Jahn-Teller effect (Barckholtz et al. 1998). On a more visible scale, some insects can change their direction in flight by using the Coriolis effect on their rapidly rotating wings. On a somewhat larger scale, the Coriolis effect must be taken into account with rotating machinery such as the motion of water on waterwheels (an example that Coriolis himself used).

One can see the Coriolis effect on the path of bullets from cannons, which can be as much as 1 kilometer deviation for a range of 120 kilometers. The Coriolis effect is responsible for the rotation of a Foucault pendulum over the course of a day. On a larger scale, the tendency of winds to move from high pressure to low pressure is balanced by the Coriolis effect that pushes winds to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The balance of forces yields counter-clockwise motion of winds around high-pressure systems and clockwise motion of winds around low-pressure systems. Figure 1 shows the resulting circular motion of winds in a hurricane.

The opposite directions hold in the Southern Hemisphere. Since Earth's surface is curved, the Coriolis effect is largest at the poles, declining to zero at the equator where Earth's surface is parallel to the axis of rotation. This pattern suggests, for example, that hurricanes, which rotate rapidly, would not form near the equator, where the Coriolis effect is weak. And in fact, no hurricane has ever begun between 10 degrees north of the equator and 10 degrees south of the equator. Tornadoes are an extreme example of the Coriolis effect in action.

In the ocean, the Coriolis effect causes water to move to the right of the force of the wind in the Northern Hemisphere. At the equator, water driven by the trade winds will be forced to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Water moving upward to compensate for that divergent motion is an upwelling of nutrient-rich water leading to high biological diversity. The Gulf Stream is affected both by the Coriolis effect and by the fact that as it moves north, it is subject to a changing Coriolis effect. Far from Earth, the Coriolis effect is a controlling factor in the rotation of sunspots.

Figure 1. *A computer-generated image of Hurricane Fran, using data from the GOES weather satellites.* © DENNIS HALLINAN / ALAMY

SEE ALSO *Atmosphere, General Circulation Models of the; Climate Change; Gulf Stream; Ocean Circulation; Weather Forecasting by Numerical Processes.*

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COSMIC MICROWAVE BACKGROUND

The cosmic microwave background (CMB) radiation was discovered in 1965 by the American physicist Arno Allan Penzias (1933–) and the American astronomer Robert Woodrow Wilson (1936–). The CMB comes from all directions in the sky and is believed to be relic radiation left over from the hot Big Bang origin of our universe. The CMB is thermal microwave radiation at a temperature of approximately 2.7 degrees above absolute zero (about −270°C or −455°F). Its discovery transformed the hot Big Bang model into the standard model for the origin of the universe. The Big Bang model naturally explains the CMB as red-shifted remnant radiation from a time 380,000 years after the Big

Bang when hot electrons and protons cooled and combined into neutral hydrogen, making the universe transparent for the first time.

BIG BANG OR STEADY STATE?

The story of the CMB, like most of modern cosmology, begins with the equations of General Relativity developed by the German-born American theoretical physicist Albert Einstein (1879–1955) and published in 1916. Solutions to Einstein's equations were found that correspond to an expanding universe and, soon thereafter, astronomers found evidence for this expansion: distant galaxies were all moving away from our vantage point within the Milky Way Galaxy. The discovery of the expanding universe inspired two competing cosmological models, both of which incorporated the expansion. In the steady-state model championed by the English astronomer Fred Hoyle (1915–2001), the universe had no beginning. It was infinitely old and had been expanding forever. Through the continual creation of matter it kept a constant density of stars and galaxies.

In the Big Bang model, advocated by the Belgian astronomer Georges Lemaître (1894–1966) and the Russian-born American theoretical physicist George Gamow (1904–1968), the universe has changed dramatically. It started out too dense and too hot for atoms or even atomic nuclei to exist. The early universe was a primordial soup of neutrons and protons bathed in a hot bath of high-energy photons. Gamow thought that the relative abundances of all atomic elements could be explained in the Big Bang model. As the universe expanded and cooled, protons and neutrons combined to form atomic nuclei and the bath of hot radiation cooled and became a bath of cold radiation: the CMB. Gamow and his students made various predictions for the cold temperature of this potentially observable radiation: $\sim$ 50 Kelvin (K), $\sim$5 K, and $\sim$28 K.

Independently, the American physicist Robert Henry Dicke (1916–1997) and his group at Princeton University were also interested in the hot Big Bang—not to make the elements (as Gamov wanted) but to destroy them. Dicke hypothesized that the universe was infinitely old and had been through many phases of expansion and contraction. The hot Big Bang was the latest contraction that had heated and destroyed the elements from the previous cycle, converting them back to neutrons and protons. Dicke and colleagues wanted to detect the radiation from this hot, element-destroying cosmic contraction. They also made various predictions for the temperature of the CMB: less than 20 K, $\sim$ 45 K, and 10 K. All these temperatures have intensities that peak in the microwave part of the electromagnetic spectrum.

PENZIAS AND WILSON DISCOVER CMB RADIATION

Technological advances during and after World War II (1939–1945) made the detection of such low temperature radiation plausible. In the early 1960s Dicke's group was developing both theoretical and observational programs and was building a sensitive microwave radiometer to try to detect the CMB. At the same time, 40 kilometers (25 miles) away in Holmdel, New Jersey, Penzias and Wilson, two young radio astronomers were working for Bell Labs trying to recommission a relatively new horn antenna (see Figure 1). The antenna resembled an alpenhorn the size of a railroad boxcar. It was built in 1960 to pick up microwaves reflected off an orbiting Mylar balloon known as the Echo *satelloon* (a combination of the words *satellite* and *balloon*). At 30 meters (98 feet) in diameter, it was larger than a brontosaurus. The invention of transceivers for satellites ended the Echo satelloon program and made the Holmdel antenna unnecessary for satellite communications.

In 1963–1964 Penzias and Wilson were not trying to detect radiation from the Big Bang. Instead, they were carefully reconfiguring, calibrating, and converting the relatively small Holmdel horn antenna into an instrument with which they could perform radio astronomy. Penzias's PhD thesis had been a search for neutral hydrogen (at 21-centimeter wavelengths) in clusters of galaxies. He was trying to detect enough mass in the clusters to hold them together gravitationally. Wilson's PhD thesis had been to produce a map of the Milky Way Galaxy at 31-centimeter wavelengths. Building on their thesis research, they wanted to detect a radio-emitting halo around the Milky Way by converting the Holmdel

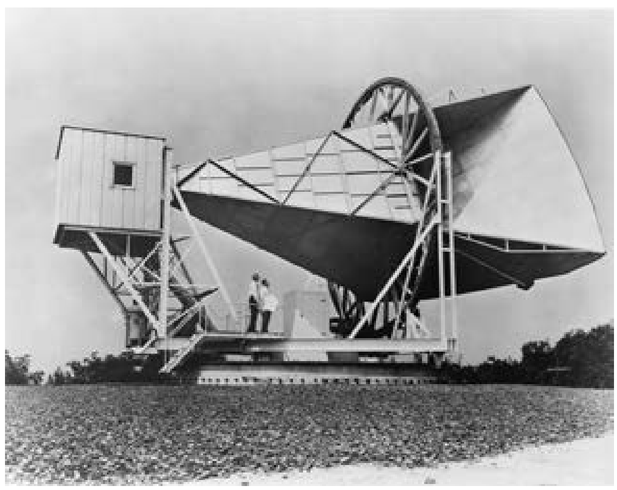

Figure 1. *The radio horn antenna in Holmdel, New Jersey, where Arno Penzias and Robert Wilson (standing under the antenna) detected an excess antenna noise.* NASA

antenna into the world's most sensitive radio telescope for wide-angle sources (sources subtending angles larger than the antenna beam width). During this reconfiguration, they ran into an anomalous source of excess noise. Was it the receiver? The antenna? Or, was it something else? For several years, they carefully considered and eliminated the various possibilities:

- microwave absorption of the atmosphere
- microwave noise polllution (e.g., from nearby New York City)
- emission from the Milky Way or other extraterrestrial radio sources
- antenna problems

To investigate antenna problems, they took apart the narrow throat section of the antenna, put aluminum tape over the riveted joints of aluminum sheets, and evicted a pair of band-tailed pigeons that were nesting in the antenna. In the process they removed a *white dielectric material* (Penzias's name for pigeon poo). None of these efforts seemed to make a difference. The excess noise persisted. While they were performing these checks, a year passed. The sky above them had changed, so they could now also rule out Solar System objects, emission from the Milky Way, or any other radio source that would change with the seasons. They also considered and rejected the idea of the source being the recently detected Van Allen belts that might have been filled with persistent ionized particles from the high altitude nuclear explosions in 1962.

In February 1965 the Canadian-American physicist James Peebles (1935–), a young postdoctoral student in Dicke's group at Princeton made a presentation at the Johns Hopkins University about the Big Bang research they were doing. Bernard F. "Bernie" Burke, an American radio astronomer from the Massachusetts Institute of Technology, heard about Peebles's presentation and was given a preprint of the paper. Burke also heard from Penzias about the persistent excess noise, which by this time had become a frustrating mystery. Burke told Penzias about Peebles's preprint, which predicted a 10 K signal in the Holmdel antenna. Burke suggested that Penzias contact the Princeton group. A few days later, after receiving the mimeographed copy of Peebles's preprint from Burke, Penzias telephoned Dicke. When Dicke heard about this excess noise, he immediately interpreted it as the remnant radiation from the Big Bang that his group at Princeton had been gearing up to detect. After hanging up the phone, he summarized the conversation for his research group: "Well boys, we've been scooped."

After visits to each other's labs, it was decided that each group would submit separate papers to the *Astrophysical Journal*. Penzias and Wilson's paper described the discovery of excess noise coming from all directions corresponding to a temperature of 3.5 +/− 1.0 K at a wavelength of 7 centimeters (cm). Dicke and colleagues' paper interpreted the excess noise as the relict radiation from the hot Big Bang. The papers were quickly accepted for publication in the July 1965 issue; however, Walter Sullivan, a science reporter at the *New York Times*, found out about them before publication, and on May 21, 1965, the front page of the newspaper announced the discovery of the CMB: "Signals Imply a 'Big Bang' Universe." Years later Wilson recalled: "We were pleased that the mysterious noise appearing in our antenna had an explanation of any kind, especially one with such significant cosmological implications" (1979, p. 871).

Following the announcement came the realization that the CMB radiation had been measured before by various observers, but not at a high enough signal-to-noise ratio to induce the observers to doggedly track down the source. For their discovery of the CMB, Penzias and Wilson received the Nobel Prize in Physics in 1978. Six months after the discovery, P. G. Roll and David Wilkinson published the Princeton group's results at 3-cm wavelength (shorter wavelengths than the 7 cm of the Penzias and Wilson result). They found a temperature of 3.0 +/− 0.5 K, consistent with the earlier measurement.

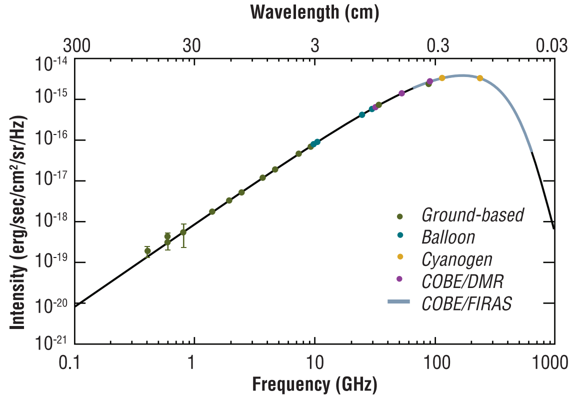

Figure 2. *Measurements of the CMB at various frequencies show it to have the spectrum of blackbody radiation, as predicted by the Big Bang model. The dotted line is the intensity of a 2.726 K blackbody. FIRAS measurements from NASA's COBE satellite (red) span the peak of the emission and represent the most precise measurements of a blackbody spectrum. Convincing deviations from a 2.726 K blackbody spectrum have not been detected.* NASA/ARCADE PROJECT

CMB PREDICTS HOT BIG BANG MODEL

Rarely does a single observation clearly distinguish two opposing models. However, the CMB was an important predicted feature of the hot Big Bang model. No such background radiation was expected in the steady-state model. Thus, the discovery of the CMB removed the steady-state model from serious contention. The Big Bang model predicted that the CMB would have a thermal blackbody spectrum. From a succession of temperature measurements at different frequencies, this appeared to be the case (see Figure 2). In 1990 results from the Far Infra-Red Absolute Spectrophotometer (FIRAS) instrument aboard the National Aeronautics and Space Administration's (NASA) Cosmic Background Explorer (COBE) satellite definitively established the blackbody nature of the CMB at a temperature of approximately 2.7 K. The American astrophysicist and cosmologist John C. Mather (1946–) shared the 2006 Nobel Prize in Physics for his leading contribution to this result.

Although the spectrum of the CMB was found to be precisely thermal, it was expected that the temperature would not be exactly the same in every direction. The largest of these anisotropies was expected to be due to Earth's motion. The CMB should appear hotter in the direction of Earth's motion and cooler in the opposite direction. However, Earth's motion is complicated. Earth orbits the Sun, while the Sun orbits the center of the Milky Way Galaxy, and the Milky Way Galaxy is falling toward the Virgo cluster of galaxies. A cosmic dipole anisotropy corresponding to this combined motion—a great cosine in the sky—should be visible at the milli-Kelvin level ($\Delta T / T \sim 10^3$). During the 1970s and 1980s this expected dipole was pinned down by a series of increasingly precise dipole anisotropy observations (reviewed in Lineweaver 1997). Thus, the observed CMB dipole is a convenient speedometer.

After removing the dipole due to Earth's motion, theories of large-scale structure formation predicted that the CMB would not have the exact same temperature in all directions. To produce the large-scale structure seen around Earth (voids, clusters, filaments, and walls of galaxies) slight under-densities and over-densities of matter must have produced slight differences in temperature a factor of ten or one hundred smaller than the dipole. The detection of these small anisotropies was important because if they did not exist, the Big Bang model would have no explanation for the origin of structure in the universe.

THE GREATEST DISCOVERY OF THE CENTURY

In 1992 the American astrophysicist George Smoot (1945–) and colleagues announced the detection of the expected structure in full-sky maps of the CMB radiation at the level of about one hundred times smaller than the dipole, using the differential microwave radiometers aboard the COBE satellite. (See the top panel of Figure 3.) Smoot explained the importance of the result to the press by saying: "If you're religious it's

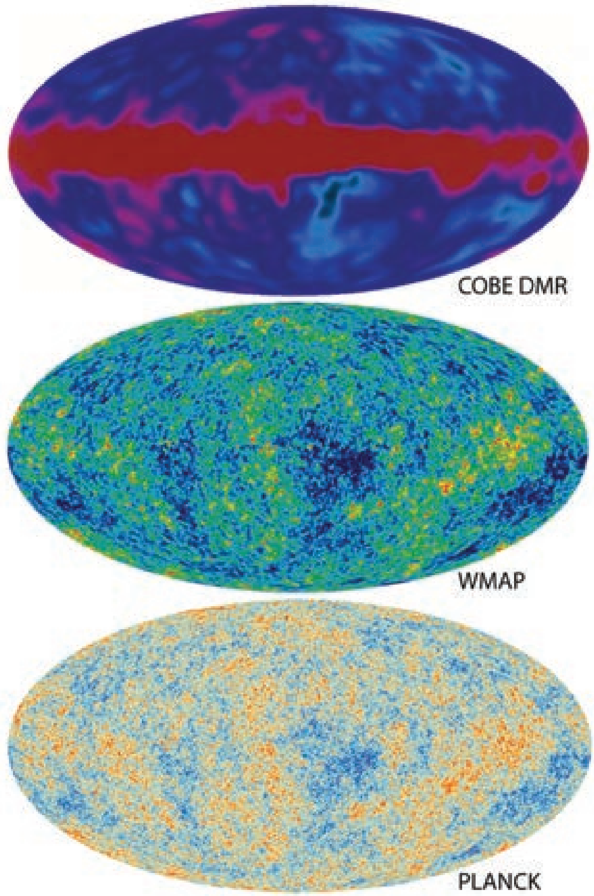

Figure 3. *Progress made since the 1980s in CMB anisotropy observations. Full-sky maps of the CMB temperature anisotropies from the COBE DMR (Cosmic Background Explorer Differential Microwave Radiometer, launched 1989), WMAP (Wilkinson Microwave Anisotropy Probe, launched 2001), and Planck (European Space Agency's CMB satellite, launched 2009). The angular resolution has improved from ~7 degrees (COBE DMR) to ~0.5 degree (WMAP) to ~0.1 degrees (Planck). Only the DMR map includes emission from the plane of the Milky Way Galaxy stretching horizontally across the image. Wider ranges in frequency have allowed the WMAP and Planck teams to remove galactic emission. Different false-color schemes have been used in each map, but the darkest blue is cold in each map. The temperature differences are approximately 0.0001 K hotter and colder than the average CMB temperature of 2.726 K.* TOP: COBE SCIENCE WORKING GROUP; MIDDLE: NASA / WMAP SCIENCE TEAM; BOTTOM: ESA AND THE PLANCK COLLABORATION

like looking at God'' (Associated Press 1992, p. 1). The English theoretical astrophysicist Stephen Hawking (1942–) called Smoot's team's discovery ''the greatest discovery of the century if not of all time'' (Maugh 1992). These statements sound less hyperbolic after one understands the implications of the detection of temperature fluctuations at angular scales greater than a few degrees (see Figure 4). CMB anisotropies at angular scales larger than a few degrees are acausal in the sense that points on the surface of last scattering, which are separated by more than a few degrees, have past light cones that do not intersect. They cannot have been in causal contact and yet they seem to be part of the same coherent hot spot or cold spot.

Thus, in the standard Big Bang model there should be no temperature correlations at angular separations greater than a few degrees. Yet there they are. These have been interpreted as remnants of an inflationary epoch at a time 10^{-43} or 10^{-35} seconds after the Big Bang. Smoot shared the Nobel Prize in Physics in 2006 for his leading role in this discovery of large-scale anisotropy in the CMB radiation.

Temperature differences are displayed as a function of position in the maps of Figure 3. In Figure 4, the amplitudes of these same temperature differences are displayed as a function of their angular size. The detailed bumps and wiggles of this CMB power spectrum contains a wealth of data about the age, composition, topology, and expansion of the universe and has now become the basis of precision cosmology and the standard Lambda-CDM cosmological model.

A telescope is a time machine. When astronomers look beyond the stars of Earth's galaxy—at the most distant galaxies—they see light emitted billions of years ago. When astronomers look beyond the most distant galaxies, in every direction, as far back in time as it is possible to look, they can see the hot photosphere of the universe—an opaque curtain of plasma called the surface of last scattering from which comes the CMB radiation.

Since the discovery of the CMB radiation in 1965, increasingly precise observations have helped convert cosmology from speculation based on a few observable facts, into a data-rich science that can tell cosmologists the precise age and composition of the universe and how fast it is expanding. CMB observations also suggest that the expansion of the universe is accelerating, and that the universe is spatially infinite. As the Holmdel antenna and the FIRAS and DMR instruments have shown, whenever the sensitivity of an instrument is improved by an order of magnitude, something important is often discovered. The current mysteries of dark matter and dark energy may be solved by more precise measurements of CMB

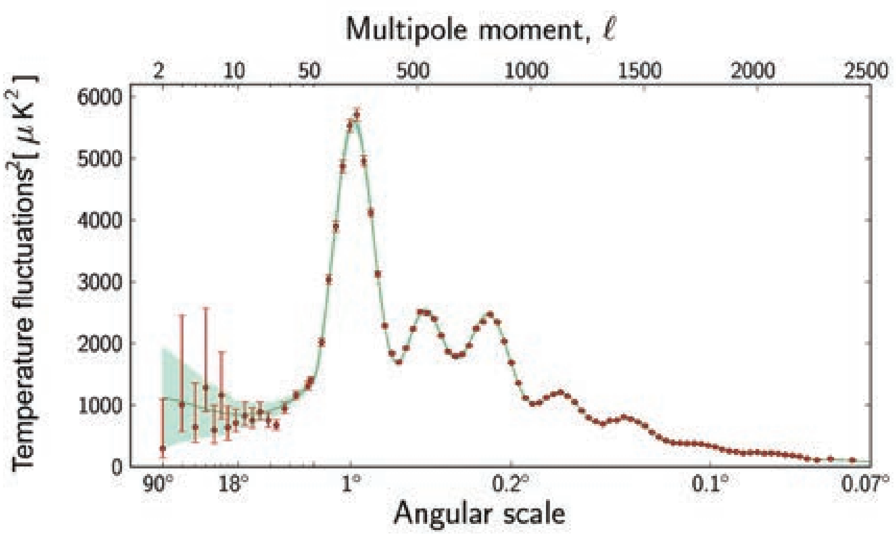

Figure 4. *The amount of power in the temperature fluctuations of the full-sky Planck anisotropy map (see bottom of Figure 3) as a function of angular scale. The COBE DMR map gave the normalization of this plot for angular scales greater than ~ 7 degrees. The higher angular resolution WMAP map (see middle of Figure 3) gave this plot for angular scales greater than ~ 0.5 degrees. The latest Planck results now give the power for angular scales greater than ~ 0.1 degree. The green shade is cosmic variance: the uncertainty expected when one samples only a limited number of regions of the sky at large angular scale.* ESA AND THE PLANCK COLLABORATION

anisotropies by the European Space Agency's Planck satellite or by the next generation of CMB satellites that will probe the details of the oldest photons that astronomers have access to—the cosmic microwave background.

SEE ALSO *Big Bang; Cosmic Rays; Dark Matter; Early Universe and Unified Field Theories; Galaxies, Nature of; Hubble's Law; Inflationary Universe.*

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COSMIC RAYS

The Austrian physicist Victor Franz Hess (1883–1964), who shared the Nobel Prize in Physics in 1936 with American Carl D. Anderson (1905–1991), was honored for his discovery of cosmic rays during high-altitude balloon flights in 1912. Anderson was honored for his 1932 discovery of the first antiparticle, the positron, found among the tracks of cosmic ray particles in his cloud chamber.

Hess was born in the county of Styria, Austria, on June 24, 1883. He was educated at the University of Graz, receiving his doctor of philosophy (PhD) in 1906. At the time of his cosmic ray discovery, he was an assistant at the Institute for Radium Research of the Viennese Academy of Sciences. Because Hess's wife was Jewish, in 1938 they fled to the United States to escape Nazi persecution. From 1938 until retirement in 1958, Hess was a professor of physics at Fordham University in New York. He died on December 17, 1964.

Hess's research started during a time of great scientific excitement in the study of atmospheric electricity. This subject has a long history that broadened into new directions after the discovery of x-rays in 1895, followed rapidly by the discoveries of radioactivity, along with radium and polonium. In the early years of this research and before details of the nature of the ionization process were understood, the prime tool of research was the electrometer. Emanations from radioactive materials ionized the surrounding air, increasing its electrical conductivity. It was this effect that was measured by many scientists, using electrometers as they explored the properties of the newly discovered phenomena.

A widely used electrometer was designed by Father Theodor Wulf (1868–1946), a Jesuit priest and German physicist, in 1909. A central component of the instrument was a pair of wires made of metallized glass suspended from an electrically insulated rod. When connected to a battery (typically producing a few hundred volts), these wires were both given an electric charge. Repulsion between the like charges on the two wires caused their visible separation, which decreased as electric charge leaked away. Leakage could come from less-than-perfect electrical insulation from the surroundings, or from an increase in ionization of the electrometer's air; thus increasing its electrical conductivity. External sources of radiation produced ionization and so the electrometer's measurements of charge leakage were proxies for direct measurement of the strength of the radiation.

It was soon observed that even well-insulated electrometers lost their electric charge although no obvious source of radiation was near. Effectively, cosmic ray research began with the hunt for the cause of this residual leakage. Many attempts were made to minimize the effects of all known or suspected causes. For example,