenomenon, known as Olbers' Paradox, was first noted by Johannes Kepler in 1610, and later by Edmund Halley and Jean-Philippe-Loys de Cheseaux. Why is the sky dark at night? If the universe were infinitely old, infinitely large, static, and homogeneous, then any line of sight would eventually end up on the surface of a star. The whole sky should be as bright as the sun, which it manifestly is not. Thus one of the above assumptions is wrong. Actually, Olbers' Paradox can be restated in a more fundamental way, as has been pointed out by the cosmologist George Ellis. The real cosmological question is not why is the sky dark at night, but rather, why does the sun shine by day? Because stars shine by thermonuclear burning and because there's a limited amount of fuel available, if the universe were infinitely old, then all the thermonuclear material would have been used up infinitely long ago, unless there were some spontaneous method of generating energy. Therefore, all the stars that had ever existed would now just be dead hunks of rock. The answer to the paradox, as we now know from the Big Bang, is that the universe is not infinitely old (and neither is it static); there is still free energy around to be turned into heavier elements by thermonuclear burning.



The next important step in cosmology came in 1916, when Albert Einstein produced the general theory of relativity. This wonderful theory is the basis of all modern cosmology. But there was a flaw in it—or so Einstein thought. His theory predicted that the universe was not static, but had to be either expanding or contracting. He didn't believe this and was very worried about it, so he added a fudge factor called the cosmological constant. If the cosmological constant is positive, then it endows space with a property that acts like antigravity. With this fudge factor added, Einstein's theory does produce a static model of the universe.

However, in 1929, a few miles away from Caltech up on top of Mount Wilson, the astronomer Edwin Hubble made an astonishing discovery. Building on work that had been done earlier by Vesto Melvin Slipher and others, in which they had found that galaxies outside our small local group are all moving away from us, Hubble found that the farther away a galaxy is, the faster it's moving away from us. He found that there's actually a linear relationship between speed and distance, as shown at left. The scientific community immediately accepted this as evidence that the universe was expanding, at which point



In 1964 AT&T scientists Wilson and Penzias discovered the microwave background radiation, a relic of the radiation produced in the early universe. As the universe expands, it cools, and the peak of this radiation moves to longer wavelengths (right). It can now be detected most easily at radio wavelengths, and this is what the two scientists observed as a uniform temperature of 2.7K (Kelvin) in all directions.

Einstein wished that he had never invented his fudge factor. Had he not, he would instead have made a remarkable prediction. It's there in his theory, but he didn't believe it. The universe is expanding, and Einstein didn't need the cosmological constant. The cosmological constant never really died, however, and has gone in and out of favor over the years. Right now it's back in favor as a very important ingredient in the inflationary theories of cosmology.

The proportionality constant in Hubble's relationship, that is, the slope of the line, is called the Hubble constant. The determination of this constant is important in cosmology, since it tells us the size and age of the universe. Much effort has been put into measurements of the Hubble constant over the last six decades, but it is still known only to within about 50 percent (which is why the age of the universe is known only to lie between 10 billion and 15 billion years). This is one of the major unsolved problems of modern astrophysics.

Another important cosmological parameter is the "density parameter," which describes the amount of matter in the universe. The expansion of the universe is slowing down, due to the effects of gravity. There is a critical density for the universe such that if the actual density is below this value, then expansion will continue forever; if the actual density equals the critical density, then the expansion will just stop in an infinite amount of time; and if the actual density exceeds the critical density then the expansion will one day be reversed, the universe will contract, and it will end in a "Big Crunch"—the opposite of the Big Bang. The density parameter (Ω) is the ratio of the actual density to the critical density, so that the three possibilities we've just discussed correspond to $\Omega < 1$, $\Omega = 1$ and $\Omega > 1$.

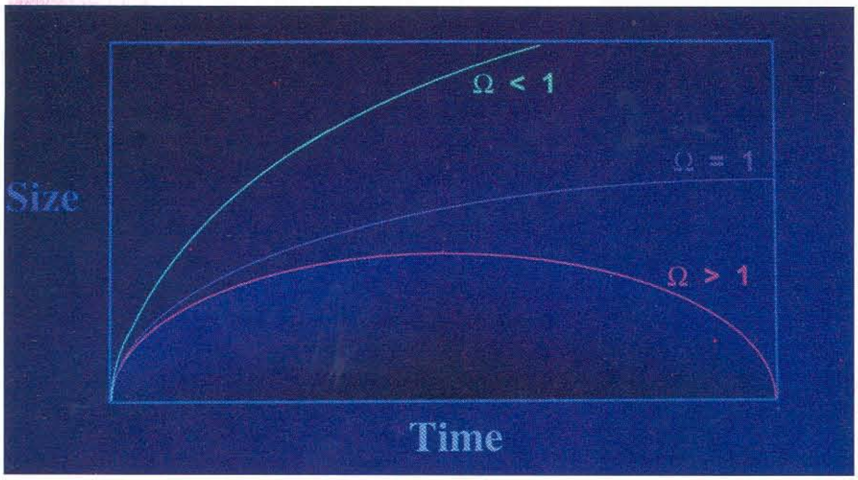
The three constants, or parameters, that we have discussed—the cosmolgical constant, the Hubble constant, and the density parameter—are the most important in cosmology. If present theories are to be believed, then measurements of the small temperature fluctuations seen in different directions should enable us to determine these three numbers with considerable precision.

Now, as we have already seen, because the universe is expanding it must be cooling, which means that it must have been much hotter when it was young. In other words this is a "hot Big Bang" universe. This means that there must have been a lot of radiation produced in the early universe. This fact was pointed out by George Gamow in 1948. He also pointed out that the relics of this radiation would still be around today, but its wavelength would have been stretched (by the expansion of the universe) from the optical part of the spectrum all the way down into the radio part. Thus Gamow predicted the existence of the microwave background radiation based solely on a simple Big Bang model of the universe.

In 1949, two of Gamow's students, Ralph Alpher and Robert Herman, calculated that the temperature of the microwave background radiation today would be about 5K (Kelvin). Remarkably, this prediction was ignored by observational astronomers for the next 15 years!

The microwave background radiation was finally discovered accidentally in 1964 by Arno Penzias and Robert Wilson (PhD '62), while they were measuring noise inherent in radio receivers. They had made an extremely sensitive radio receiver and calibrated it very well, but wherever they looked in the sky, they found that it was a

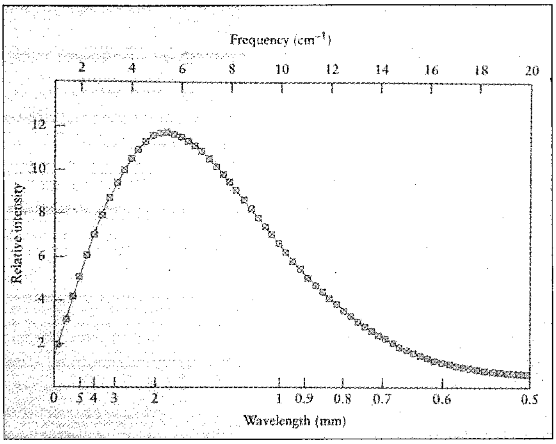
The amount of matter in the universe is described by the density parameter—Ω. If the critical density is less than the actual density ($\Omega < 1$), the universe will expand forever. If $\Omega = 1$, the expansion will just stop, and if $\Omega > 1$, the universe will contract in the "Big Crunch."



little hotter than they expected. They thought something was wrong with their receiver, but it turned out that they had discovered the microwave background radiation, which is seen at a temperature of 2.7K in all directions. This is the relic, or fossil, radiation left over from the Big Bang, and this, more than anything else, has convinced astronomers and physicists that we are indeed living in a hot Big Bang universe. In 1978, Penzias and Wilson received the Nobel Prize for their discovery.

The COBE (Cosmic Background Explorer) satellite, which was launched in 1989 to study this cosmic background radiation, has been very successful. One of its great accomplishments has been to measure the spectrum of this radiation. In the illustration at right, the curve is not a fit to the observed data points; it's actually the curve predicted by thermodynamics for an object that is a perfect emitter and absorber of radiation (blackbody curve). This well-known curve, first worked out by Max Planck in 1900, laid the foundation for quantum mechanics. It is one of the cornerstones of physics and is not in any doubt. It so happens that this is also the spectrum expected for the microwave background radiation. We see that the COBE observations fit the theoretical curve with exquisite precision.

The COBE observations of the spectrum of the microwave background radiation conform precisely to the theoretical prediction of the spectrum from a perfect absorber and emitter of radiation. This is called blackbody radiation.



With the discovery of the microwave background radiation cosmology came of age. It has taken 30 years, however, to develop the tools that will enable us to reap the benefits of that discovery.

Since the discovery of the microwave background radiation in 1964, there have been many observations of this radiation to try to detect variations in temperature along different lines of sight. One of the remarkable facts of astrophysics to emerge over the last 32 years has been the extraordinary smoothness of this fossil radiation. We now know that the temperature of the radiation varies by less than one part in 30,000 on all angular scales, once one has made the correction for the Doppler effect caused by the earth's motion relative to it. The amazing smoothness of the microwave background radiation tells us that the universe underwent a "simple" Big Bang or, to put it more explicitly, the universe is "simple" in the sense that it is both homogeneous and isotropic. In other words, if we look at the content of a small volume of the universe (that is, small compared to the universe but much larger than our local system of galaxies) and compare it to any other such volume, the average properties will be the same (that is, the universe is homogeneous); and if we look in any direction and consider a small area (one that is a small fraction of the celestial sphere) the average properties will be the same (that is, the universe is isotropic).

Now it might have been the case that the universe underwent a "compound" Big Bang, in which case the average properties of the universe from cell to cell would have been very different—the universe would not have been homogeneous and isotropic. In this case we would not have been able to draw conclusions about the large-scale structure of the universe. Cosmology would have been difficult, or most likely impossible, because what you would see would depend critically on just where you happened to be sitting.

Even a simple Big Bang contains many mysteries, but it seems that we are now poised to make critical observations that should elucidate the basic nature of the universe. With the discovery of the microwave background radiation, cosmology came of age. It has taken 30 years, however, to develop the tools that will enable us to reap the benefits of that discovery.

Before going on to discuss the CBI, I want to discuss a major mystery of astrophysics and cosmology that is fundamental to the interpretation of observations of the microwave background radiation. This is the mystery of dark matter, which has been growing more and more mysterious for the last three decades.

M31, the great nebula in Andromeda, must have far more mass than we would deduce from the starlight in this picture, because the stars at the outside of the spiral are orbiting at the same speed as those close to the center. This invisible mass is known as "dark matter."

If we look at our neighboring sister galaxy, the great nebula in Andromeda, M31 (above), we see a system that is pretty much a twin of the Milky Way. M31 is 2 million light-years away; the light that is reaching us today left the galaxy when our australopithecine forebears were stalking the plains of Africa. The galaxy seems to be about 100,000 light-years in diameter and to be fairly isolated. This is an illusion. It turns out that there is much more matter in this galaxy than is revealed through its starlight, which is all that we see in this photograph.

How can we trace mass if not through the light of stars? One simple method is to look for the gravitational effects of the mass. You can figure out the amount of mass in a galaxy by looking at the rotation speed of material around the galactic center. If the mass were distributed like the visible stars are—highly concentrated toward the center and dropping off rapidly toward the outer edges—then we would have a centrally condensed system, like the solar system. In such a system the rotation speed of the stars about the center of the galaxy would fall off with distance from the center, just as is observed for the planets in our solar system. However, in M31 we find that the rotation speed is constant with distance from the center. Even the most distant stars from the center show no evidence of a drop in orbital speed. There can be only one explanation of this—namely, that there is far more material in M31 than is revealed by starlight. Thus this galaxy must have a very substantial component of "dark matter," which is distributed differently than the stars.

M31's behavior turns out to be common. This means that galaxies must be much more massive and much larger than they appear. If you look at a cluster of galaxies, you see that the galaxies appear to be separated by vast regions of empty space that are typically about 10 galaxy diameters across—

If we could see all the dark matter associated with galaxies, we would find that the galaxies are almost touching each other and are composed primarily of dark matter. This poses one of the great mysteries of modern astrophysics—what is this dark matter made of?

about the same as the apparent distance between our galaxy and M31. This is also an illusion. If we could see all the dark matter associated with galaxies, we would find that the galaxies are almost touching each other and are composed primarily of dark matter. This poses one of the great mysteries of modern astrophysics—what is this dark matter made of?

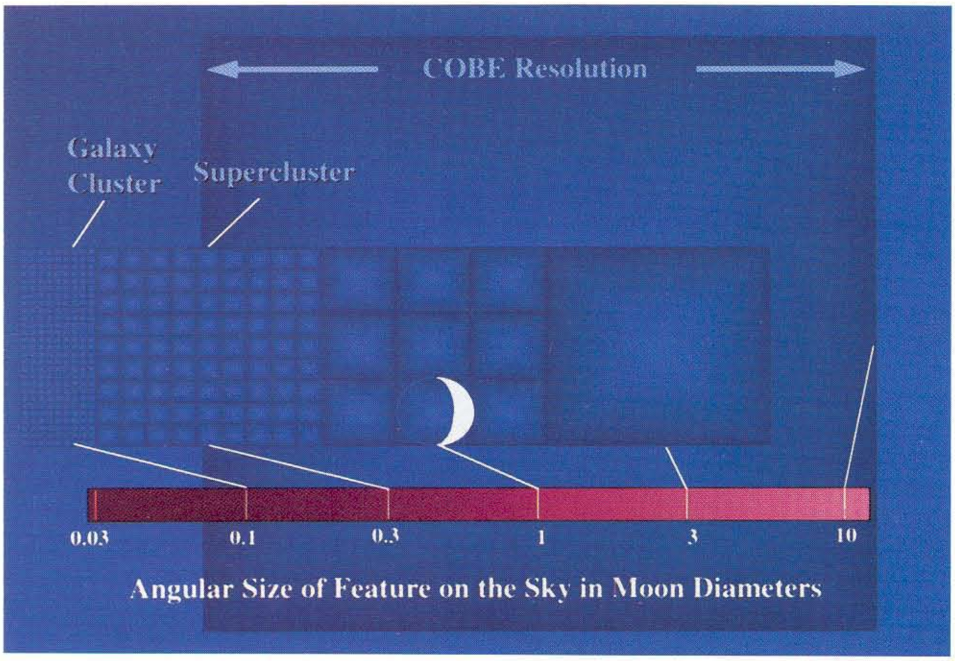
There's a lot of very complicated physics going on in nearby galaxies, which makes it very difficult to address this question. It's much easier to study by looking at the microwave background radiation, which is left over from a time when the fluctuations in the density and temperature of matter were very small. The equations governing this regime are relatively simple, and we think we understand them pretty well.

We have already made a number of observations of the microwave background radiation with the 40- and five-meter radio telescopes at Caltech's Owens Valley Radio Observatory, 250 miles north of Los Angeles. What we have found, and what has been found by a number of other astronomers, is that within about one part in 30,000 there are no variations in the temperature of the microwave background at all. This is perplexing, because it's hard to see how quasars could form within a billion years after the Big Bang, if you start out with a very smooth universe. It takes longer than that for the material to accumulate into clumps by gravitational attraction. In fact, it is now widely accepted that these results show that it is simply not possible to begin with fluctuations of only the strength inferred from the microwave background radiation observations and produce galaxies on the required time scale.

If we wish to produce galaxies on the required time scale, and quasars one billion years after the Big Bang, we must have larger seeds than the density fluctuations that we infer from the microwave background radiation. It's not easy to get around this difficulty as long as we assume that the seed fluctuations are fluctuations of ordinary matter composed of protons and neutrons. Protons and neutrons are called baryons, and wherever there are protons and neutrons there are also electrons—one for every proton. Light photons (and radio photons) interact strongly with electrons. So if the seed fluctuations consisted of baryons, then we would see fluctuations in the microwave background radiation since matter and radiation are strongly coupled. But we don't. This rules out baryons as the major constituent of the seeds. As a result, many cosmologists now believe that the seed fluctuations consist of nonbaryonic dark matter, and that it is the same nonbaryonic dark matter that constitutes the majority of the matter in galaxies.

Therefore, a significant fraction of the universe—perhaps as much as 99 percent of its matter—may consist of nonbaryonic matter. There are other lines of evidence beyond the rotational speeds of galaxies that support this conclusion. For one thing, the relative abundances of the light elements depend critically on the primordial photon-to-baryon ratio, and the observed abundances of these elements tell us that the amount of baryons in the universe is about two percent of the critical density. Yet other observations, based on the calculated gravitation between groups of galaxies, imply that the universe's total density (baryonic and nonbaryonic matter combined) is at least 20 percent of the critical density. Hence baryonic matter can account for, at most, 10 percent of the universe's total matter content. The remainder could possibly be neutrinos, but this seems unlikely, for reasons we don't have space to discuss here. It could also be material that's completely different from any of the material that we're familiar with. But it's still a bit of a reach to try to get out of a theoretical difficulty like this by saying, "Well, 90 to 99 percent of the matter in the universe is in a bizarre form that we just haven't been able to detect yet."

I now want to discuss the CBI, and tell you how it could throw light on all of the above questions. We are currently finalizing the design of this instrument, and testing prototypes of its major components, in Robinson Laboratory here on campus. There is a small local team, consisting of myself; Member of the Professional Staff Steve Padin, the chief scientist, who is responsible for all of the detailed instrument design; Tim Pearson, who is responsible for the data reduction and analysis; Martin Shepherd, who is designing the instrument's computer-control and data-acquisition systems; John Cartwright, an astronomy graduate student; and Walt Schaal and John Yamasaki, engineers working part time on the project. Off campus, Marshall Joy of the Marshall



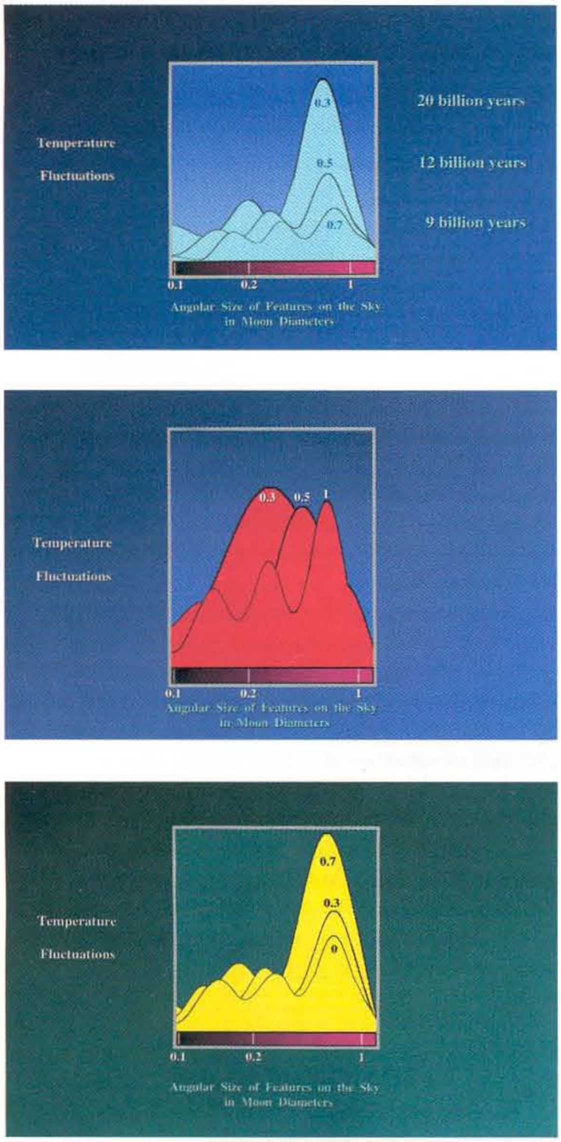
The angular size of features in the sky can be seen here in terms of moon diameters. One moon diameter projected onto the background radiation could resolve structures 300,000 light-years across, the maximum size for regions that are "causally connected." At 0.3 moon diameters, we would be able to see something the size of superclusters, and at 0.1 moon diameter, galaxy clusters. The CBI will be able to measure temperature over all these angular scales—a much higher resolution than that of COBE.

Space Flight Center is responsible for building the telescope dish molds. We're also collaborating with a group, headed by John Carlstrom of the University of Chicago and including people from the Center for Astrophysical Research in Antarctica, that is building a complementary instrument that will look at slightly larger angular scales than the CBI.

Let me give you some idea of the angular scales of interest. In the plot above and in those that follow, I'll use the size of the moon, which is half a degree, as a fiducial angular size. I don't do this for capricious reasons—it turns out that this angular size is a very important size for the microwave background. If you take the moon's diameter and project it back onto the microwave background, it turns out to be 300,000 light-years across. This is just the size of the regions of the universe that can interact with each other. Larger regions span more space than light could have traveled since the Big Bang, so they cannot interact. We say that they are not causally connected. This means that within one lunar diameter, we can expect to see structures that are collapsing under their own self-gravity. Larger-scale structures will not do this, since they have not had time to feel the effect of their own gravity. (The highest resolution of the COBE observations is much larger than the causally connected parts of the universe.) At one-third of a lunar diameter we're in the regime of superclusters, and at one-tenth in the regime of galaxy clusters. The instrument that we're building at Caltech is designed to observe over this range of angular scales.

Over the last decade there has been a tremendous flurry of theoretical activity to work out different possible cosmological models that predict the expected change in temperature of the microwave background radiation over a range of angular scales. These calculations have been carried out for various assumed values of the three parameters we discussed earlier—the Hubble constant, the density parameter, and the cosmological constant. The three plots at right provide a graphic demonstration of why the angular scale corresponding to the moon's diameter is important—nearly all of the models predict a peak in temperature fluctuations at this or a slightly smaller size. In the top plot we see theoretical predictions for three different values of the Hubble constant if we assume that $\Omega = 1$, that is, the density parameter equals the critical density. (There are no estimates of Ω—which are generally based on observations of galaxy velocities—that are significantly greater than 1.) If we could make good observations of the microwave background radiation, we should be able to discriminate clearly between values of the Hubble constant corresponding to an age of the universe of 20, 12, and 9 billion years. Similarly, if we look at models in which we fix the Hubble constant and vary the density parameter, we see that the main peak in the temperature fluctuations varies (middle). Thus, for example, if the density parameter is 0.3—corresponding to an open universe—we see that the peak occurs at about a half a lunar diameter, that is, at one quarter of a degree. Thus, measuring the position of the main peak should tell us the mean density of the universe, and hence whether the expansion will one day turn into a contraction and head for a Big Crunch. By varying the cosmological constant we produce a third family of curves (bottom). It turns out that there's enough information in these different curves that if you could just measure the temperature fluctuations with enough precision, you should be able to determine the values of these three parameters.

The early predictions of the magnitude of the fluctuations were off by a factor of 100, and any theory that assumes that more than 90 percent of the matter in the universe is in some bizarre form that we know nothing about deserves a certain amount of skepticism.



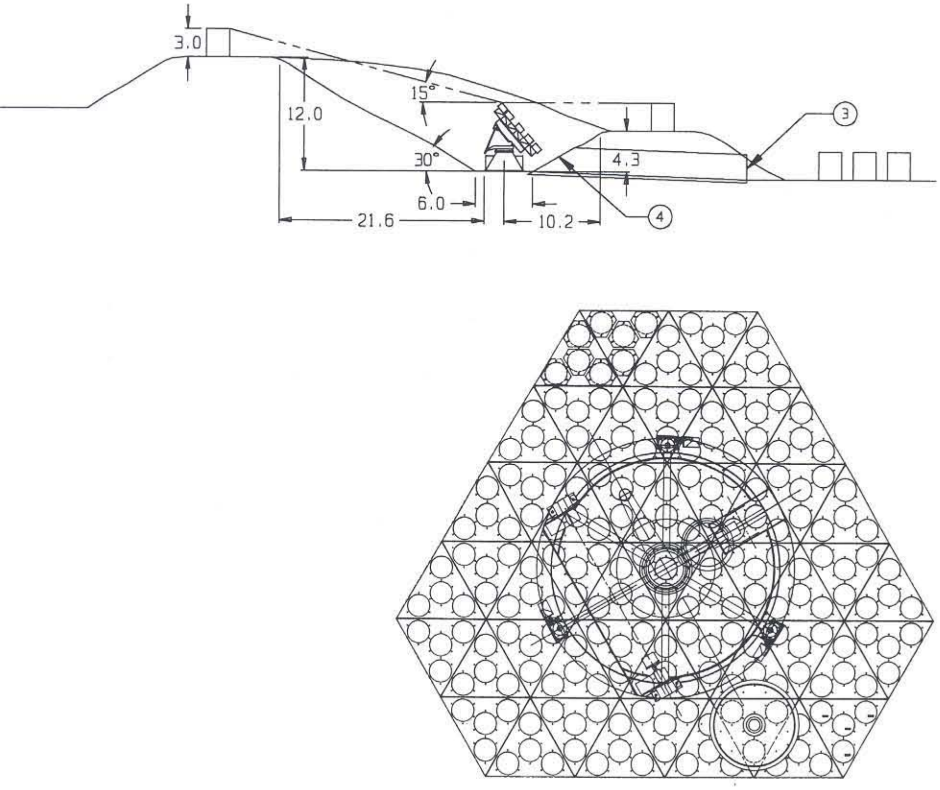
Theoretical calculations for the various cosmological models have predicted the expected temperature fluctuations over a range of angular scales. The top graph of three values of the Hubble constant (related to different ages of the universe) shows a peak at ranges within the CBI's view. In the middle graph, which varies the density parameter (with a fixed Hubble constant), there are several peaks from 0.3 to 1 moon diameter. The bottom set of curves varies the cosmological constant.

We should, however, be careful about taking these models too seriously; they could all be wrong. The early predictions of the magnitude of the fluctuations were off by a factor of 100, and any theory that assumes that more than 90 percent of the matter in the universe is in some bizarre form that we know nothing about deserves a certain amount of skepticism. On the other hand, the models may be right, so what we want is an instrument that will enable us to make the images needed to measure the actual variations in temperature over this range of angular scales. We may end up finding something that's completely different from any of these models, but whatever we discover is bound to be very interesting.

The CBI will be a radio interferometer consisting of 13 antennas, each with its own receiver, mounted on a 6.5-meter platform. The signals from each pair of antennas (78 in all) will be combined in a correlator and then recorded. This is a standard radio-astronomy technique, which enables us to make images of the sky that reveal, in this case, very small variations in temperature.

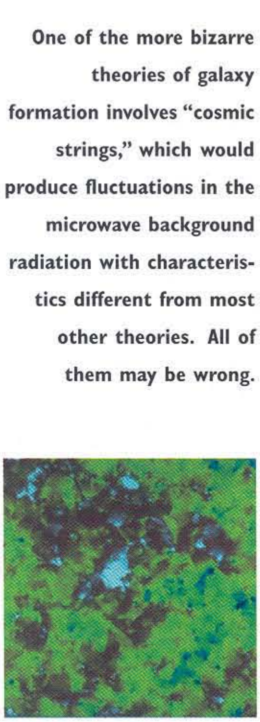
The CBI has to measure temperature differences of only 10 millionths of a degree—a very difficult achievement. We have to use extremely sensitive receivers, which have to be cooled to 15K and kept at this temperature for many months. In addition to thermal noise, which we minimize by using cooled receivers, there are a number of sources of systematic error that can easily swamp the signals that we are trying to detect. One of the largest of these error sources is so-called "cross talk" between adjacent antennas, in which some of the noise from one receiver leaks back out of the front of its antenna and is picked up by an adjacent antenna. When the signals from the two antennas are correlated, the noise shows up as a correlated signal—mimicking a signal from the sky. Steve Padin has used a novel antenna design to minimize this cross talk, and his prototype tests show that the cross talk can be further reduced to an acceptable level if we add a third axis of rotation to the telescope. In addition to rotating about two axes to point in the right direction, the telescope will rotate about its optical axis. This will enable us to discriminate between signals coming from the sky and signals generated within the instrument itself—the former will remain fixed in the heavens as the telescope rotates. This extra rotation, plus very careful design of the antennas themselves, has solved the cross talk problem.

Another problem is caused by radio-frequency emissions from our own galaxy. We are observing the microwave background radiation through a rather dirty window—the radiation from dust and from free electrons within our galaxy is comparable to the signals we wish to observe. Fortunately, the spectrum of this foreground radiation is very different from that of the microwave background radiation. Therefore, by observing at a



The plan for the CBI installation and ground screen is shown at top left. The instrument will be placed in a small crater-shaped hollow lined with reflecting material. In this way none of the 13 radio telescopes on the platform will be able to receive radiation directly from the ground, thus reducing the effects of signals from the ground to an acceptable level. At bottom left is a face-on view of the CBI. A single one-meter telescope is shown as a circle near the lower right. It will be possible to center the 13 individual telescopes on any of the smaller circles; the large variety of configurations will enable scientists to tailor the resolution of the instrument to the observations in hand. The large circle in the center is a bearing supporting the array.

One of the more bizarre theories of galaxy formation involves "cosmic strings," which would produce fluctuations in the microwave background radiation with characteristics different from most other theories. All of them may be wrong.



number of different frequencies, we can subtract out the foreground signals to get a clear image of the microwave background radiation itself. The CBI will therefore observe in 10 frequency bands, each one gigahertz wide, between 26 gigahertz and 36 gigahertz.

A third serious difficulty for any instrument observing the microwave background radiation is the atmosphere. Small fluctuations in the levels of water vapor in the atmosphere add noise to the observations, and contaminate the images. Consequently, it can take months to make an image that could be obtained in a few days in the absence of the atmosphere. To minimize the effects of the atmosphere, a number of high, dry sites are being considered for the CBI: the White Mountains, in California; Mauna Kea, in Hawaii; Antarctica; and sites in the high Andes in Chile and Argentina. The photo on page 30 shows the terrain near one of the prime sites we are considering in Chile.

Finally, thermal radiation from the ground underfoot can easily swamp the microwave background radiation signals. In order to eliminate this radiation, the CBI will have a reflecting ground screen, so that the ground will not be visible from any of the antennas at any time.

This is a competitive field, and in order to be in the lead we need to have the CBI fully operational and making images within two years. Our work thus far has been made possible by generous gifts from Ronald and Maxine Linde and from Caltech, who provided the required matching funds that enabled us to obtain a $2,000,000 grant from the National Science Foundation. We now have half of the CBI's total cost of $6,500,000 in hand, and are actively exploring funding possibilities for the remainder. We hope we succeed, because a scientific opportunity of this magnitude is extremely rare, and it's hard to imagine a more exciting prospect than seeing this critical stage in the birth of the universe. These images should tell us how all structures formed in the universe. They should also tell us whether the dark matter that we know is out there is composed of normal material, or whether it is an exotic substance that has thus far eluded direct detection. Nature is continually surprising us, and the CBI may well reveal unforeseen aspects of the early universe that could revolutionize our understanding of cosmology, and possibly of basic physics itself. □

Tony Readhead, who earned his bachelor's degree from the University of Witwatersrand, South Africa, in 1968 and his PhD from the University of Cambridge, England, in 1972, came to Caltech as a research fellow in 1974. He was named professor of radio astronomy in 1981 and professor of astronomy in 1990. From 1981 to 1986 Readhead served as director of the Owens Valley Radio Observatory and from 1990 to 1992 as executive officer for astronomy. This article was adapted from the Watson Lecture he delivered last February.