DESTINY

Scientists may soon glimpse the universe's beginnings by studying the subtle ripples made by gravitational waves

Echoes from the big bang

BY ROBERT R. CALDWELL AND MARC KAMIONKOWSKI

Cosmologists are still asking the same questions that the first stargazers posed as they surveyed the heavens. Where did the universe come from? What, if anything, preceded it? How did the universe arrive at its present state, and what will be its future? Although theorists have long speculated on the origin of the cosmos, until recently they had no way to probe the universe's earliest moments to test their hypotheses. In recent years, however, researchers have identified a method for observing the universe as it was in the very first fraction of a second after the big bang. This method involves looking for traces of gravitational waves in the cosmic microwave background (CMB), the cooled radiation that has permeated the universe for nearly 15 billion years.

The CMB was emitted about 400,000 years after the big bang, when electrons and protons in the primordial plasma—the hot, dense soup of subatomic particles that filled the early universe—first combined to form hydrogen atoms. Because this radiation provides a snapshot of the universe at that time, it has become the Rosetta stone of cosmology. After the CMB was discovered in 1965, researchers found that its temperature—a measure of the intensity of the black body radiation—was very close to 2.7 kelvins, no matter which direction they looked in the sky. In other words, the CMB appeared to be isotropic, which indicated that the early universe was remarkably uniform. In the early 1990s, though, a satellite called the Cosmic Background Explorer (COBE) detected minuscule variations—only one part in 100,000—in the radiation's temperature. These variations provide evidence of small lumps and bumps in the primordial plasma. The inhomogeneities in the distribution of mass later evolved into the large-scale structures of the cosmos: the galaxies and galaxy clusters that exist today.

In the late 1990s several ground-based and balloon-borne detectors observed the CMB with much finer angular resolution than COBE did, revealing structures in the primordial plasma that subtend less than one degree across the sky. (For comparison, the moon subtends about half a degree.) The size of the primordial structures indicates that the geometry of the universe is flat. The observations are also consistent with the theory of inflation, which postulates that an epoch of phenomenally rapid cosmic expansion took place in the first few moments after the big bang. In June 2001 NASA launched the Microwave Anisotropy Probe (MAP), to extend the precise observations of the CMB to the entire sky [see "A Cosmic Cartographer," on page 74]. Currently gathering data from its deep orbit 1.5 million kilometers beyond the earth, MAP is expected to deliver its first scientific results by early 2003. The European Space Agency's Planck spacecraft, to launch in 2007, will conduct an even more detailed mapping. Cosmologists expect that the observations will unearth a treasure trove of information about the early universe.

In particular, researchers are hoping to find direct evidence of the epoch of inflation. The strongest evidence—the "smoking gun"—would be the observation of inflationary gravitation-

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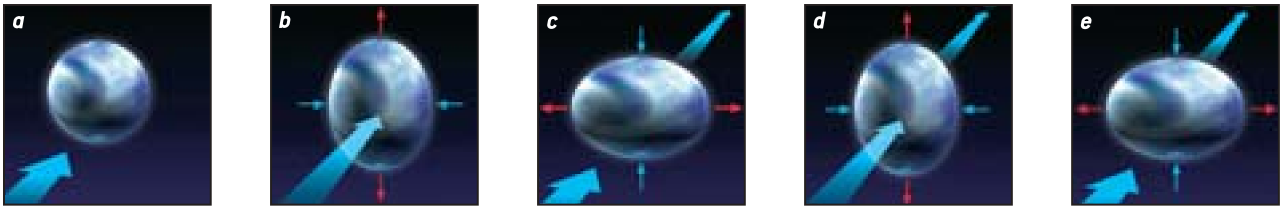
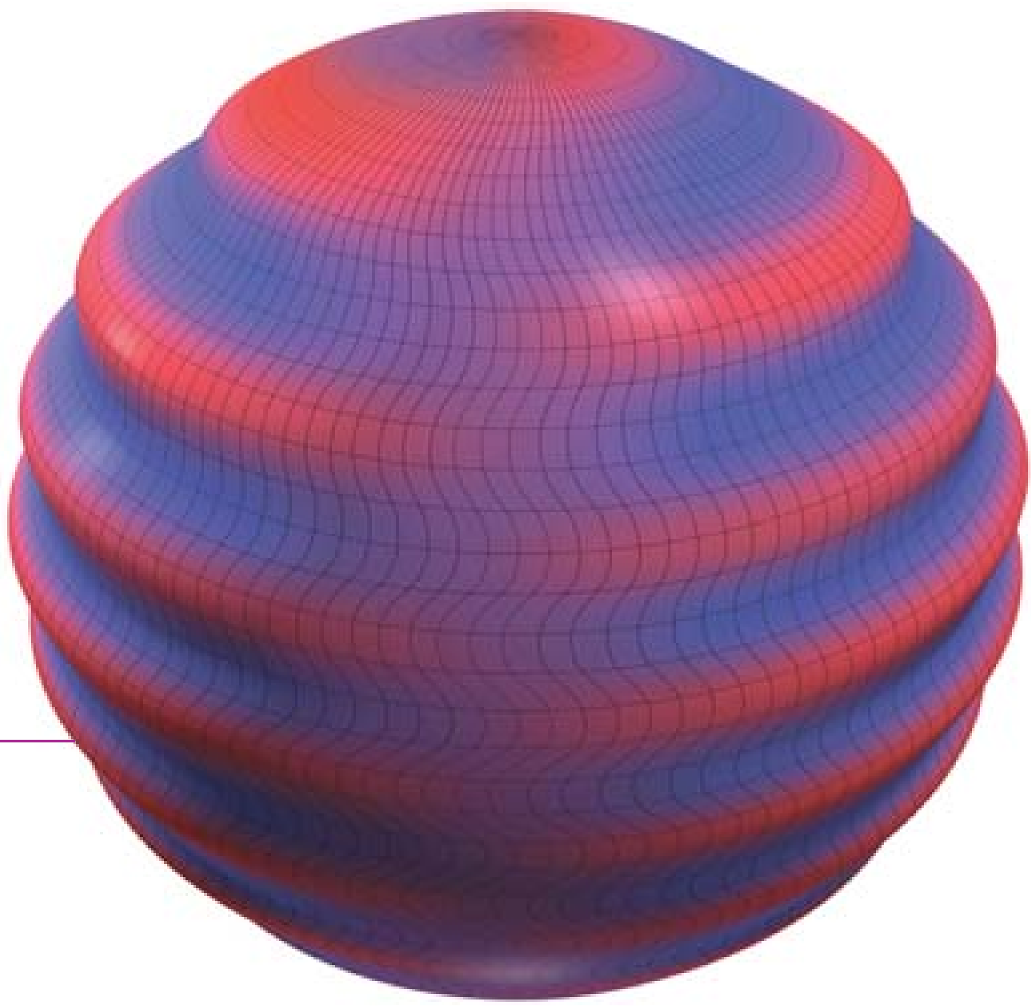


GRAVITATIONAL WAVES

Although gravitational waves have never been directly observed, theory predicts that they can be detected because they stretch and squeeze the space they travel through. On striking a spherical mass (*a*), a wave first stretches the mass in one direction and squeezes it in a perpendicular direction (*b*). Then the effects are reversed (*c*), and the distortions oscillate at the wave's frequency (*d* and *e*). The distortions shown here have been greatly exaggerated; gravitational waves are usually too weak to produce measurable effects.



DISTORTED UNIVERSE

The fantastically rapid expansion of the universe immediately after the big bang should have produced gravitational waves. These waves would have stretched and squeezed the primordial plasma, inducing motions in the spherical surface that emitted the cosmic microwave background, or CMB. These motions, in turn, would have caused redshifts and blueshifts in the radiation's temperature and polarized the CMB. The illustration above shows the effects of a gravitational wave traveling from pole to pole, with a wavelength that is one quarter the radius of the sphere.

ILLUSTRATIONS BY SLIM FILMS

al waves. In 1918 Albert Einstein predicted the existence of gravitational waves as a consequence of his theory of general relativity. They are analogues of electromagnetic waves, such as x-rays, radio waves and visible light, which are moving disturbances of an electromagnetic field. Gravitational waves are moving disturbances of a gravitational field. Like light or radio waves, gravitational waves can carry information and energy from the sources that produce them. Moreover, gravitational waves can travel unimpeded through material that absorbs all forms of electromagnetic radiation. Just as x-rays allow doctors to peer through substances that visible light cannot penetrate, gravitational waves should allow researchers to view astrophysical phenomena that cannot be seen otherwise. Although gravitational waves have never been directly detected, astronomical observations have confirmed that pairs of extremely dense objects such as neutron stars and black holes generate the waves as they spiral toward each other.

The plasma that filled the universe during its first 400,000 years was opaque to electromagnetic radiation, because any emitted photons were immediately scattered in the soup of subatomic particles. Therefore, astronomers cannot observe any electromagnetic signals dating from before the CMB. In contrast, gravitational waves could propagate through the plasma. What is more, the theory of inflation predicts that the explosive expansion of the universe 10^{-38} second after the big bang should have produced gravitational waves. If the theory is correct, these waves would have echoed across the early universe and, 400,000 years later, left subtle ripples in the CMB that can be observed today.

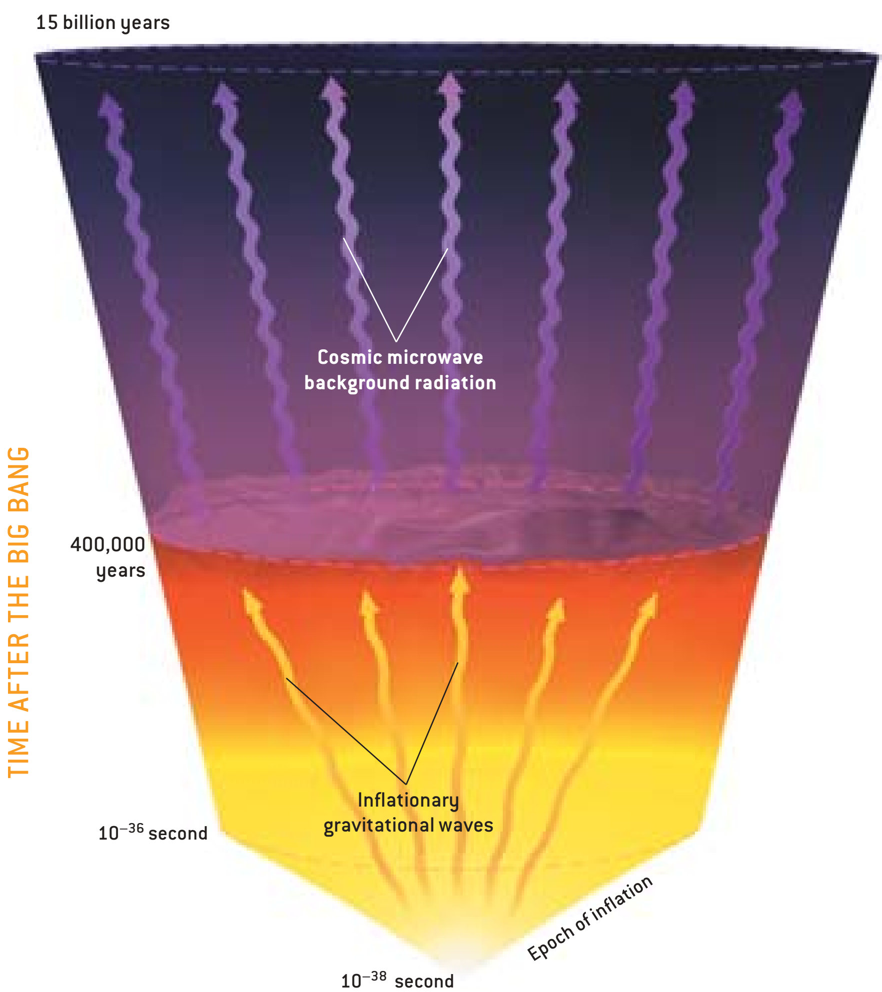
Waves from Inflation

TO UNDERSTAND HOW inflation could have produced gravitational waves, let's examine a fascinating consequence of quantum mechanics: empty space is not so empty. Virtual pairs of particles are spontaneously created and destroyed all the time. The Heisenberg uncertainty principle declares that a pair of particles with energy ΔE may pop into existence for a time Δt before they annihilate each other, provided that $\Delta E \, \Delta t < \hbar/2$, where $\hbar$ is the reduced Planck's constant (1.055×10^{-34} joule-second). You need not worry, though, about virtual apples or bananas popping out of empty space, because the formula applies only to elementary particles and not to complicated arrangements of atoms.

One of the elementary particles affected by this process is the graviton, the quantum particle of gravitational waves (analogous to the photon for electromagnetic waves). Pairs of virtual gravitons are constantly popping in and out of existence. During inflation, however, the virtual gravitons would have been pulled apart much faster than they could have disappeared back into the vacuum. In essence, the virtual particles would have become real particles. Furthermore, the fantastically rapid expansion of the universe would have stretched the graviton wavelengths from microscopic to macroscopic lengths. In this way, inflation would have pumped energy into the production of gravitons, generating a spectrum of gravitational waves that reflected the conditions in the universe in those first moments after the big bang. If inflationary gravitational waves do indeed exist, they would be the oldest relic in the universe, created 400,000 years *before* the CMB was emitted.

■ COSMIC TIME LINE

During the epoch of inflation—the tremendous expansion of the universe that took place in the first moments after the big bang—quantum processes generated a spectrum of gravitational waves. The waves echoed through the primordial plasma, distorting the CMB radiation that was emitted about 400,000 years later. By carefully observing the CMB today, cosmologists may detect the plasma motions induced by the inflationary waves.



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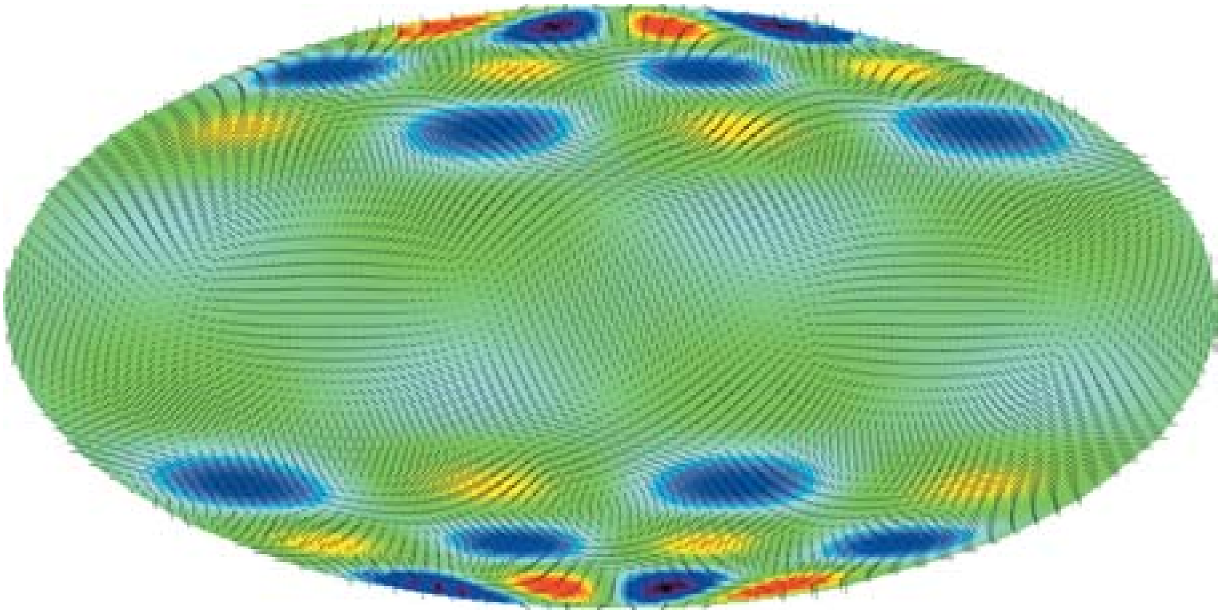

RELIC IN THE RADIATION

Inflationary gravitational waves would have left a distinctive imprint on the CMB. This illustration depicts the simulated temperature variations and polarization patterns that would result from the distortions shown in the bottom illustration on page 77. The red and blue spots represent colder and hotter regions of the CMB, and the small line segments indicate the orientation angle of the polarization in each region of the sky.

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Whereas the microwave radiation in the CMB is largely confined to wavelengths between one and five millimeters (with a peak intensity at two millimeters), the wavelengths of the inflationary gravitational waves would span a much broader range: one centimeter to 10^{23} kilometers, which is the size of the present-day observable universe. The theory of inflation stipulates that the gravitational waves with the longest wavelengths would be the most intense and that their strength would depend on the rate at which the universe expanded during the inflationary epoch. This rate is proportional to the energy scale of inflation, which was determined by the temperature of the universe when inflation began. And because the universe was hotter at earlier times, the strength of the gravitational waves ultimately depends on the time at which inflation started.

Unfortunately, cosmologists cannot pinpoint this time, because they do not know in detail what caused inflation. Some physicists have theorized that inflation started when three of the fundamental interactions—the strong, weak and electromagnetic forces—became dissociated soon after the universe's creation. According to this theory, the three forces were one and the same at the very beginning but became distinct 10^{-38} second after the big bang, and this event somehow triggered the sudden expansion of the cosmos. If the theory is correct, inflation would have had an energy scale of 10^{15} to 10^{16} GeV. (One GeV is the energy a proton would acquire while being accelerated through a voltage drop of one billion volts. The largest particle accelerators currently reach energies of 10^3 GeV.) On the other hand, if inflation were triggered by another physical phenomenon occurring at a later time, the gravitational waves would be weaker.

Once produced during the first fraction of a second after the big bang, the inflationary gravitational waves would propagate forever, so they should still be running across the universe. But how can cosmologists observe them? First consider how an ordinary stereo receiver detects a radio signal. The radio waves consist of oscillating electrical and magnetic fields, which cause the electrons in the receiver's antenna to move back and forth. The motions of these electrons produce an electric current that the receiver records.

Similarly, a gravitational wave can induce an oscillatory stretching and squeezing of the space it travels through. These oscillations would cause small motions in a set of freely floating test masses. In the late 1950s physicist Hermann Bondi of King's College London tried to convince skeptics of the physical reality of such waves by describing a hypothetical gravitational-wave detector. The idealized apparatus was a pair of rings hanging freely on a long, rigid bar. An incoming gravitational wave of amplitude h and frequency f would cause the distance L between the two rings to alternately contract and expand by an amount $h \times L$, with a frequency f. The heat from the friction of the rings rubbing against the bar would provide evidence that the gravitational wave carries energy.

Researchers are currently building sophisticated gravitational-wave detectors, which will use lasers to track the tiny motions of suspended masses [*see box on next page*]. The distance between the test masses determines the band of wave-

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Wave Hunters

New detectors will soon be ready

THE GRAVITATIONAL WAVES produced by quantum processes during the inflationary epoch are by no means the only ones believed to be traveling across the universe. Many astrophysical systems, such as orbiting binary stars, merging neutron stars and colliding black holes, should also emit powerful gravitational waves.

The problem with detecting the waves is that their strength fades as they spread outward while traveling hundreds of millions of light-years to the earth. To measure such minuscule oscillations, researchers are preparing the Laser Interferometer Gravitational-Wave Observatory (LIGO), which consists of facilities in Livingston, La. (*above*), and Hanford, Wash. Results from the facilities will be compared to rule out local effects that mimic gravitational waves, such as seismic activity, acoustic noise and laser instabilities [see "Ripples in Spacetime," on page 88].

Physicists are also building smaller detectors that will work in tandem with LIGO, allowing researchers to triangulate the sources of gravitational waves. Examples of these observatories are TAMA (near Tokyo), Virgo (near Pisa, Italy) and GEO (near Hannover, Germany). And to monitor gravitational waves with longer wavelengths, NASA and the European Space Agency are planning to launch the Laser Interferometer Space Antenna in 2010. Unfortunately, none of these proposed observatories will be sensitive enough to detect the gravitational waves produced by inflation. Only the cosmic microwave background radiation can reveal their presence. *—R.R.C. and M.K.*

lengths that the devices can monitor. The largest of the ground-based detectors, which has a separation of four kilometers between the masses, will be able to measure the oscillations caused by gravitational waves with wavelengths from 30 to 30,000 kilometers; a planned space-based observatory may be able to detect wavelengths about 1,000 times longer. The gravitational waves generated by neutron star mergers and black hole collisions have wavelengths in this range, so they can be detected by the new instruments. But the inflationary gravitational waves in this range are much too weak to produce measurable oscillations in the detectors.

The strongest inflationary gravitational waves are those with the longest wavelengths, comparable to the diameter of the observable universe. To detect these waves, researchers need to observe a set of freely floating test masses separated by similarly large distances. Serendipitously, nature has provided just such an arrangement: the primordial plasma that emitted the CMB radiation. During the 400,000 years between the epoch of inflation and the emission of the CMB, the ultralong-wavelength gravitational waves echoed across the early universe, alternately stretching and squeezing the plasma [*see illustration on page 78*]. Researchers can observe these oscillatory motions today by looking for slight Doppler shifts in the CMB.

If, at the time when the CMB was emitted, a gravitational wave was stretching a region of plasma toward us—that is, toward the part of the universe that would eventually become our galaxy—the radiation from that region will appear bluer to observers because it has shifted to shorter wavelengths (and hence a higher temperature). Conversely, if a gravitational wave was squeezing a region of plasma away from us when the CMB was emitted, the radiation will appear redder because it has shifted to longer wavelengths (and a lower temperature). By surveying the blue and red spots in the CMB—which correspond to hotter and colder radiation temperatures—researchers could conceivably see the pattern of plasma motions induced by the inflationary gravitational waves. The universe itself becomes a gravitational-wave detector.

Particulars of Polarization

THE TASK IS NOT so simple, however. As we noted at the beginning of this article, mass inhomogeneities in the early universe also produced temperature variations in the CMB. (For example, the gravitational field of the denser regions of plasma would have redshifted the photons emitted from those regions, producing some of the temperature differences observed by COBE.) If cosmologists look at the radiation temperature alone, they cannot tell what fraction (if any) of the variations should be attributed to gravitational waves. Even so, scientists at least know that gravitational waves could not have produced any more than the one-in-100,000 temperature differences observed by COBE and the other CMB radiation detectors. This fact puts an interesting constraint on the physical phenomena that gave rise to inflation: the energy scale of inflation must be less than about 10^{16} GeV, and therefore the epoch could not have occurred earlier than 10^{-38} second after the big bang.

But how can cosmologists go further? How can they get around the uncertainty over the origin of the temperature fluctuations? The answer lies with the *polarization* of the CMB. When light strikes a surface in such a way that the light scatters at nearly a right angle from the original beam, it becomes linearly polarized—that is, the waves become oriented in a particular direction. This is the effect that polarized sunglasses exploit: because the sunlight that scatters off the ground is typically polarized in a horizontal direction, the filters in the glasses reduce the

ALEX DESSELLE *Skyview Technologies*

glare by blocking light waves with this orientation. The CMB is polarized as well. Just before the early universe became transparent to radiation, the CMB photons scattered off the electrons in the plasma for the last time. Some of these photons struck the particles at large angles, which polarized the radiation.

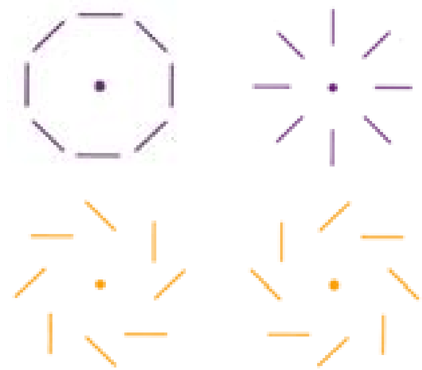
The key to detecting the inflationary gravitational waves is the fact that the plasma motions caused by the waves produced a different pattern of polarization than the mass inhomogeneities did. The idea is relatively simple. The linear polarization of the CMB can be depicted with small line segments that show the orientation angle of the polarization in each region of the sky [*see illustration on page 79*]. These line segments are sometimes arranged in rings or in radial patterns. The segments can also appear in rotating swirls that are either right- or left-handed—that is, they seem to be turning clockwise or counterclockwise [*see illustration at right*].

The "handedness" of these patterns is the clue to their origin. The mass inhomogeneities in the primordial plasma could not have produced such polarization patterns, because the dense and rarefied regions of plasma had no right- or left-handed orientation. In contrast, gravitational waves do have a handedness: they propagate with either a right- or left-handed screw motion. The polarization pattern produced by gravitational waves will look like a random superposition of many rotating swirls of various sizes. Researchers describe these patterns as having a curl, whereas the ringlike and radial patterns produced by mass inhomogeneities have no curl.

Not even the most keen-eyed observer can look at a polarization diagram, such as the one shown on page 79, and tell by eye whether it contains any patterns with curls. But an extension of Fourier analysis—a mathematical technique that can break up an image into a series of waveforms—can be used to divide a polarization pattern into its constituent curl and curl-free patterns. Thus, if cosmologists can measure the CMB polarization and determine what fraction came from curl patterns, they can calculate the amplitude of the ultralong-wavelength inflationary gravitational waves. Because the amplitude of the waves was determined by the energy of inflation, researchers will get a direct measurement of that energy scale. This finding, in turn, will help answer the question of whether inflation was triggered by the unification of fundamental forces.

What are the prospects for detecting the gentle rings and curls and swirls of the polarized CMB sky? That is the next goal of CMB scientists. Although theorists are confident that the relic radiation is polarized, observational verification has eluded researchers. Roughly a dozen experiments worldwide are striving to measure the variation of the polarization pattern, and we can expect exciting results soon. But theorists also predict that the strength of the curl-free polarization component is much stronger than the curl component—the "smoking gun" of the inflationary gravitational waves we have described. So though there is a good chance the MAP satellite or one of the ground- or balloon-based experiments will detect the CMB's curl-free polarization within the next year, the curl component will remain just out of reach.

Subsequent experiments may have a better chance. If inflation was indeed caused by the unification of forces, its gravitational-wave signal may be strong enough to be detected by the Planck satellite, although an even more sensitive next-generation spacecraft might be needed. CMB scientists are already working with NASA to plan such a mission: the Cosmic Microwave Background Polarization Experiment (CMBPOL), which would fly sometime after 2014. If the inflationary theory is true, and there are ultralong-wavelength gravitational waves of primordial origin coursing through the cosmos, then CMBPOL will be able to sense the telltale signs of the squeezing and stretching of the plasma at last scattering. The discovery would extend our understanding of the universe back to the earliest fraction of a second after the big bang. But if inflation was triggered by other physical phenomena occurring at later times and lower energies, the signal from the gravitational waves will be far too weak to be detected in the foreseeable future.



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POLARIZATION PATTERNS

The polarization of the CMB may hold important clues to the history of the early universe. Density variations in the primordial plasma would cause ringlike and radial patterns of polarization (*top*). Gravitational waves, in contrast, would produce right- and left-handed swirls (*bottom*).

Because cosmologists are not certain about the origin of inflation, they cannot definitively predict the strength of the polarization signal produced by inflationary gravitational waves. But if there is even a small chance that the signal is detectable, then it is worth pursuing. Its detection would not only provide incontrovertible evidence of inflation but also give us the extraordinary opportunity to look back at the very earliest times, just 10^{-38} second after the big bang. We could then contemplate addressing one of the most compelling questions of the ages: Where did the universe come from? SA

MORE TO EXPLORE

First Space-Based Gravitational-Wave Detectors. Robert R. Caldwell, Marc Kamionkowski and Leven Wadley in *Physical Review D,* Vol. 59, Issue 2, pages 27101–27300; January 15, 1999.

Recent observations of the cosmic microwave background are described at these Web sites: **pupgg.princeton.edu/~cmb/**; **www.physics.ucsb.edu/~boomerang/**; **cosmology.berkeley.edu/group/cmb/**

Details of the MAP and Planck missions are available at **map.gsfc.nasa.gov/**; **astro.estec.esa.nl/astrogen/planck/mission_top.html**

More information on gravitational-wave detectors is available at **www.ligo.caltech.edu**; **lisa.jpl.nasa.gov**