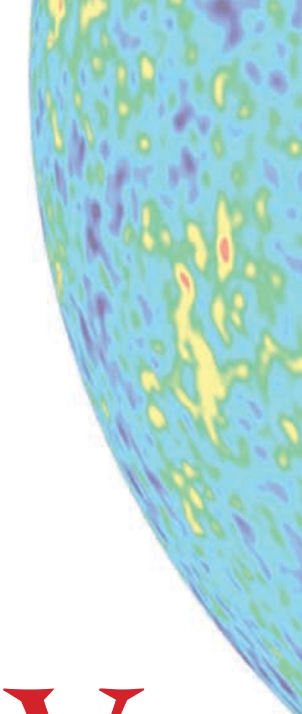


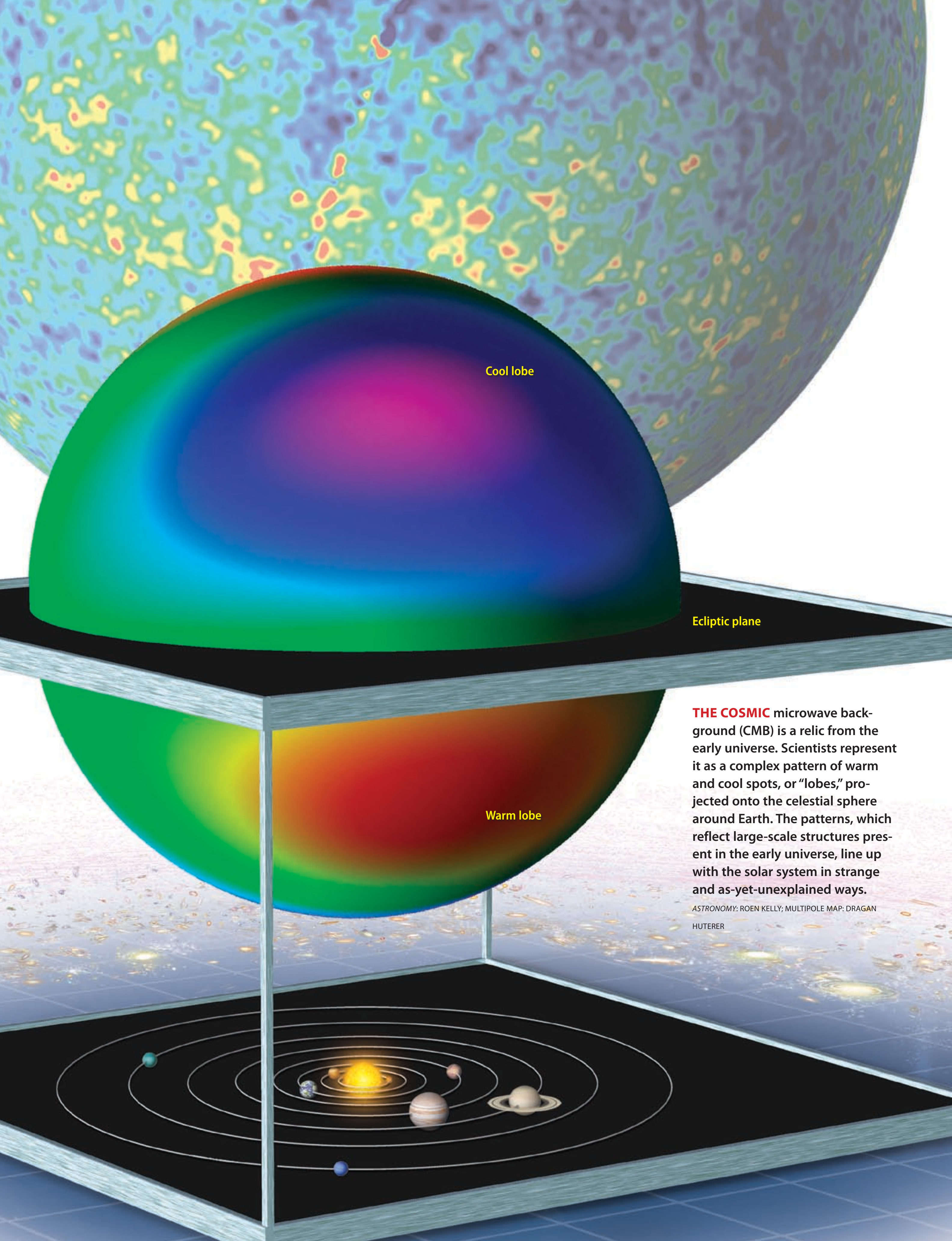
Why is the solar system cosmically aligned?

The solar system seems to line up with the largest cosmic features. Is this mere coincidence or a signpost to deeper insights? /// **BY DRAGAN HUTERER**

Imagine visiting a Museum of Cosmology, where the signature display is a giant case that contains a realistic model of the observable universe. Herein lie all the stars and galaxies we can see from Earth — the parts of the universe from which light has had enough time to reach us in the 13.7 billion years since the Big Bang. The museum curators have done an excellent job, and the model is complete with planets, stars, and galaxies.

As you stand in front of the display and squint, you can barely discern the smallest-scale features: billions of individual stars, many with planets and moons. As you step a good distance away from the display to get a better perspective, you notice the larger structures: star clusters and galaxies, each containing a sea of suns. Stepping back farther, you start to discern a web of filaments in the vastness, and notice that clusters of galaxies lie at the intersections of the largest filaments. At this distance from the display, you can see patterns that extend 45 billion light-years, all the way out to the edge of the observable universe.

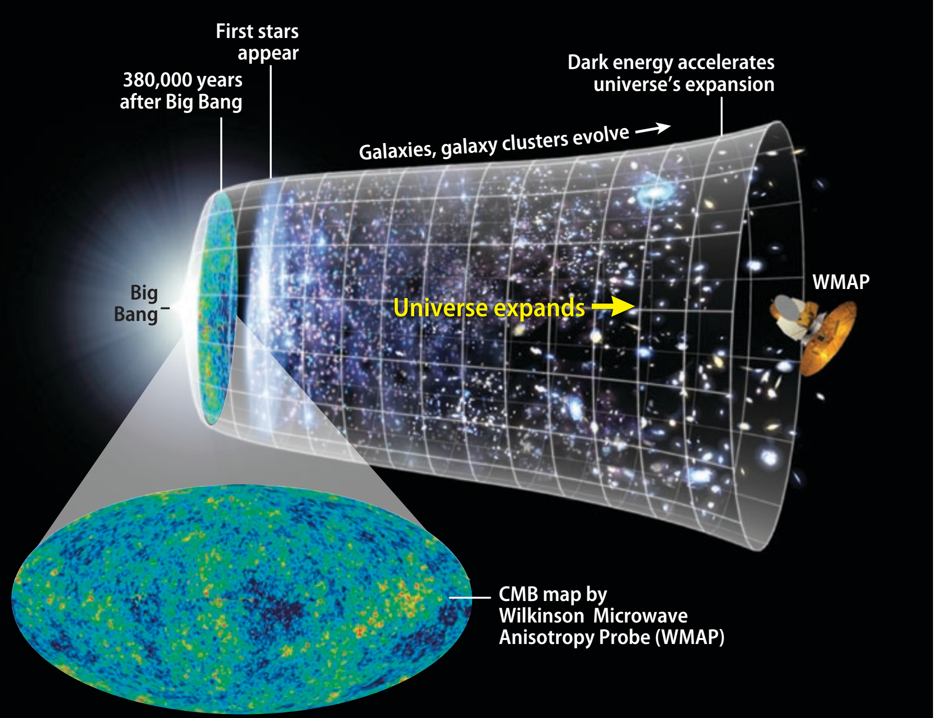
Intrigued by this zoo of structures on different scales, you walk over to the opposite end of the huge Main Hall to get a sense of the big picture. And you are



THE COSMIC microwave background (CMB) is a relic from the early universe. Scientists represent it as a complex pattern of warm and cool spots, or "lobes," projected onto the celestial sphere around Earth. The patterns, which reflect large-scale structures present in the early universe, line up with the solar system in strange and as-yet-unexplained ways.

ASTRONOMY: ROEN KELLY; MULTIPOLE MAP: DRAGAN HUTERER

The CMB in cosmic history



IN THE FIRST moments after the Big Bang, the universe underwent a period of rapid expansion. About 380,000 years later, the universe expanded enough to become transparent to radiation. From that time forward, particles of light (photons) traveled freely throughout the cosmos. The cosmic microwave background (CMB) is a record of the universe's state at that moment. As the universe expanded, stars and galaxies evolved. Later, large-scale structures such as galaxy clusters emerged. The Wilkinson Microwave Anisotropy Probe (WMAP) mapped the cosmic microwave background. NASA/WMAP SCIENCE TEAM

shocked to see vast patterns within all those stars and galaxies that seem to line up with the direction of the Sun's motion through the universe. Even stranger, some aspects of the cosmic geometry seem more flattened than spherical, and line up nearly perpendicular to the plane along which the planets race around the Sun.

In reality, you would need a very special kind of vision to see the alignments cosmologists have begun to find in the geometry of the universe. Seeing them requires sophisticated mathematical analysis that enables us to explore the finest details of how the universe is put together.

Careful analyses have confirmed these alignments exist. But we don't know whether they are bizarre coincidences or if something more fundamental is at work.

The origins of the universe's structure lie in the first moments after the Big Bang. But how could the early universe possibly have "known" about the solar system's geometry when it developed 4.5 billion years ago? Could such a bizarre alignment have arisen in the early universe, or is the answer in the solar system itself — some as-yet-unknown factor that skews our observations?

The quest for an answer has whetted the appetites of cosmologists to understand the structure of the universe on its largest scales. Moreover, solving the mystery of cosmic alignments may ultimately require us to revise some bedrock assumptions of modern cosmology and what happened in the first moments after the Big Bang.

A look in the microwave

With modern telescopes and sensitive instruments, we can observe distant galaxies and clusters of galaxies, and accurately map their distribution. Unfortunately, it's not possible to "zoom out" from our present moment in time and space to observe the entire universe. Moreover, even with a perfect telescope and nothing blocking our view, we could only see galaxies that are no farther than 45 billion light-years from us. Light from the more distant objects simply has not had time to reach us yet.

To map the universe's structure we would need something like a fossil record preserving information about conditions in the early universe, when the seeds were planted that grew into structures we observe 13.7 billion years later.

Fortunately, we have such a fossil. It's called the cosmic microwave background (CMB). Arno Penzias and Robert Wilson of Bell Laboratories discovered it in 1965.

In the early universe, photons (particles of light with zero mass) and protons and electrons (particles found in atoms) swarmed in a dense mass, like a vast number of bees trapped in a box. Around 380,000 years after the Big Bang, however, an important transition occurred: The expanding universe became transparent to radiation, and the photons were free to travel. Today we observe the CMB as a fog of microwave photons coming at us from all directions, filling the entire universe.

Cosmic snapshot

The CMB is a snapshot of the early universe. After the Big Bang, gravity drew the densest regions together. These concentrations of matter evolved over eons of time into galaxies, galaxy clusters, and all the other cosmic structures we observe today.

The less-dense, rarefied regions evolved into vast expanses of cosmic emptiness, filling the space between galaxies. You can see the results of gravitational collapse in the night sky as a seemingly random pattern of stars and galaxies.

The CMB's temperature is nearly uniform across the sky, measuring just 2.73 Kelvin, or 2.73° Celsius above absolute zero. But the CMB is not completely uniform; it contains many small patches where the background temperature is warmer or cooler, varying slightly above and below 2.73 K. These variations in the sea of radiation are small, about one part in 100,000, or equivalent to the roughness of dust on a billiard ball's surface.

The CMB's rough spots, called anisotropies, reflect inhomogeneity in the early universe — ripples, if you will, on the surface of the vast photon sea that existed after the Big Bang. Unlike stars, anisotropies in the CMB are extremely faint, invisible to the naked eye and even to most telescopes.

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In 1992, the Cosmic Background Explorer (COBE) satellite famously mapped the anisotropies for the first time. Seeing COBE's map of the CMB, cosmologist Stephen Hawking proclaimed it "the discovery of the millennium, if not all time," precisely because COBE had detected the seeds of all cosmic structure today.

Later, scientists mapped out the CMB at much higher resolution with another space telescope, the Wilkinson Microwave Anisotropy Probe (WMAP). Its remarkable findings — first published in 2003 and still continually refined as WMAP continues its observations — have revolutionized our understanding of the universe.

Within each square degree of sky, WMAP revealed many finer variations in the CMB's temperature. It was like switching from a handheld magnifying glass to a microscope. Cosmologists use WMAP data to measure the distribution of anisotropies and compare it to what current theories predict. WMAP's observations also enable astronomers to more accurately measure the abundance of dark matter, the stuff in and around galaxies that we can't see with conventional telescopes but still has gravity.

Finally, with WMAP we can also study dark energy, the mysterious component causing the universe to expand at an ever-faster rate.

CALTECH

UPON SEEING anisotropies in the cosmic microwave background revealed by COBE, cosmologist Stephen Hawking proclaimed it "the discovery of the millennium, if not all time."

The cosmic orchestra

Just looking at the WMAP picture of the universe reveals only so much information. More valuable insights await discovery in the underlying patterns of warm and cool spots in the microwave map. Mathematics allows us to break down the speckles into more fundamental patterns and probe the underlying processes that produced the CMB's complexity. We do this by describing the pattern of warm and cool spots in terms of mathematical functions called multipoles.

To understand the multipoles, think of the microwave background as a cosmic orchestra with a large number of instruments, each playing a simple musical part. The simultaneous performance of all these individual parts adds up to a symphony. But what if you wanted to focus on a particular portion of the whole, like the string section, or even a single violin?

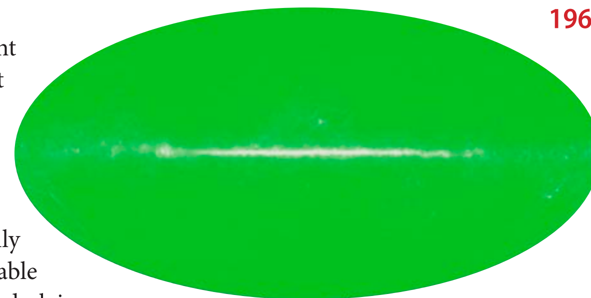
For analyzing music, you would perform a Fourier analysis. When a violinist bows a string to make a high C note, the sound actually contains many individual subcomponents called harmonics. Each harmonic is a pure, wavering tone — like that of a tuning fork. Hypothetically, you could use a computer to synthesize a large number of harmonics, add them back together, and reproduce a sound similar to that of the bowed violin string.

You could also perform a Fourier analysis of the whole orchestra. It, too, can be represented as a sum of a large number of pure harmonics. A computer synthesizer could easily reproduce a symphony or an opera as a complicated sum of many

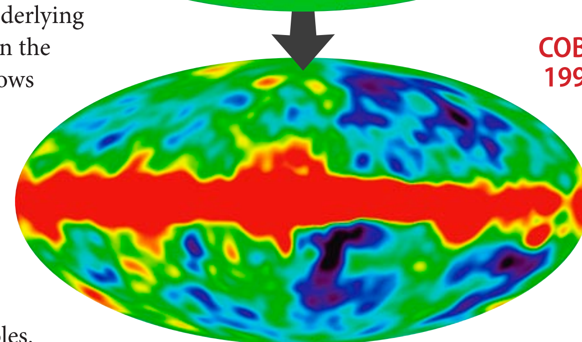
Mapping the CMB: our evolving view

The CMB mapped onto the celestial sphere.

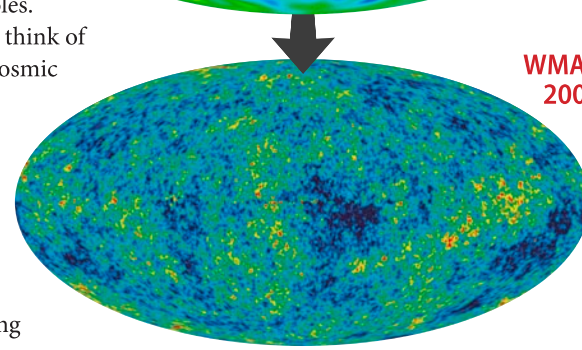
Penzias & Wilson 1965



COBE 1992

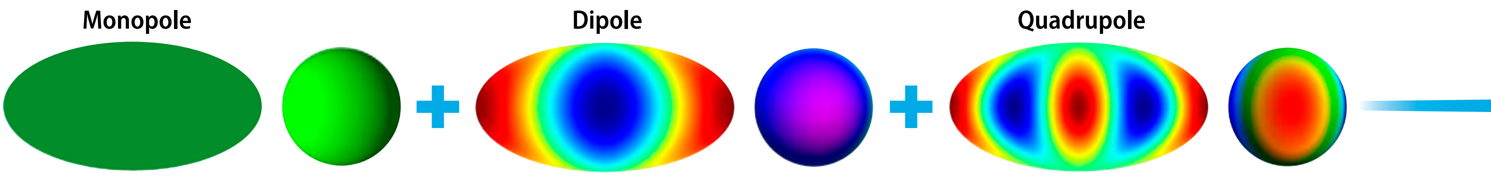


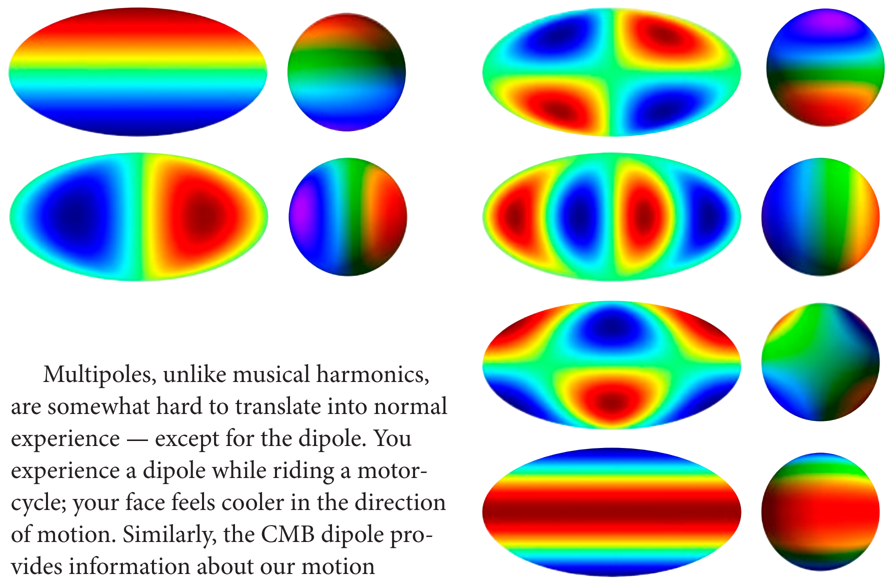
WMAP 2003



WE OBSERVE the CMB on the sky, so it can be mapped onto a sphere. But to make the entire CMB visible on the page, scientists map it onto an oval. Upon its discovery in 1965 by Arno Penzias and Robert Wilson, the CMB's temperature appeared largely uniform. With the launch of the COBE satellite, followed by WMAP, a far more detailed picture of the CMB has emerged. *ASTRONOMY*: ROEN KELLY; CMB MAPS: NASA/WMAP SCIENCE TEAM

From multipoles to WMAP





TO PROBE WMAP's temperature variations, scientists decompose them into sets of simpler patterns called multipoles. Combining all the multipoles reproduces the original speckle pattern of warm and cool regions in the microwave background radiation. Only three multipoles are shown here, but it takes hundreds to reproduce WMAP's complexities. *ASTRONOMY*: ROEN KELLY; MULTIPOLE MAPS: DRAGAN HUTERER

individual, pure harmonics. Scientists use a similar approach to study the CMB.

Magnificent multipoles

Using mathematical objects called spherical harmonics, we can decompose WMAP's complex speckle pattern into an infinite series of warm and cool regions, or lobes, arranged in increasingly complex patterns on a sphere. These basic patterns are called multipoles. They have taught us a lot.

The simplest multipole in the CMB is called the monopole. It corresponds to the CMB's average temperature, 2.73 K.

The next-highest multipole is the dipole. It tells us the overall direction in which the CMB is cooler or warmer, and by how much. The dipole is described by three different modes. In each mode, the CMB temperature is warmer in one hemisphere and cooler in the opposite hemisphere.

Next comes the quadrupole (5 modes) and the octopole (7 modes). Each higher multipole has modes with more complex combinations of warm and cool lobes. Each multipole is associated with a number specifying its overall contribution to the whole.

In principle, an infinite number of multipoles are needed to describe a temperature map. However, because all maps based on actual observations and measurements have a finite resolution, a limited number of multipoles can fully describe a map.

For example, COBE's map of the CMB has an angular resolution of 7° and requires about 20 multipoles to describe it. In contrast, WMAP's observations have a resolution of about ¼ of a degree and require several hundred multipoles to create a full description of its complexities.

Multipoles, unlike musical harmonics, are somewhat hard to translate into normal experience — except for the dipole. You experience a dipole while riding a motorcycle; your face feels cooler in the direction of motion. Similarly, the CMB dipole provides information about our motion through space: Much like the motorcyclist, the orientation of the warm and cool lobes of the dipole tells us the solar system's direction of motion through the CMB.

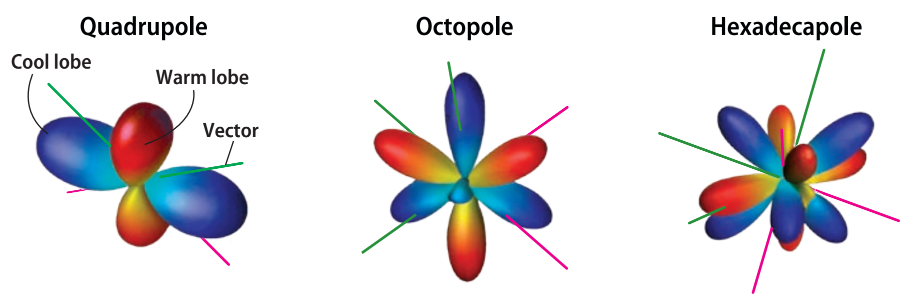
The orientation of the multipoles is important, because they describe a pattern of temperature variations on the observable universe all around us. So imagine yourself looking out on the sky; you are surrounded by a spherical surface painted with the cosmic microwave background as measured by COBE and WMAP. The pattern can be recreated by combining the hot-and-cool patterns on a series of multipoles arranged the right way in relation to each other.

Strange alignments

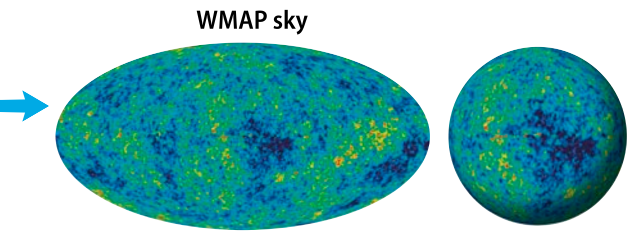
Soon after WMAP returned its first data, researchers began to see odd features of the CMB multipoles. For example, Max Tegmark and Angelica de Oliveira-Costa of the Massachusetts Institute of Technology and Andrew Hamilton from the University of Colorado looked at individual multipoles of CMB anisotropies at large scales.

Tegmark and de Oliveira-Costa found the warm and cool lobes of the octopole lie in a single plane. Furthermore, the quadrupole lies nearly in the same plane. This

What are multipole vectors?



THE TEARDROP-SHAPED lobes in these figures, called multipole vectors, represent large-scale patterns in the CMB temperature. The vectors (little "sticks" sprouting between the lobes) encode information about how the warm and cool lobes are oriented in space and to each other. Studies employing multipole vectors have revealed the various ways our solar system is parallel or perpendicular to large-scale temperature patterns in the CMB and, therefore, to the biggest structures in the universe. DRAGAN HUTERER/CRAIG COPI



could happen by chance only about 0.1 percent of the time.

Around the same time, I and two other physicists at Case Western Reserve University, Craig Copi and Glenn D. Starkman, developed a novel method to represent CMB temperature anisotropies. Our new method reduced the warm and cool lobes in the multipoles to a set of "sticks" with directions encoding the lobes' physical orientation in space.

Multipole vectors naturally define directions and planes, making it easier to identify alignments. Developing the multipole vectors allowed us to examine how the CMB's large-scale features align with each other and the ecliptic — the plane of Earth's orbit around the Sun. We also looked for alignments with large-scale structures such as the Local Group of nearby galaxies and the Milky Way itself.

Ecliptic oddities

Armed with multipole vectors, and joined by Dominik J. Schwarz of the European Organization for Nuclear Research (CERN), we have discovered unexpected patterns in the CMB. Not only are the quadrupole and octopole planar, but their planes are nearly perpendicular to the ecliptic. Moreover, we found that the ecliptic plane lies precisely between the warmest and coolest lobes of the combined quadrupole plus octopole map.

The likelihood of these alignments happening by chance is less than 0.1 percent. Finally, the quadrupole and octopole planes are also perpendicular with the CMB dipole, which points to the direction of motion of the solar system. Why CMB patterns are oriented to the solar system is not at all understood at this time.

Other researchers found similarly unlikely alignments. For example, Kate Land and João Magueijo of Imperial College in London found that temperature anisotropies in multipoles 4 through 7 also align with a particular axis close to the CMB dipole, and to the Sun's motion through space. They have humorously dubbed this odd alignment — apparently the same one we found — the "axis of evil."

The elusive explanation

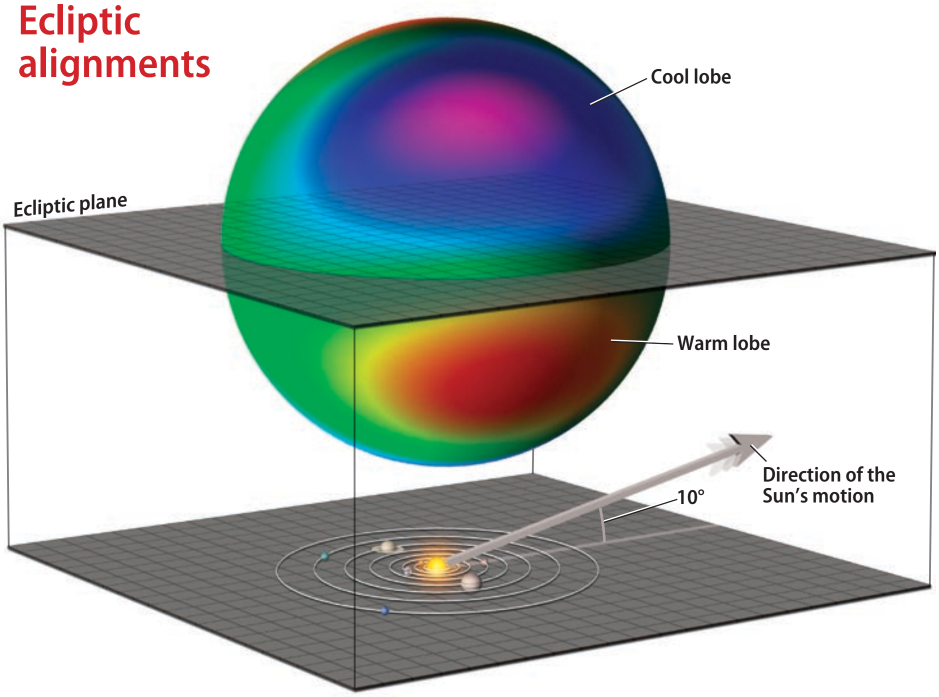
Many cosmologists find the various CMB alignments extremely unlikely to have occurred by chance. Moreover, nearly all the alignments point to the solar system's motion or the orientation of the ecliptic plane. Is there a deeper explanation?

Researchers have considered a variety of possibilities. One might be some kind of imperfection in WMAP's detector that introduces the patterns, but there's no evidence for this. It is also possible that some as-yet-undiscovered signal — a huge cloud of dust in the solar system, for example — is masquerading as a cosmological CMB. Another speculation is that a preferred direction of the CMB arose early in the universe and has persisted. In each case, the explanation either introduces more coincidences than it solves, or else is simply not consistent with our knowledge of the solar system or the universe's structure.

The search for explanations is ongoing. We also eagerly expect new data, such as additional temperature maps from WMAP. In a few years, we will also have data from the European Space Agency's Planck satellite. Like WMAP, Planck is a space telescope that scans the whole sky. But Planck's observational technique is different from that of WMAP and it will, therefore, provide a crucial complement and cross-check to WMAP's measurements. Finally, planned wide-field telescope surveys at optical wavelengths — covering large chunks of the sky and looking at nearby galaxies and others billions of light-years away — might be able to shed light on the distribution of the largest structures.

In the meantime, we can appreciate WMAP's gift to cosmology. It has provided exciting data to test theories of the universe's origin and evolution and posed new conundrums that will only deepen our appreciation for the cosmic symphony that plays in the sky.

Ecliptic alignments



ODD ALIGNMENTS hide within the multipoles of the cosmic microwave background. In this combination of the quadrupole and octopole, a plane bisects the sphere between the largest warm and cool lobes. The ecliptic — the plane of Earth's orbit projected onto the celestial sphere — is aligned parallel to the plane between the lobes. In addition, the Sun's direction of motion through the universe is only 10° from lying in the same plane.

ASTRONOMY: ROEN KELLY; MULTIPOLE MAP: DRAGAN HUTERER

WEB EXTRA See a video about WMAP and the cosmic microwave background at www.Astronomy.com/toc.