The Wilkinson Microwave Anisotropy Probe
Charting the New Cosmology

BIG BANG AND WMAP PRIMER

Part I: The Origin and Evolution of Big Bang Theory
Part II: How Microwave Light Speaks of the Nature of the Universe

Part I: How old is the Universe? When did the stars first turn on? What is the shape of the Universe? How fast is the Universe stretching? What kinds of matter and energy exist, and how common or unusual are they? NASA's Wilkinson Microwave Anisotropy Probe (WMAP) has provided the most precise answers yet to these profound and perplexing questions through an all-sky survey of the oldest light in the Universe. The satellite's measurements lend further support for the Big Bang theory.

In ancient times, people might not have thought of the Universe as having an evolution spanning billions of years. Some viewed the Universe as eternal, others as very young. The stars shine coldly from the heavens, their positions seemingly fixed and eternal. The night sky appears permanent, and the few changes observable with the unaided eye usually repeat, such as the phases of the Moon and the slow drift of the constellations. Besides the motion of a few "wandering stars," later determined to be the planets, not much happens. The occasional burst from an exploding star or visit from a comet was a terrifying and portentous event.

In the twentieth century, scientific instruments told a different story. Using the 100-inch telescope at Mt. Wilson Observatory in Pasadena, California, in 1929, Edwin Hubble saw that galaxies — immense congregations of stars held together by their mutual gravity — were rushing away from us. Hubble's work built upon observations in the preceding decade of redshifted light, by Vesto Slipher, and of the period-luminosity scale, by Henrietta Leavitt. In general, the farther away the galaxy, the faster it was receding. Scientists called the recession velocity the Hubble constant, and its discovery set the stage for the Big Bang theory.

With the existence of billions of galaxies, it seems unlikely that our own, the Milky Way galaxy, somehow occupies a unique place in the Universe at the center of some cosmic "galaxy explosion." Scientists realized a more likely explanation was that space itself is expanding, and carrying all galaxies farther apart as it stretches. If this is so, an observer in any galaxy would see all others moving away. Furthermore, since remote galaxies have more space between them than nearby ones, they would appear to us to recede faster as the Universe expands.

Imagine galaxies as white dots painted on an infinite sheet of dark elastic. Stretching the elastic increases the distances between the white dots, and any dot would "see" other dots rushing away. Thus, receding galaxies are evidence for the Big Bang theory, a cosmology that simply states that the Universe is stretching and, as a result, is cooling down.

The simple theory leads to some startling conclusions. First, if space is stretching and if you could "run the movie backwards," there must have been less space between galaxies in the past. At some point in time, the distances between all points in space must have been infinitesimally small, perhaps zero. Scientists mark the "age of the universe" from this point. We can now follow time back until we reach a point where our physics theories no longer apply.

Second, an expanding Universe must cool down. There is a certain amount of heat in the universe. As the universe stretches, the fixed amount of heat gets spread out and hence the temperature drops. Again, working backwards, this meant that the Universe must have been warmer in the past. In fact, if the distances shrank to almost zero, it would have been ferociously hot — too hot, at the very beginning, for even protons and electrons to exist. It was only after this furnace expanded and cooled that the first elements formed, namely hydrogen, helium, and lithium, from primordial subatomic particles. (All heavier elements were later created from these light elements by nuclear fusion inside stars and subsequent star explosions.) Observations of the amounts of light elements in the cosmos agree with the theoretical calculations, giving astronomers more confidence that they are on the right track with Big Bang cosmology.

If the Universe was indeed more densely packed, another consequence of its extreme heat would have been intense radiation. This light would have originally been high-energy gamma rays, the most energetic form of light. But like the Universe itself, the gamma rays would have "cooled" to less-energetic forms as the Universe expanded. Calculations predicted that the first light from the Big Bang should now be in the microwave energy range. This light is called the Cosmic Microwave Background (CMB), first observed inadvertently in 1964 by Arno Penzias and Robert Wilson at the Bell Telephone Laboratories in Murray Hill, New Jersey. (Penzias and Wilson won the 1978 Nobel Prize in Physics for this discovery; they shared half the Prize with Pyotr Leonidovich Kapitsa, a Russian scientist who was an expert in low-temperature physics.)

Calculations also predicted that the CMB should now be just a few degrees above absolute zero, and that its temperature range should follow a certain distribution around that frigid temperature, called a blackbody spectrum. In 1992, NASA's Cosmic Background Explorer (COBE) satellite found that the CMB's temperature was uniform, approximately 2.725 degrees above absolute zero — another major success for the Big Bang theory.

The CMB fills the Universe and can be detected everywhere we point a microwave telescope. In fact, if we could see microwaves with our eyes, the entire sky would glow with a brightness that is astonishingly uniform in every direction. The temperature is uniform to better than one part in a thousand! This uniformity is one compelling reason to interpret the light as remnant heat from the Big Bang; it would be very difficult to imagine localized sources of radiation this uniform and with the precision blackbody spectrum. Many scientists have tried to devise alternative explanations for the source of the CMB, but none have succeeded.

Thus, Big Bang cosmology continues to ring true with evidence from (1) the recession of galaxies, (2) the nucleosynthesis of light elements, (3) the uniform temperature of the cosmic microwave background, and (4) the blackbody spectrum, as well as from other measurements.

Part II: How do scientists deduce the nature of the Universe by studying the CMB? The CMB is a relic of the newborn Universe, encoded with the conditions of its origin, composition, and fate. No other light carries this amount of information.

Scrutinizing the CMB is crucial for our understanding of the origin and evolution of the Universe, because the Big Bang theory doesn't answer all cosmological questions. The Big Bang theory does not predict how much or what types of matter and energy exist in the Universe, nor how it evolved into the structures (like stars and galaxies) we see today. It does not predict a unique shape for the Universe, or claim that it is infinite in extent or instead somehow bounded. It doesn't even address how or why the Big Bang happened in the first place. The Big Bang is just a basic framework. Information encoded in the CMB allows scientists to build upon the Big Bang.

There are many competing models to explain these additional questions. Each model makes specific predictions about the properties of the CMB. The WMAP mission studies the CMB over the entire sky with unprecedented accuracy, precision, and reliability. The WMAP team compares the unique "fingerprint" of patterns imprinted on the CMB with fingerprints predicted by various models. These fingerprints are temperature fluctuations seen in the light today.

Imagine the impact of matter and energy on space after the Big Bang as a handful of rocks thrown into a pond. The rocks will make ripples in the pond. The shape of those ripples is determined by the strength and number of the rocks and the murkiness of the pond. Likewise, the CMB ripples reflect of the contents and properties of space itself.

The CMB is a fossilized record of the impact of the early Universe's expanding contents on fourth-dimensional spacetime, frozen at the moment light finally broke free. The CMB light was emitted 380,000 years after the Big Bang, long before stars or galaxies ever existed. Prior to this, the Universe was a dense fog of light particles, electrons, protons, and a stew of subatomic particles. Light could not shine though, constantly bouncing off of electrons — just like on a cloudy day on Earth, where light bounces off "cloud" particles in the cloud and cannot break through.

As the Universe cooled, protons could latch on to electrons (called recombination) and light particles broke free (called decoupling). This light is the CMB. Temperature fluctuations seen today in the CMB reflect density fluctuations moments after the Big Bang. Areas of slightly enhanced density had stronger gravity than low-density areas. The gravity from high-density areas “pulled back” on the background radiation, making it appear slightly cooler in those directions. The slight difference in density led to our current structure of galaxies, galaxy clusters, and voids of seemingly empty space.

Various cosmological models describing the shape of the Universe or its mass and energy content make specific predictions about the extent of temperature fluctuations from region to region. WMAP captures the reality, and the WMAP team searches for theoretical matches to this reality. Similarly, the temperature patters offers information about the Universe’s age, the era of first starlight, and other parameters. Again, WMAP detects the reality, allowing the team to find a theoretical match. The team compares fingerprints of suspects (the theories) with the fingerprint left at the event (the CMB), just like a detective.

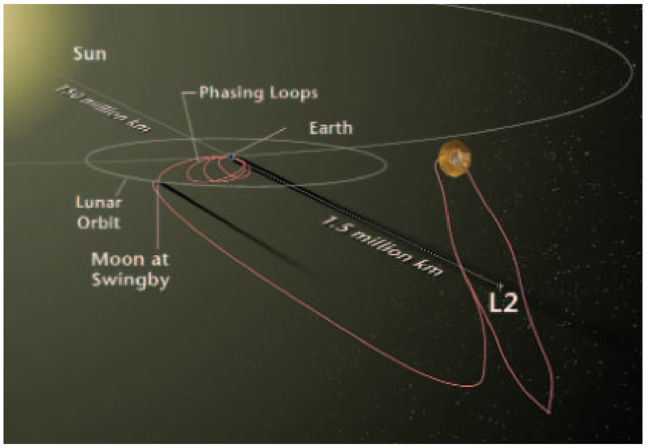
As NASA has announced in February 2003, the team has found a match. The scientists have now combined their new cosmic baby picture with an array of complementary observations to present a new cosmic consistency. The baby picture allows scientists to accomplish two main things: (1) reach back to earlier times to see what produced these patterns; and (2) look forward from the time of the picture to predict how the Universe would develop, and compare this to what is seen observed by other means (with galaxies, supernovae, etc.) to get the cosmic consistency.

WMAP will continue to survey the CMB for three years. This additional windfall of data will help scientists further narrow the range of possibilities and illuminate some of the deepest mysteries of earliest moments of the Universe.

For more information, refer to: http://map.gsfc.nasa.gov/m_uni.html

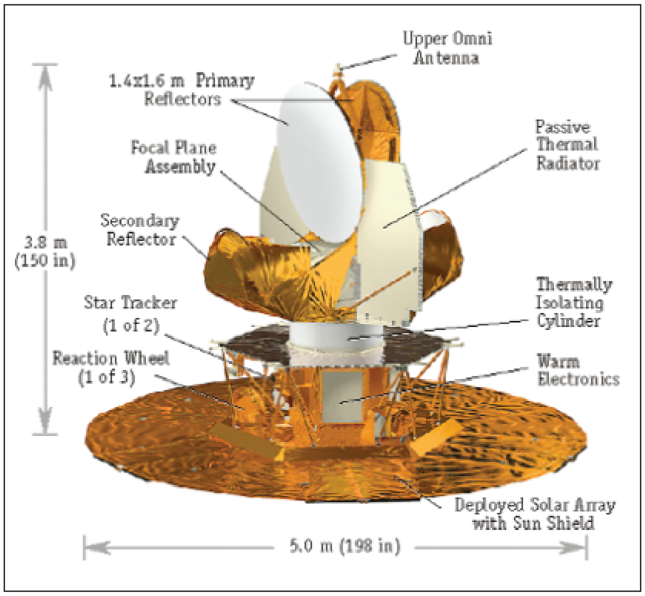
The Wilkinson Microwave Anisotropy Probe

WMAP AT A GLANCE



MISSION OVERVIEW

Launch date: June 30, 2001, 3:46 p.m. EDT
Launch site: Pad B at Space Launch Complex 17, Cape Canaveral Air Force Station, Florida
Launch vehicle: Delta II 7425-10
Orbit: Lissajous orbit about the L2 Sun-Earth Lagrange point, 1.5 million km (1 million miles) from Earth
Size: 5 meters (16.4 feet) wide, 3.8 meters (12.5 feet) high
Mass/Power: 840 kg (1,848 pounds), 419 watts



INSTRUMENT OVERVIEW

Radiometer: Differential pseudo-correlation with polarization
Optics: Dual Gregorian, 1.4 x 1.6 meter (4.6 x 5.2 foot) primary reflectors
Thermal: Passive radiative cooling to 95 Kelvin
Frequencies (GHz): 22, 30, 40, 60, 90

More information available at
http://map.gsfc.nasa.gov