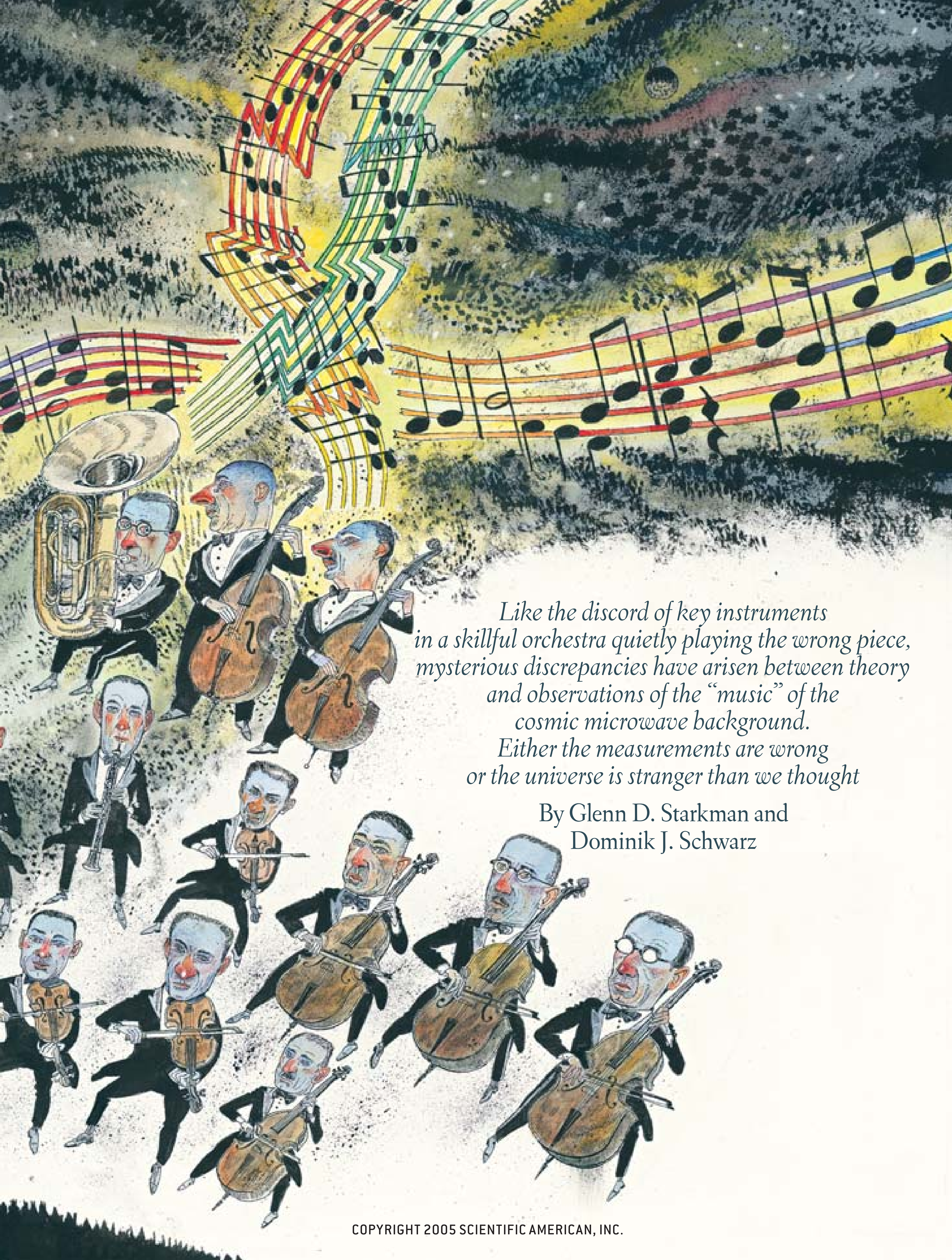
Is the Universe OUT OF TUNE?



Like the discord of key instruments in a skillful orchestra quietly playing the wrong piece, mysterious discrepancies have arisen between theory and observations of the "music" of the cosmic microwave background. Either the measurements are wrong or the universe is stranger than we thought

By Glenn D. Starkman and Dominik J. Schwarz

IMAGINE a fantastically large orchestra

playing expansively for 14 billion years. At first, the strains sound harmonious. But listen more carefully: something is off key. Puzzlingly, the tuba and bass are softly playing a different song.

So it is when scientists "listen" to the music of the cosmos played in the cosmic microwave background (CMB) radiation, our largest-scale window into the conditions of the early universe. Shortly after the big bang, random fluctuations—probably thanks to the actions of quantum mechanics—apparently arose in the energy density of the universe. They ballooned in size and ultimately became the galaxy clusters of today. The fluctuations were a lot like sound waves (ordinary sound waves are oscillations in the density of air), and the "sound" ringing throughout the cosmos 14 billion years ago was imprinted on the CMB. Now we see a map of that sound drawn on the sky in the form of CMB temperature variations.

As with a sound wave, the CMB fluctuations can be analyzed by splitting them into their component harmonics—like a collection of pure tones of different frequencies or, more picturesquely, different instruments in an orchestra. Certain of those harmonics are playing more quietly than they should be. In addition, the harmonics are aligned in strange ways—they are playing the wrong tune. These bum notes mean that the otherwise very successful standard model of cosmology is flawed—or that something is amiss with the data.

Scientists have constructed and corroborated the standard model of cosmology over the past few decades. It accounts for an impressive array of the universe's characteristics. The model explains the abundances of the lightest elements (various isotopes of hydrogen, helium and lithium) and gives an age for the universe (14 billion years) that is consistent with the estimated ages of the oldest known stars. It predicts the existence and the near homogeneity of the CMB and explains how many other properties of the universe came to be just the way they are.

Overview/*Heavenly Discord*

- A theory known as the inflationary lambda cold dark matter model explains many properties of the universe very well. When certain data are analyzed, however, a few key discrepancies arise.
- The puzzling data come from studies of the cosmic microwave background (CMB) radiation. Astronomers divide the CMB's fluctuations into "modes," similar to splitting an orchestra into individual instruments. By that analogy, the bass and tuba are out of step, playing the wrong tune at an unusually low volume.
- The data may be contaminated, such as by gas in the outer reaches of the solar system, but even so, the otherwise highly successful model of inflation is seriously challenged.

Called the inflationary lambda cold dark matter model, its name derives from its three most significant components: the process of inflation, a quantity called the cosmological constant symbolized by the Greek letter lambda, and invisible particles known as cold dark matter.

According to this model, inflation was a period of tremendously accelerated growth that started in the first fraction of a second after the universe began and ended with a burst of radiation. Inflation explains why the universe is so big, so full of stuff and so close to being homogeneous. It also explains why the universe is not precisely homogeneous: because random quantum fluctuations in the energy density were inflated up to the size of galaxy clusters and larger.

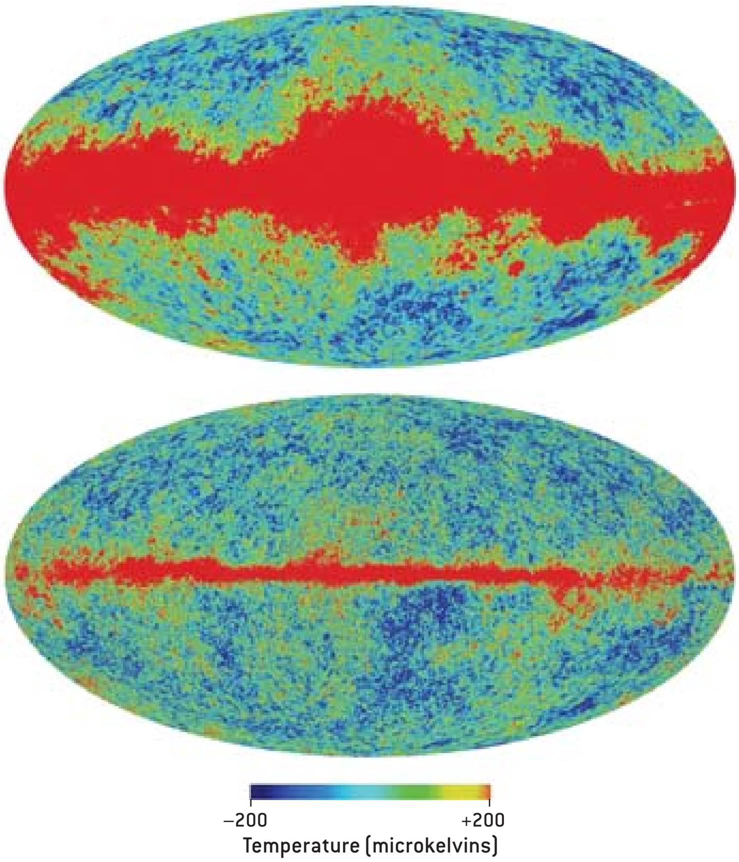
The model predicts that after inflation terminated, gravity caused the regions of extra density to collapse in on themselves, ultimately forming the galaxies and clusters we see today. That process had to have been helped along by cold dark matter, which is made up of huge clouds of particles that are detectable only through their gravitational effects. The cosmological constant (lambda) is a strange form of antigravity responsible for the present speedup of the cosmic expansion [see "A Cosmic Conundrum," by Lawrence M. Krauss and Michael S. Turner; SCIENTIFIC AMERICAN, September 2004].

The Most Ancient Light

DESPITE THE MODEL'S great success at explaining all those features of the universe, problems show up when astronomers measure the CMB's temperature fluctuations. The CMB is cosmologists' most important probe of the largest-scale properties of the universe. It is the most ancient of all light, originating only a few hundred thousand years after the big bang, when the rapidly expanding and cooling universe made the transition from dense opaque plasma to transparent gas. In transit for 14 billion years, the CMB thus reveals a picture of the early universe. Coming from the farthest reaches, that picture is also a snapshot of the universe at its largest size scale.

Arno Penzias and Robert Wilson of Bell Laboratories first detected the CMB and measured its temperature in 1965. More recently, the cutting edge of research has been studies of fluctuations in the temperature as seen when viewing different areas of the sky. (Technically, these fluctuations are called temperature anisotropies.) The differences in temperature across the sky reflect the universe's early density fluctuations. In 1992 the COBE (Cosmic Background Explorer) sat-

JACK UNRUH (*preceding pages*)



MICROWAVE SKY is measured in the K-band (23 gigahertz, *top*), the W-band (94 gigahertz, *bottom*) and three other bands (*not shown*) by the WMAP satellite. The entire sphere of the sky is projected onto the oval shape, like a map of the earth. The horizontal red band is radiation from the Milky Way. Such "foreground" radiation changes with wave band, allowing it to be identified and subtracted from the data, whereas the cosmic microwave background does not.

NASA/WMAP SCIENCE TEAM

ellite first observed those fluctuations; later, the WMAP (Wilkinson Microwave Anisotropy Probe) satellite has made high-resolution maps of them.

Models such as the lambda cold dark matter model cannot calculate the exact pattern of the fluctuations. Yet they can predict their statistical properties, similar to predicting their average size and the range of sizes they span. Some of these statistical features are predicted not only by the lambda cold dark matter model but also by numerous other simple inflationary models that physicists have considered at one time or another as possible alternatives. Because such properties arise in many different inflationary models, they are considered "generic" predictions of inflation; if inflation is true at all, these predictions hold irrespective of the finer details of the model. To falsify one of them would be to challenge the scenario of inflation in the most serious way a scientific theory can be challenged. That is what the anomalous CMB measurements may do.

The predictions are best expressed by first breaking down the temperature fluctuations into a spectrum of modes called spherical harmonics, much as sound can be separated into a spectrum of notes [*see box on page 53*]. As mentioned earlier, we can consider the density fluctuations, before they grow into galaxies, to be sound waves in the universe. If this breakdown into modes seems mysterious, recall the orchestra analogy: each mode is a particular instrument, and the whole map of temperatures across the sphere of the sky is the complete sound produced by the orchestra.

The first of inflation's generic predictions about the fluctuations is "statistical isotropy." That is, the CMB fluctuations neither align with any preexisting preferred directions (for example, the earth's axis) nor themselves collectively define a preferred direction.

Inflation further predicts that the amplitude of each of the modes (the volume at which each instrument is playing, if we think about an orchestra) is random, from among a range of possibilities. In particular, the distribution of probabilities follows the shape of a bell curve, known as a Gaussian. The most likely amplitude, the peak of the curve, is at zero, but in general nonzero values occur, with decreasing probability the more the amplitude deviates from zero. Each mode has its own Gaussian curve, and the width of its Gaussian distribution (the wider the base of the "bell") determines how much power (how much sound) is in that mode.

Inflation tells us that the amplitudes of all the modes should have Gaussian distributions of very nearly the same width. This property comes about because inflation, by stretching the universe exponentially, erases, like a pervasive cosmic iron, all traces of any characteristic scales. The resulting power spectrum is called flat because of its lack of distinguishing features. Significant deviations from flatness should occur only in those modes produced at either the end or the beginning of inflation.

Missing Notes

SPHERICAL HARMONICS represent progressively more complicated ways that a sphere can vibrate in and out. As we look closer at the harmonics, we begin to see where the observations run into troubling conflicts with the model. These modes are convenient to use, because all our information about the distant universe is projected onto a single sphere—the sky. The lowest note (labeled l=0) is the monopole—the entire sphere pulses as one. The monopole of the CMB is its average temperature—just 2.725 degrees above absolute zero [*see box on page 53*].

The next lowest note (labeled l=1) is the dipole, in which the temperature goes up in one hemisphere and down in the other. The dipole is dominated by the Doppler shift of the solar system's motion relative to the CMB; the sky appears slightly hotter in the direction the sun is traveling.

In general, the oscillation for each value of l (0, 1, 2 ...) is called a multipole. Any map drawn on a sphere, whether it be the CMB's temperature or the topography of the earth, can be broken down into multipoles. The lowest multipoles are the largest-area, continent- and ocean-size undulations on our temperature map. Higher multipoles are like successively smaller-area plateaus, mountains and hills (and trenches and valleys) inserted in orderly patterns on top of the larger features. The entire complicated topography is the sum of the individual multipoles.

For the CMB, each multipole l has a total intensity, C_l—roughly speaking, the average heights and depths of the mountains and valleys corresponding to that multipole, or the average volume of that instrument in the orchestra. The collection of intensities for all different values of l is called the angular power spectrum, which cosmologists plot as a graph.

The graph begins at C_2 because the real information about cosmic fluctuations begins with l=2. The illustration on page 54 shows both the measured angular power spectrum from WMAP and the prediction from the inflationary lambda cold dark matter model that most closely matches all the measurements. The measured intensities of the two lowest-l multipoles, C_2 and C_3, the so-called quadrupole and octopole, are considerably lower than the predictions. The COBE team first noticed this deficiency in the low-l power, and WMAP recently confirmed the finding. In terms of topography, the largest continents and oceans are mysteriously low and shallow. In terms of music, we are missing bass and tuba.

The effect is even more dramatic if instead of looking at the total intensities (the C_l's) one looks at the so-called angular correlation function, $C(\theta)$. To understand this function, imagine we look at two points in the sky separated by an angle θ and examine whether they are both hotter (or both colder) than average, or one is hotter and one colder. $C(\theta)$ measures the extent to which the two points are correlated in their temperature fluctuations, averaged over all the points in the sky. Experimentally we find that the $C(\theta)$ for our universe is nearly zero at angles greater than about 60 degrees, which means that the fluctuations in directions separated by more than about 60 degrees are completely uncorrelated. This result is another sign that the low notes of the universe that inflation promised are missing.

The absence of large-angle power is in striking disagreement with most inflationary theories.

This lack of large-angle correlations was first revealed by COBE, and WMAP has now confirmed it. The smallness of $C(\theta)$ at large angles means not only that C_2 and C_3 are small but that the ratio of the values of the first few total intensities—up to at least C_4—are also unusual. The absence of large-angle power is in striking disagreement with *all* generic inflationary models.

This mystery has three potential solutions. First, the unusual results may be just a meaningless statistical fluke. In particular, uncertainties in the data may be larger than have been estimated, which would make the observed results less improbable. Second, the correlations may be an observational artifact—an unexpected physical effect that has not been compensated for in the WMAP team's analysis of its data. Finally, they may indicate a deeper problem with the theory.

Several authors have championed the first option. George Efstathiou of the University of Cambridge was first, in 2003, to raise questions about the statistical methods used to extract the quadrupole strength and its uncertainty, and he claimed that the data implied a much larger uncertainty. Since then, many others have looked at the methods by which the WMAP team extracted the low-l C_l and concluded that uncertainties caused by the emissions of our own Milky Way galaxy are larger than what researchers originally inferred.

Mysterious Alignments

TO ASSESS THESE DOUBTS about the significance of the discrepancy, several groups have looked beyond the information contained in the C_l's, which represent the total intensity of a mode. In addition to C_l, each multipole holds directional information. The dipole, for instance, has the direction of the hottest half of the sky. Higher multipoles have even more directional information. If the intensity discrepancy is indeed just a fluke, then the directional information from the same data would be expected to show the correct generic behavior. That does not happen, however.

The first odd result came in 2003, when Angelica de Oliveira-Costa, Max Tegmark, both then at the University of Pennsylvania, Matias Zaldarriaga of Harvard University and Andrew Hamilton of the University of Colorado at Boulder noticed that the preferred axes of the quadrupole modes, on the one hand, and of the octopole modes, on the other, were remarkably closely aligned. These modes are the same ones that seemed to be deficient in power. The generic inflationary model predicts that each of these modes should be completely independent—one would not expect any alignments.

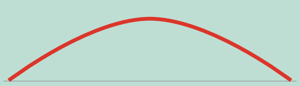
Also in 2003 Hans Kristian Eriksen of the University of Oslo and his co-workers presented more results that hinted at alignments. They divided the sky into all possible pairs of hemispheres and looked at the relative intensity of the fluctuations on the opposite halves of the sky. What they found contradicted the standard inflationary cosmology—the hemispheres often had very different amounts of power. But what was most surprising was that the pair of hemispheres that were the most different were the ones lying above and below the ecliptic, the plane of the earth's orbit around the sun. This result was the first sign that the CMB fluctuations, which were supposed to be cosmological in origin, with some contamination by emission in our own galaxy, have a solar system signal in them—that is, a type of observational artifact.

Detecting Harmonics in the Heavenly Music

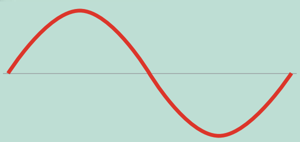
When scientists say that certain instruments in the cosmic microwave background (CMB) seem to be quietly playing off key, what do they mean—and how do they know that?

CMB researchers study fluctuations in temperature measured in all directions in the sky. They analyze the fluctuations in terms of mathematical functions called spherical harmonics. Imagine a violin string. It can sound an infinite number of possible notes, even without a finger pressing it to shorten it. These notes can be labeled n, the number of spots (called nodes) on the string other than its ends that do not move when the note is sounded.

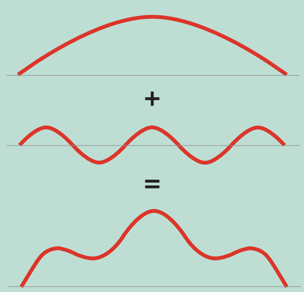
The lowest note, that is, no node ($n=0$), is called the fundamental tone. The entire string, except for the ends, moves back and forth in unison (*below*).



The note with a single node in the middle ($n=1$) is the first harmonic oscillation. In this case, half of the string moves one way while the other half moves the other (*below*). If you sing *do-re-mi-fa-so-la-ti-do,* the final *do* is the first harmonic to the fundamental tone of the first *do*. The note with two equally spaced nodes is the second harmonic, and so on.

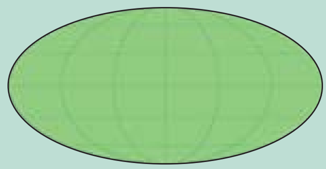


Any complicated way that the string vibrates can be broken down into its component harmonics. For example, we can consider the vibration below as the sum of the fundamental tone ($n=0$) and the fourth harmonic ($n=4$). Note that the fourth harmonic has a lower amplitude (its waves are shallower) in the sum than the fundamental tone. In the orchestra analogy, instrument number four is playing more softly than instrument number zero. In general, the more irregular the vibration of the string, the more harmonics are needed in the sum.

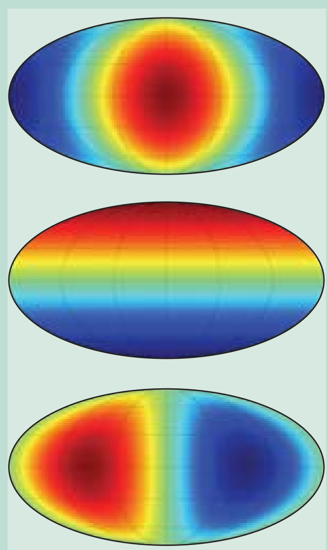


Now let us examine spherical harmonics—denoted Y_{lm}—in which the modes occur around a spherical "drum." Because the surface of the sphere is two-dimensional, we now need two numbers, l and m, to describe the modes. For each value of l (which can be 0, 1, 2, ...), m can be any whole number between $-l$ and l. The combination of all the different notes with the same value of l and different values of m, each with its respective amplitude (or in audio terms, the volume), is called a multipole.

We cannot easily draw the spherical harmonics as we drew the violin string. Instead we present a map of the sphere colored according to whether a given region is at a higher or lower temperature than the average. (The map's shape comes from being stretched flat, just like maps of the earth hung in schoolrooms.) The monopole, or $l=0$, is the entire spherical drum pulsing as one (*below*).

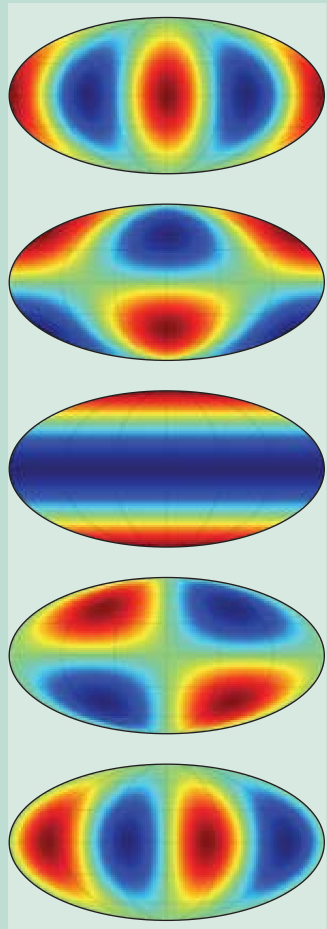


The dipole ($l=1$) has half the drum pulsing outward (*red*) and half pulsing in (*blue*). There are three dipole modes ($m=-1$, 0, 1) in the three perpendicular directions of space (in and out of the page, up and down, and left and right).



The regions of green color are at the average temperature; these nodal lines are the analogues of nodes on the violin string. As l increases, so does the number of nodal lines.

The quadrupole ($l=2$) has five modes, each with a more complicated pattern of oscillations or temperature variations on the sphere (*below*).

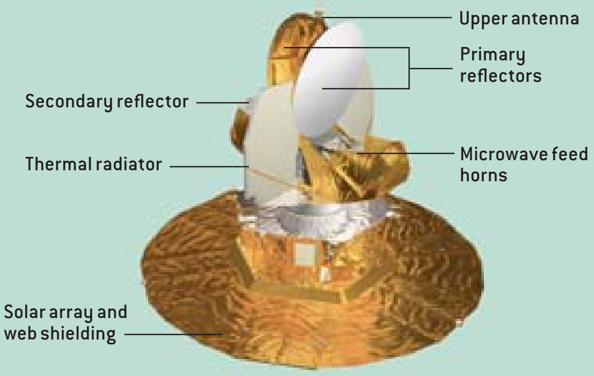


We can break down any pattern of temperature distributions on a spherical surface into a sum of these spherical harmonics, just as any vibration of the violin string can be broken down into a sum of harmonic oscillations. In the sum, each spherical harmonic has a particular amplitude, in essence representing the amount of that harmonic that is present or how loudly that cosmic "instrument of the orchestra" is playing. *—G.D.S. and D.J.S.*

CRAIG COPI *Case Western Reserve University (spherical harmonics images)*; ALISON KENDALL *(strings)*

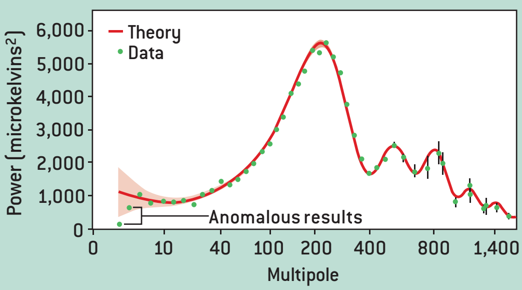
MYSTERIES FROM WMAP

WMAP SATELLITE produces data that are mysterious in three ways.



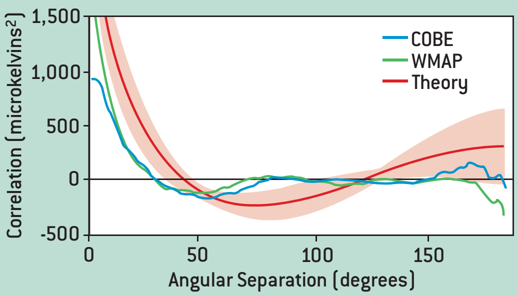
1 ANGULAR POWER SPECTRUM

Most of the WMAP measurements, like those from earlier experiments, are in excellent agreement with values predicted from the inflationary lambda cold dark matter model. But the first two data points (multipoles)—the quadrupole and octopole—are anomalously low in power.



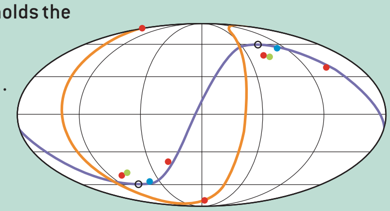
2 ANGULAR CORRELATION FUNCTION

This function relates data from points in the sky separated by a given angle. The data curves from COBE and WMAP should follow the theoretical curve. Instead they are virtually zero beyond about 60 degrees.



3 ALIGNMENT OF THE FIRST TWO MULTIPOLES

The quadrupole (*blue*) and octopole (*red*) should be randomly scattered, but instead they clump close to the equinoxes (*open circles*) and the direction of the solar system's motion (dipole, *green*). They also lie mostly on the ecliptic plane (*purple*). Two are on the supergalactic plane that holds the Milky Way and most of its neighboring galaxies and galactic clusters (*orange*). The probability of these alignments occurring by chance is less than one in 10,000.



Meanwhile one of us (Starkman), together with Craig Copi and Dragan Huterer, then both at Case Western Reserve University, had developed a new way to represent the CMB fluctuations in terms of vectors (a mathematical term for arrows). This alternative allowed us (Schwarz, Starkman, Copi and Huterer) to test the expectation that the fluctuations in the CMB will not single out special directions in the universe. In addition to confirming the results of de Oliveira-Costa and company, we revealed some unexpected correlations in 2004. Several of the vectors lie surprisingly close to the ecliptic plane. Within that plane, they sit unexpectedly close to the equinoxes—the two points on the sky where the projection of the earth's equator onto the sky crosses the ecliptic. These same vectors also happen to be suspiciously close to the direction of the sun's motion through the universe. Another vector lies very near the plane defined by the local supercluster of galaxies, termed the supergalactic plane.

Each of these correlations has less than a one in 300 chance of happening by accident, even using conservative statistical estimates. Although they are not completely independent of one another, their combined chance probability is certainly less than one in 10,000, and that reckoning does not include all the odd properties of the low multipoles.

Some researchers have expressed concern that all these results have been derived from maps of the full CMB sky. Using the full-sky map might seem like an advantage, but in a band around the sky centered on our own galaxy the reported CMB temperatures may be unreliable. To infer the CMB temperature in this galactic band, one must first strip away the contributions of the galaxy. Perhaps the techniques that the WMAP team or other groups have used to remove the galactic thumbprints are not reliable enough. Indeed, the WMAP team cautions other researchers against using its full-sky map; for its own analysis, it uses only those parts of the sky outside the galaxy. When Uros Seljak of Princeton University and Anze Slosar of the University of Ljubljana excluded the galactic band, they found that the statistical significance of some of these alignments declined at some wavelengths. Yet they also found that the correlations increased at other wavelengths. Our own follow-up work suggests that the effects of the galaxy cannot explain the observed correlations. Indeed, it would be very surprising if a misunderstanding of the galaxy caused the CMB to be aligned with the solar system.

The case for these connections between the microwave

THE AUTHORS

GLENN D. STARKMAN and *DOMINIK J. SCHWARZ* first worked together in 2003, when they were at CERN near Geneva. Starkman is Armington Professor at the Center for Education and Research in Cosmology and Astrophysics in the departments of physics and astronomy at Case Western Reserve University. Schwarz has done research on cosmology since he graduated from the Vienna University of Technology in Austria. He recently accepted a faculty position at the University of Bielefeld in Germany. His main scientific interests are the substance of the universe and its early moments.

NASA/WMAP SCIENCE TEAM (*image*); ALISON KENDALL (*graphs*) background and the solar system being real is strengthened when we look more closely at the angular power spectrum. Aside from the lack of power at low *l,* there are three other points—*l*=22, *l*=40 and *l*=210—at which the observed power spectrum differs significantly from the spectrum predicted by the best-fit lambda cold dark matter model. Whereas this set of differences has been widely noticed, what has escaped most cosmologists' attention is that these three deviations are correlated with the ecliptic, too.

Two explanations stand out as the most likely for the correlation between the low-*l* CMB signal and features of the solar system. The first is an error in the construction or understanding of the WMAP instruments or in the analysis of the WMAP data (so-called systematics). Yet the WMAP team has been exceedingly careful and has done numerous cross-checks of its instruments and its analysis procedure. It is difficult to see how spurious correlations could accidentally be introduced. Moreover, we have found similar correlations in the map produced by the COBE satellite, which used different instruments and analysis and so would have had mostly independent systematics.

The results could send us back to the drawing board about the early universe.

A more probable explanation is that an unexpected source or absorber of microwave photons is contaminating the data. This new source should somehow be associated with the solar system. Perhaps it is some unknown cloud of dust on the outskirts of our solar system. But this explanation is itself not without problems: How does one get a solar system source to glow at approximately the wavelength of the CMB brightly enough to be seen by CMB instruments, or to absorb at CMB wavelengths, yet remain sufficiently invisible in all other wavelengths not to have yet been discovered? We hope we will be able eventually to study such a foreground source well enough to decontaminate the CMB data.

Back to the Drawing Board?

AT FIRST GLANCE, the discovery of a solar system contaminant in the CMB data might appear to solve the conundrum of weak large-scale fluctuations. Actually, however, it makes the problem even worse. When we remove the part that comes from the hypothetical foreground, the remaining cosmological contribution is likely to be even smaller than previously believed. (Any other conclusion would require an accidental cancellation between the cosmic contribution and our supposed foreground source.) It would then be harder to claim that the absence of low *l* power is just a statistical accident. It looks like inflation is getting into a major jam.

A statistically robust conclusion that less power than expected exists on large scales could send us back to the drawing board about the early universe. The current alternatives to generic inflation are not terribly attractive: a carefully designed inflationary model could produce a glitch in the power spectrum at just the right scale to give us the observed absence of large-scale power, but this "designer inflation" stretches the limits of what we look for in a compelling scientific theory—an exercise akin to Ptolemy's addition of hypothetical epicycles to the orbits of heavenly bodies so that they would conform to an Earth-centered cosmology.

One possibility is that the universe has an unexpectedly complex cosmic topology [see "Is Space Finite?" by Jean-Pierre Luminet, Glenn D. Starkman and Jeffrey R. Weeks; SCIENTIFIC AMERICAN, April 1999]. If the universe is finite and wrapped around itself in interesting ways, like a doughnut or pretzel, then the vibrational modes it allows will be modified in very distinctive ways. We might be able to hear the shape of the universe, much as one can hear the difference between, say, church bells and wind chimes. For this purpose, the lowest notes—the largest-scale fluctuations—are the ones that would

most clearly echo the shape (and the size) of the universe. The universe could have an interesting topology but have been inflated precisely enough to take that topology just over the horizon, making it not just hard to see but very difficult to test.

Is there hope to resolve these questions? Yes, we expect more data from the WMAP satellite, not only on the temperature fluctuations of the sky but also on the polarization of the received light, which may help reveal foreground sources. In 2007 the European Space Agency will launch the Planck mission, which will measure the CMB at more frequency bands and at higher angular resolution than WMAP did. The higher angular resolution is not expected to help solve the low-*l* puzzle, but observing the sky in many more microwave "colors" will give us much better control over systematics and foregrounds. Cosmological research continues to bring surprises—stay tuned. SA

MORE TO EXPLORE

First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results. C. L. Bennett et al. in *Astrophysical Journal Supplemental,* Vol. 148, page 1; 2003.

The Cosmic Symphony. Wayne Hu and Martin White in *Scientific American,* Vol. 290, No. 2, pages 44–53; February 2004.

The WMAP Web page is at **http://wmap.gsfc.nasa.gov/**