**Cosmic Microwave Radiation**

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*"CMB" redirects here. For other uses, see* [*CMB (disambiguation)*](http://en.wikipedia.org/wiki/CMB_%28disambiguation%29)*.*

*"cosmic background radiation" redirects here. For other uses, see* [*cosmic background*](http://en.wikipedia.org/wiki/Cosmic_background)*.*

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In [cosmology](http://en.wikipedia.org/wiki/Physical_cosmology), **cosmic microwave background (CMB) radiation** (also **CMBR**, **CBR**, **MBR**, and **relic radiation**) is a form of [electromagnetic radiation](http://en.wikipedia.org/wiki/Electromagnetic_radiation) filling the [universe](http://en.wikipedia.org/wiki/Universe). With a traditional [optical telescope](http://en.wikipedia.org/wiki/Optical_telescope), the space between stars and galaxies (the *background*) is pitch black. But with a [radio telescope](http://en.wikipedia.org/wiki/Radio_telescope), there is a faint background glow, almost exactly the same in all directions, that is not associated with any star, galaxy, or other object. This glow is strongest in the [microwave](http://en.wikipedia.org/wiki/Microwave) region of the radio spectrum, hence the name *cosmic microwave background radiation*. The CMB's discovery in 1964 by radio astronomers [Arno Penzias](http://en.wikipedia.org/wiki/Arno_Penzias) and [Robert Wilson](http://en.wikipedia.org/wiki/Robert_Woodrow_Wilson)[[2]](http://en.wikipedia.org/wiki/Cosmic_microwave_background_radiation#cite_note-1#cite_note-1) was the culmination of work initiated in the 1940s, and earned them the 1978 [Nobel Prize](http://en.wikipedia.org/wiki/Nobel_Prize_in_Physics).

The CMBR is well explained by the [Big Bang](http://en.wikipedia.org/wiki/Big_Bang) model: When the universe was young, before the formation of stars and planets, it was smaller, much hotter, and filled with a uniform glow from its white-hot fog of hydrogen [plasma](http://en.wikipedia.org/wiki/Plasma_%28physics%29). As the universe expanded, both the plasma and the radiation filling it grew cooler. When the universe cooled enough, stable atoms could form. These atoms could no longer absorb the [thermal radiation](http://en.wikipedia.org/wiki/Thermal_radiation), and the universe became transparent instead of being an opaque fog. The photons that existed at that time have been propagating ever since, though growing fainter and less energetic, since the exact same photons fill a greater and greater universe. This is the source for the term *relic radiation*, another name for the CMBR.

Precise measurements of cosmic background radiation are critical to cosmology, since any proposed model of the universe must explain this radiation. The CMBR has a thermal [black body](http://en.wikipedia.org/wiki/Black_body) spectrum at a temperature of 2.725 K, thus the spectrum peaks in the [microwave](http://en.wikipedia.org/wiki/Microwave) range frequency of 160.2 GHz, corresponding to a 1.9 mm wavelength. The glow is almost but not quite uniform in all directions, and shows a [very specific pattern](http://en.wikipedia.org/wiki/Cosmic_microwave_background_radiation#Primary_anisotropy#Primary_anisotropy) equal to that expected if the inherent randomness of a red-hot gas is blown up to the size of the universe. In particular, the spatial [power spectrum](http://en.wikipedia.org/wiki/Spectral_density) (how much difference is observed versus how far apart the regions are on the sky) contains small [anisotropies](http://en.wikipedia.org/wiki/Anisotropy), or irregularities, which vary with the size of the region examined. They have been measured in detail, and match what would be expected if small thermal fluctuations had expanded to the size of the observable space we can detect today. This is still a very active field of study, with scientists seeking both better data (for example, the [Planck spacecraft](http://en.wikipedia.org/wiki/Planck_%28spacecraft%29) ) and better interpretations of the initial conditions of expansion.

Although many different processes might produce the general form of a black body spectrum, no model other than the [Big Bang](http://en.wikipedia.org/wiki/Big_Bang) has yet explained the fluctuations. As a result, most cosmologists consider the Big Bang model of the universe to be the best explanation for the CMBR.

**Features**

The cosmic microwave background spectrum measured by the FIRAS instrument on the [COBE satellite](http://en.wikipedia.org/wiki/COBE) is the most-precisely measured [black body](http://en.wikipedia.org/wiki/Black_body) spectrum in nature. The [data points](http://en.wikipedia.org/wiki/Data_point) and [error bars](http://en.wikipedia.org/wiki/Standard_error_of_estimation) on this graph are obscured by the theoretical curve.

The cosmic microwave background is [isotropic](http://en.wikipedia.org/wiki/Isotropic) to roughly one part in 100,000: the [root mean square](http://en.wikipedia.org/wiki/Root_mean_square) variations are only 18 µK. *The Far-Infrared Absolute* [*Spectrophotometer*](http://en.wikipedia.org/wiki/Spectrophotometer) (*FIRAS*) instrument on the [NASA](http://en.wikipedia.org/wiki/NASA) [Cosmic Background Explorer](http://en.wikipedia.org/wiki/COBE) (COBE) satellite has carefully measured the spectrum of the cosmic microwave background. The FIRAS project members compared the CMB with an internal reference [black body](http://en.wikipedia.org/wiki/Black_body) and the spectra agreed to within the experimental error. They concluded that any deviations from the black body form that might still remain undetected in the CMB spectrum over the wavelength range from 0.5 to 5 mm must have a weighted [rms](http://en.wikipedia.org/wiki/Root_mean_square) value of at most 50 parts per million (0.005%) of the CMB peak brightness. This made the CMB spectrum the most precisely measured black body spectrum in nature.

The cosmic microwave background is perhaps the main prediction of the [Big Bang](http://en.wikipedia.org/wiki/Big_Bang) model. In addition, [Inflationary Cosmology](http://en.wikipedia.org/wiki/Inflation_%28cosmology%29) predicts that after about 10−37 seconds the nascent universe underwent [exponential growth](http://en.wikipedia.org/wiki/Exponential_growth) that smoothed out nearly all inhomogeneities. This was followed by [symmetry breaking](http://en.wikipedia.org/wiki/Symmetry_breaking); a type of phase transition that set the [fundamental forces](http://en.wikipedia.org/wiki/Fundamental_forces) and [elementary particles](http://en.wikipedia.org/wiki/Elementary_particle) in their present form. After 10−6 seconds, the early universe was made up of a hot [plasma](http://en.wikipedia.org/wiki/Plasma_%28physics%29) of [photons](http://en.wikipedia.org/wiki/Photon), [electrons](http://en.wikipedia.org/wiki/Electrons), and [baryons](http://en.wikipedia.org/wiki/Baryon). The photons were constantly interacting with the plasma through [Thomson scattering](http://en.wikipedia.org/wiki/Thomson_scattering). As the universe [expanded](http://en.wikipedia.org/wiki/Metric_expansion_of_space), adiabatic cooling caused the plasma to cool until it became favorable for [electrons](http://en.wikipedia.org/wiki/Electrons) to combine with [protons](http://en.wikipedia.org/wiki/Protons) and form [hydrogen](http://en.wikipedia.org/wiki/Hydrogen) atoms. This [recombination](http://en.wikipedia.org/wiki/Timeline_of_the_Big_Bang#Recombination:_ca_377.2C000_years) event happened at around 3000 K or when the universe was approximately 379,000 years old. At this point, the photons scattered off the now electrically-neutral atoms and began to travel [freely](http://en.wikipedia.org/wiki/Free_streaming) through space, resulting in the [decoupling](http://en.wikipedia.org/wiki/Decoupling) of matter and radiation.

The [color temperature](http://en.wikipedia.org/wiki/Color_temperature) of the photons has continued to diminish ever since; now down to 2.725 K, their temperature will continue to drop as the universe expands. According to the Big Bang model, the radiation from the sky we measure today comes from a spherical surface called *the surface of last scattering*. This represents the collection of spots in space at which the decoupling event is believed to have occurred, less than 400,000 years after the Big Bang, and at a point in time such that the photons from that distance have just reached observers. The estimated age of the Universe is 13.7 billion years. However, because the Universe has continued expanding since that time, the [comoving distance](http://en.wikipedia.org/wiki/Comoving_distance) from the Earth to the edge of the [observable universe](http://en.wikipedia.org/wiki/Observable_universe) is now at least 46.5 billion light years.

The Big Bang theory suggests that the cosmic microwave background fills all of observable space, and that most of the radiation energy in the universe is in the cosmic microwave background, which makes up a fraction of roughly 6×10−5 of the total density of the universe.

Two of the greatest successes of the big bang theory are its prediction of its almost perfect [black body](http://en.wikipedia.org/wiki/Black_body) spectrum and its detailed prediction of the anisotropies in the cosmic microwave background. The recent [Wilkinson Microwave Anisotropy Probe](http://en.wikipedia.org/wiki/Wilkinson_Microwave_Anisotropy_Probe) has precisely measured these anisotropies over the whole sky down to angular scales of 0.2 degrees. These can be used to estimate the parameters of the standard [Lambda-CDM model](http://en.wikipedia.org/wiki/Lambda-CDM_model) of the big bang. Some information, such as the [shape of the Universe](http://en.wikipedia.org/wiki/Shape_of_the_Universe), can be obtained straightforwardly from the cosmic microwave background, while others, such as the [Hubble constant](http://en.wikipedia.org/wiki/Hubble_constant), are not constrained and must be inferred from other measurements.[[15]](http://en.wikipedia.org/wiki/Cosmic_microwave_background_radiation#cite_note-apjss148-19#cite_note-apjss148-19) The latter value gives the [redshift](http://en.wikipedia.org/wiki/Redshift) of galaxies (interpreted as the [recessional velocity](http://en.wikipedia.org/wiki/Recessional_velocity)) as a proportion of their distance.

**History**

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| **Timeline of the CMB** |
| Important people and dates |
| *1941* | [Andrew McKellar](http://en.wikipedia.org/wiki/Andrew_McKellar) reported the observation of an average bolometric temperature of 2.3 K based on the study of interstellar absorption lines.  |
| *1946* | [Robert Dicke](http://en.wikipedia.org/wiki/Robert_Dicke) predicts ".. radiation from cosmic matter" at <20 K but did not refer to background radiation |
| *1948* | [George Gamow](http://en.wikipedia.org/wiki/George_Gamow) calculates a temperature of 50 K (assuming a 3-billion-year old Universe), commenting it ".. is in reasonable agreement with the actual temperature of interstellar space", but does not mention background radiation. |
| *1948* | [Ralph Alpher](http://en.wikipedia.org/wiki/Ralph_Alpher) and [Robert Herman](http://en.wikipedia.org/wiki/Robert_Herman) estimate "the temperature in the Universe" at 5 K. Although they do not specifically mention microwave background radiation, it may be inferred.  |
| *1950* | Ralph Alpher and Robert Herman re-estimate the temperature at 28 K. |
| *1953* | [George Gamow](http://en.wikipedia.org/wiki/George_Gamow) estimates 7 K.  |
| *1955* | Émile Le Roux of the Nançay Radio Observatory, in a sky survey at λ=33 cm, reported a near-isotropic background radiation of 3 kelvins, plus or minus 2.  |
| *1956* | [George Gamow](http://en.wikipedia.org/wiki/George_Gamow) estimates 6 K.  |
| *1957* | Tigran Shmaonov reports that "the absolute effective temperature of the radio emission background ... is 4±3K". It is noted that the "measurements showed that radiation intensity was independent of either time or direction of observation... it is now clear that Shmaonov did observe the cosmic microwave background at a wavelength of 3.2 cm" |
| *1960s* | Robert Dicke re-estimates a MBR (microwave background radiation) temperature of 40 K |
| *1964* | [A. G. Doroshkevich](http://en.wikipedia.org/wiki/A._G._Doroshkevich) and [Igor Novikov](http://en.wikipedia.org/wiki/Igor_Dmitriyevich_Novikov) publish a brief paper, where they name the CMB radiation phenomenon as detectable.  |
| *1964–65* | [Arno Penzias](http://en.wikipedia.org/wiki/Arno_Penzias) and [Robert Woodrow Wilson](http://en.wikipedia.org/wiki/Robert_Woodrow_Wilson) measure the temperature to be approximately 3 K. Robert Dicke, [P. J. E. Peebles](http://en.wikipedia.org/wiki/P._J._E._Peebles), P. G. Roll, and [D. T. Wilkinson](http://en.wikipedia.org/wiki/David_Todd_Wilkinson) interpret this radiation as a signature of the big bang. |
| *1983* | [RELIKT-1](http://en.wikipedia.org/wiki/RELIKT-1) Soviet CMB anisotropy experiment was launched. |
| *1990* | FIRAS measures the black body form of the CMB spectrum with exquisite precision. |
| *Jan 1992* | Scientists who analyzed data from [RELIKT-1](http://en.wikipedia.org/wiki/RELIKT-1) spacecraft report the discovery of anisotropy at the Moscow astrophysical seminar.  |
| *Apr 1992* | Scientists who analyzed data from [COBE](http://en.wikipedia.org/wiki/COBE) DMR announce the discovery of the primary temperature anisotropy.  |
| *1999* | First measurements of acoustic oscillations in the CMB anisotropy angular power spectrum from the TOCO, BOOMERANG, and Maxima Experiments. |
| *2002* | Polarization discovered by DASI.  |
| *2004* | E-mode polarization spectrum obtained by the CBI.  |
| *2005* | [Ralph A. Alpher](http://en.wikipedia.org/wiki/Ralph_A._Alpher) is awarded the [National Medal of Science](http://en.wikipedia.org/wiki/National_Medal_of_Science) for his groundbreaking work in nucleosynthesis and prediction that the universe expansion leaves behind background radiation, thus providing a model for the Big Bang theory. |
| *2006* | Two of COBE's principal investigators, [George Smoot](http://en.wikipedia.org/wiki/George_F._Smoot) and [John Mather](http://en.wikipedia.org/wiki/John_C._Mather), received the [Nobel Prize in Physics](http://en.wikipedia.org/wiki/Nobel_Prize_in_Physics) in 2006 for their work on precision measurement of the CMBR. |

See also: [Discovery of cosmic microwave background radiation](http://en.wikipedia.org/wiki/Discovery_of_cosmic_microwave_background_radiation) and [Timeline of cosmic microwave background astronomy](http://en.wikipedia.org/wiki/Timeline_of_cosmic_microwave_background_astronomy)

The cosmic microwave background was predicted in 1948 by [George Gamow](http://en.wikipedia.org/wiki/George_Gamow), [Ralph Alpher](http://en.wikipedia.org/wiki/Ralph_Alpher), and [Robert Herman](http://en.wikipedia.org/wiki/Robert_Herman). Alpher and Herman were able to estimate the temperature of the cosmic microwave background to be 5 K, though two years later they re-estimated it at 28 K. Although there were several previous estimates of the temperature of space, these suffered from two flaws. First, they were measurements of the [*effective* temperature](http://en.wikipedia.org/wiki/Effective_temperature) of space and did not suggest that space was filled with a thermal [Planck spectrum](http://en.wikipedia.org/wiki/Planck_spectrum). Next, they depend on our being at a special spot at the edge of the [Milky Way galaxy](http://en.wikipedia.org/wiki/Milky_Way_galaxy) and they did not suggest the radiation is isotropic. The estimates would yield very different predictions if Earth happened to be located elsewhere in the Universe.

The 1948 results of Alpher and Herman were discussed in many physics settings through about 1955, when each left the Applied Physics Laboratory at Johns Hopkins University. The mainstream astronomical community, however, was not intrigued at the time by cosmology. Alpher and Herman's prediction was rediscovered by [Yakov Zel'dovich](http://en.wikipedia.org/wiki/Yakov_Zel%27dovich) in the early 1960s, and independently predicted by [Robert Dicke](http://en.wikipedia.org/wiki/Robert_Dicke) at the same time. The first published recognition of the CMB radiation as a detectable phenomenon appeared in a brief paper by [Soviet](http://en.wikipedia.org/wiki/Soviet_Union) astrophysicists [A. G. Doroshkevich](http://en.wikipedia.org/wiki/A._G._Doroshkevich) and [Igor Novikov](http://en.wikipedia.org/wiki/Igor_Dmitriyevich_Novikov), in the spring of 1964. In 1964, [David Todd Wilkinson](http://en.wikipedia.org/wiki/David_Todd_Wilkinson) and Peter Roll, Dicke's colleagues at [Princeton University](http://en.wikipedia.org/wiki/Princeton_University), began constructing a Dicke radiometer to measure the cosmic microwave background. In 1965, [Arno Penzias](http://en.wikipedia.org/wiki/Arno_Penzias) and [Robert Woodrow Wilson](http://en.wikipedia.org/wiki/Robert_Woodrow_Wilson) at the [Crawford Hill](http://en.wikipedia.org/wiki/Crawford_Hill) location of [Bell Telephone Laboratories](http://en.wikipedia.org/wiki/Bell_Telephone_Laboratories) in nearby [Holmdel Township, New Jersey](http://en.wikipedia.org/wiki/Holmdel_Township%2C_New_Jersey) had built a Dicke radiometer that they intended to use for radio astronomy and satellite communication experiments. Their instrument had an excess 3.5 K [antenna temperature](http://en.wikipedia.org/wiki/Noise_temperature) which they could not account for. After receiving a telephone call from Crawford Hill, Dicke famously quipped: "Boys, we've been scooped." A meeting between the Princeton and Crawford Hill groups determined that the antenna temperature was indeed due to the microwave background. Penzias and Wilson received the 1978 [Nobel Prize in Physics](http://en.wikipedia.org/wiki/Nobel_Prize_in_Physics) for their discovery.

The interpretation of the cosmic microwave background was a controversial issue in the 1960s with some proponents of the [steady state theory](http://en.wikipedia.org/wiki/Steady_state_theory) arguing that the microwave background was the result of [scattered starlight](http://en.wikipedia.org/wiki/Integrated_starlight) from distant galaxies. Using this model, and based on the study of narrow absorption line features in the spectra of stars, the astronomer [Andrew McKellar](http://en.wikipedia.org/wiki/Andrew_McKellar) wrote in 1941: "It can be calculated that the '[rotational temperature](http://en.wikipedia.org/wiki/Rotational_temperature)' of interstellar space is 2 K." However, during the 1970s the consensus was established that the cosmic microwave background is a remnant of the big bang. This was largely because new measurements at a range of frequencies showed that the spectrum was a thermal, [black body](http://en.wikipedia.org/wiki/Black_body) spectrum, a result that the steady state model was unable to reproduce.

The [Holmdel Horn Antenna](http://en.wikipedia.org/wiki/Holmdel_Horn_Antenna) on which Penzias and Wilson discovered the cosmic microwave background.

Harrison, Peebles, and Yu, and Zel'dovich realized that the early universe would have to have inhomogeneities at the level of 10−4 or 10−5. [Rashid Sunyaev](http://en.wikipedia.org/wiki/Rashid_Sunyaev) later calculated the observable imprint that these inhomogeneities would have on the cosmic microwave background. Increasingly stringent limits on the anisotropy of the cosmic microwave background were set by ground based experiments, but the anisotropy was first detected by the Differential Microwave Radiometer instrument on the [COBE](http://en.wikipedia.org/wiki/COBE) satellite.

Inspired by the COBE results, a series of ground and balloon-based experiments measured cosmic microwave background anisotropies on smaller angular scales over the next decade. The primary goal of these experiments was to measure the scale of the first acoustic peak, which COBE did not have sufficient resolution to resolve. This peak corresponds to large scale density variations in the early universe that are created by gravitational instabilities, resulting in acoustical oscillations in the plasma. The first peak in the anisotropy was tentatively detected by the [Toco experiment](http://en.wikipedia.org/wiki/Toco_experiment) and the result was confirmed by the [BOOMERanG](http://en.wikipedia.org/wiki/BOOMERanG_experiment) and [MAXIMA](http://en.wikipedia.org/wiki/Millimeter_Anisotropy_eXperiment_IMaging_Array) experiments. These measurements demonstrated that the [geometry of the Universe](http://en.wikipedia.org/wiki/Shape_of_the_Universe) is approximately flat, rather than [curved](http://en.wikipedia.org/wiki/Curved_space).[[49]](http://en.wikipedia.org/wiki/Cosmic_microwave_background_radiation#cite_note-56#cite_note-56) They ruled out [cosmic strings](http://en.wikipedia.org/wiki/Cosmic_strings) as a major component of cosmic structure formation and suggested [cosmic inflation](http://en.wikipedia.org/wiki/Cosmic_inflation) was the right theory of structure formation.

The second peak was tentatively detected by several experiments before being definitively detected by [WMAP](http://en.wikipedia.org/wiki/WMAP), which has also tentatively detected the third peak. As of 2008, several experiments to improve measurements of the polarization and the microwave background on small angular scales are ongoing. These include DASI, WMAP, BOOMERanG, and the [Cosmic Background Imager](http://en.wikipedia.org/wiki/Cosmic_Background_Imager). Forthcoming experiments include the [Planck spacecraft](http://en.wikipedia.org/wiki/Planck_%28spacecraft%29), [Atacama Cosmology Telescope](http://en.wikipedia.org/wiki/Atacama_Cosmology_Telescope), [QUIET telescope](http://en.wikipedia.org/wiki/QUIET_telescope), and the [South Pole Telescope](http://en.wikipedia.org/wiki/South_Pole_Telescope).

[WMAP](http://en.wikipedia.org/wiki/WMAP) image of the CMB temperature anisotropy.

**Relationship to the Big Bang**

Measurements of the CMB have made the inflationary Big Bang theory the standard model of the earliest eras of the universe. This theory predicts that the initial conditions for the universe are originally random in nature, and follow a roughly [Gaussian probability distribution](http://en.wikipedia.org/wiki/Normal_distribution), which when graphed in cross-section forms bell-shaped curves. By analyzing this distribution at different frequencies, a [spectral density](http://en.wikipedia.org/wiki/Spectral_density) or power spectrum is generated. The power spectrum of these fluctuations has been calculated, and agrees startlingly well with the observations, although certain observables, for example the overall amplitude of the fluctuations, are more or less free parameters of the [cosmic inflation](http://en.wikipedia.org/wiki/Cosmic_inflation) model. Therefore, meaningful statements about the inhomogeneities in the universe need to be [statistical](http://en.wikipedia.org/wiki/Statistics) in nature. This leads to [cosmic variance](http://en.wikipedia.org/wiki/Cosmic_variance) in which the uncertainties in the variance of the largest scale fluctuations observed in the universe are difficult to accurately compare to theory. The model uses a [Gaussian random field](http://en.wikipedia.org/wiki/Gaussian_random_field) with a nearly-[scale invariant](http://en.wikipedia.org/wiki/Scale_invariant) or Harrison-Zel'dovich spectrum to represent the primeval inhomogeneities.

**Temperature**

The cosmic microwave background radiation and the cosmological [red shift](http://en.wikipedia.org/wiki/Red_shift) are together regarded as the best available evidence for the [Big Bang](http://en.wikipedia.org/wiki/Big_Bang) theory. The discovery of the CMB in the mid-1960s curtailed interest in [alternatives](http://en.wikipedia.org/wiki/Non-standard_cosmology) such as the [steady state theory](http://en.wikipedia.org/wiki/Steady_state_theory). The CMB gives a snapshot of the [Universe](http://en.wikipedia.org/wiki/Universe) when, according to standard cosmology, the temperature dropped enough to allow [electrons](http://en.wikipedia.org/wiki/Electron) and [protons](http://en.wikipedia.org/wiki/Proton) to form [hydrogen](http://en.wikipedia.org/wiki/Hydrogen) atoms, thus making the universe transparent to radiation. When it originated some 380,000 years after the Big Bang—this time is generally known as the "time of last scattering" or the period of [recombination](http://en.wikipedia.org/wiki/Recombination) or [decoupling](http://en.wikipedia.org/wiki/Decoupling)—the temperature of the Universe was about 4,000 K. This corresponds to an energy of about 0.25 [eV](http://en.wikipedia.org/wiki/Electronvolt), which is much less than the 13.6 eV ionization energy of hydrogen.

Since decoupling, the temperature of the background radiation has dropped by a factor of roughly 1,100due to the expansion of the Universe. As the Universe expands, the CMB photons are [redshifted](http://en.wikipedia.org/wiki/Redshift), making the radiation's temperature [inversely proportional](http://en.wikipedia.org/wiki/Inversely_proportional) to a parameter called the Universe's [scale length](http://en.wikipedia.org/wiki/Scale_factor_%28Universe%29). The temperature *T*r of the CMB varies as the redshift *z* thus:

*T*r = 2.728(1 + *z*)

The redshift at decoupling was about *z* = 1,500, yielding the initial temperature of roughly 4,000 K.

For details about the reasoning that the radiation is evidence for the Big Bang, see [Cosmic background radiation of the Big Bang](http://en.wikipedia.org/wiki/Big_Bang#Cosmic_microwave_background_radiation).

**Primary anisotropy**

The power spectrum of the cosmic microwave background radiation temperature anisotropy in terms of the angular scale (or [multipole moment](http://en.wikipedia.org/wiki/Multipole_moment)). The data shown come from the [WMAP](http://en.wikipedia.org/wiki/WMAP) (2006), [Acbar](http://en.wikipedia.org/wiki/Arcminute_Cosmology_Bolometer_Array_Receiver) (2004) [Boomerang](http://en.wikipedia.org/wiki/BOOMERanG_experiment) (2005), [CBI](http://en.wikipedia.org/wiki/Cosmic_Background_Imager) (2004), and [VSA](http://en.wikipedia.org/wiki/Very_Small_Array) (2004) instruments. Also shown is a theoretical model (solid line).

The [anisotropy](http://en.wikipedia.org/wiki/Anisotropy) of the cosmic microwave background is divided into two sorts: primary anisotropy, due to effects which occur at the last scattering surface and before; and secondary anisotropy, due to effects such as interactions with hot gas or gravitational potentials, between the last scattering surface and the observer.

The structure of the cosmic microwave background anisotropies is principally determined by two effects: acoustic oscillations and diffusion damping (also called collisionless damping or [Silk damping](http://en.wikipedia.org/wiki/Silk_damping)). The acoustic oscillations arise because of a competition in the [photon](http://en.wikipedia.org/wiki/Photon)-[baryon](http://en.wikipedia.org/wiki/Baryon) plasma in the early universe. The pressure of the photons tends to erase anisotropies, whereas the gravitational attraction of the baryons—moving at speeds much slower than light—makes them tend to collapse to form dense haloes. These two effects compete to create acoustic oscillations which give the microwave background its characteristic peak structure. The peaks correspond, roughly, to resonances in which the photons decouple when a particular mode is at its peak amplitude.

The peaks contain interesting physical signatures. The angular scale of the first peak determines the [curvature of the Universe](http://en.wikipedia.org/wiki/Shape_of_the_Universe) (but not the [topology](http://en.wikipedia.org/wiki/Topology) of the Universe). The next peak—ratio of the odd peaks to the even peaks—determines the reduced baryon density. The third peak can be used to pull information about the dark matter density.

The locations of the peaks also give important information about the nature of the primordial density perturbations. There are two fundamental brands of density perturbations—called *adiabatic* and *isocurvature*. A general density perturbation is a mixture of both, and different theories that purport to explain the primordial density perturbation spectrum predict different mixtures.

* Adiabatic density perturbations

the fractional over density in each matter component ([baryons](http://en.wikipedia.org/wiki/Baryon), [photons](http://en.wikipedia.org/wiki/Photon) ...) is the same. That is, if there is 1% more energy in baryons than average in one spot, then with a pure adiabatic density perturbations there is also 1% more energy in photons, and 1% more energy in neutrinos, than average. [Cosmic inflation](http://en.wikipedia.org/wiki/Cosmic_inflation) predicts that the primordial perturbations are adiabatic.

* Isocurvature density perturbations

the sum of the fractional over densities is zero. That is, a perturbation where at some spot there is 1% more energy in baryons than average, 1% more energy in photons than average, and 2% *lear* energy in neutrinos than average, would be a pure isocurvature perturbation. [Cosmic strings](http://en.wikipedia.org/wiki/Cosmic_string) would produce mostly isocurvature primordial perturbations.

The CMB spectrum is able to distinguish these two because these two brands of perturbations produce different peak locations. Isocurvature density perturbations produce a series of peaks whose angular scales (*l*-values of the peaks) are roughly in the ratio 1:3:5:..., while adiabatic density perturbations produce peaks whose locations are in the ratio 1:2:3:... Observations are consistent with the primordial density perturbations being entirely adiabatic, providing key support for inflation, and ruling out many models of structure formation involving, for example, cosmic strings.

Collisionless damping is caused by two effects, when the treatment of the primordial plasma as [fluid](http://en.wikipedia.org/wiki/Fluid) begins to break down:

* the increasing [mean free path](http://en.wikipedia.org/wiki/Mean_free_path) of the photons as the primordial plasma becomes increasingly rarefied in an expanding universe
* the finite depth of the last scattering surface (LSS), which causes the mean free path to increase rapidly during decoupling, even while some Compton scattering is still occurring.

These effects contribute about equally to the suppression of anisotropies on small scales, and give rise to the characteristic exponential damping tail seen in the very small angular scale anisotropies.

The depth of the LSS refers to the fact that the decoupling of the photons and baryons does not happen instantaneously, but instead requires an appreciable fraction of the age of the Universe up to that era. One method to quantify exactly *how* long this process took uses the *photon visibility function* (PVF). This function is defined so that, denoting the PVF by P(t), the probability that a CMB photon last scattered between time t and t+dt is given by P(t)dt.

The maximum of the PVF (the time where it is most likely that a given CMB photon last scattered) is known quite precisely. The first-year [WMAP](http://en.wikipedia.org/wiki/Wilkinson_Microwave_Anisotropy_Probe) results put the time at which P(t) is maximum as 372±14 ka. This is often taken as the "time" at which the CMB formed. However, to figure out how *long* it took the photons and baryons to decouple, we need a measure of the width of the PVF. The WMAP team finds that the PVF is greater than half of its maximum value (the "full width at half maximum", or FWHM) over an interval of 115±5 ka. By this measure, decoupling took place over roughly 115,000 years, and when it was complete, the universe was roughly 487,000 years old.

**Late time anisotropy**

Since the CMB came into existence, it has apparently been modified by several subsequent physical processes, which are collectively referred to as late-time anisotropy, or secondary anisotropy. When the CMB photons became free to travel unimpeded, ordinary matter in the universe was mostly in the form of neutral hydrogen and helium atoms. However, observations of galaxies today seem to indicate that most of the volume of the [intergalactic medium](http://en.wikipedia.org/wiki/Intergalactic_medium) (IGM) consists of ionized material (since there are few absorption lines due to hydrogen atoms). This implies a period of [reionization](http://en.wikipedia.org/wiki/Reionization) during which some of the material of the universe was broken into hydrogen ions.

The CMB photons scatter off free charges such as electrons that are not bound in atoms. In an ionized universe, such charged particles have been liberated from neutral atoms by ionizing (ultraviolet) radiation. Today these free charges are at sufficiently low density in most of the volume of the Universe that they do not measurably affect the CMB. However, if the IGM was ionized at very early times when the universe was still denser, then there are two main effects on the CMB:

1. Small scale anisotropies are erased. (Just as when looking at an object through fog, details of the object appear fuzzy.)
2. The physics of how photons scatter of from free electrons ([Thomson scattering](http://en.wikipedia.org/wiki/Thomson_scattering)) induces polarization anisotropies on large angular scales. This broad angle polarization is correlated with the broad angle temperature perturbation.

Both of these effects have been observed by the WMAP spacecraft, providing evidence that the universe was ionized at very early times, at a [redshift](http://en.wikipedia.org/wiki/Redshift) more than 17. The detailed provenance of this early ionizing radiation is still a matter of scientific debate. It may have included starlight from the very first population of stars ([population III](http://en.wikipedia.org/wiki/Population_III) stars), supernovae when these first stars reached the end of their lives, or the ionizing radiation produced by the accretion disks of massive black holes.

The time following the emission of the Cosmic Microwave Background—and before the observation of the first stars—is semi-humorously referred to by cosmologists as the [dark age](http://en.wikipedia.org/wiki/Dark_Ages_%28disambiguation%29), and is a period which is under intense study by astronomers (See [21 centimeter radiation](http://en.wikipedia.org/wiki/21_centimeter_radiation)).

Two other effects which occurred between reionization and our observations of the Cosmic Microwave Background, and which appear to cause anisotropies, include the [Sunyaev-Zel'dovich effect](http://en.wikipedia.org/wiki/Sunyaev-Zel%27dovich_effect), where a cloud of high energy electrons scatters the radiation, transferring some of its energy to the CMB photons, and the [Sachs-Wolfe effect](http://en.wikipedia.org/wiki/Sachs-Wolfe_effect), which causes [photons](http://en.wikipedia.org/wiki/Photon) from the Cosmic Microwave Background to be gravitationally redshifted or blue shifted due to changing gravitational fields.

E polarization measurements as of March 2006 in terms of angular scale (or [multipole moment](http://en.wikipedia.org/wiki/Multipole_moment)). The polarization is much more poorly measured than the temperature anisotropy.

**Polarization**

Main article: [Polarization in astronomy](http://en.wikipedia.org/wiki/Polarization_in_astronomy)

The cosmic microwave background is [polarized](http://en.wikipedia.org/wiki/Polarization_%28waves%29) at the level of a few microkelvins. There are two types of polarization, called *E*-modes and *B*-modes. This is in analogy to [electrostatics](http://en.wikipedia.org/wiki/Electrostatics), in which the electric field (*E*-field) has a vanishing [curl](http://en.wikipedia.org/wiki/Curl_%28mathematics%29) and the magnetic field (*B*-field) has a vanishing [divergence](http://en.wikipedia.org/wiki/Divergence). The *E*-modes arise naturally from [Thomson scattering](http://en.wikipedia.org/wiki/Thomson_scattering) in a heterogeneous plasma. The *B*-modes, which have not been measured and are thought to have an amplitude of at most a 0.1 µK, are not produced from the plasma physics alone. They are a signal from [cosmic inflation](http://en.wikipedia.org/wiki/Cosmic_inflation) and are determined by the density of primordial [gravitational waves](http://en.wikipedia.org/wiki/Gravitational_wave). Detecting the *B*-modes will be extremely difficult, particularly given that the degree of foreground contamination is unknown, and the [weak gravitational lensing](http://en.wikipedia.org/wiki/Weak_gravitational_lensing) signal mixes the relatively strong *E*-mode signal with the *B*-mode signal.

**Microwave background observations**

Main article: [Cosmic microwave background experiments](http://en.wikipedia.org/wiki/Cosmic_microwave_background_experiments)

Subsequent to the discovery of the CMB, hundreds of cosmic microwave background experiments have been conducted to measure and characterize the signatures of the radiation. The most famous experiment is probably the [NASA](http://en.wikipedia.org/wiki/NASA) Cosmic Background Explorer ([COBE](http://en.wikipedia.org/wiki/COBE)) satellite that orbited in 1989–1996 and which detected and quantified the large scale anisotropies at the limit of its detection capabilities. Inspired by the initial COBE results of an extremely isotropic and homogeneous background, a series of ground- and balloon-based experiments quantified CMB anisotropies on smaller angular scales over the next decade. The primary goal of these experiments was to measure the angular scale of the first acoustic peak, for which COBE did not have sufficient resolution. These measurements were able to rule out [cosmic strings](http://en.wikipedia.org/wiki/Cosmic_strings) as the leading theory of cosmic structure formation, and suggested [cosmic inflation](http://en.wikipedia.org/wiki/Cosmic_inflation) was the right theory. During the 1990s, the first peak was measured with increasing sensitivity and by 2000 the [BOOMERanG experiment](http://en.wikipedia.org/wiki/BOOMERanG_experiment) reported that the highest power fluctuations occur at scales of approximately one degree. Together with other cosmological data, these results implied that the geometry of the Universe is [flat](http://en.wikipedia.org/wiki/Flat_space). A number of ground-based [interferometers](http://en.wikipedia.org/wiki/Interferometer) provided measurements of the fluctuations with higher accuracy over the next three years, including the [Very Small Array](http://en.wikipedia.org/wiki/Very_Small_Array), [Degree Angular Scale Interferometer](http://en.wikipedia.org/wiki/Degree_Angular_Scale_Interferometer) (DASI), and the [Cosmic Background Imager](http://en.wikipedia.org/wiki/Cosmic_Background_Imager) (CBI). DASI made the first detection of the polarization of the CMB and the CBI provided the first E-mode polarization spectrum with compelling evidence that it is out of phase with the T-mode spectrum.

In June 2001, [NASA](http://en.wikipedia.org/wiki/NASA) launched a second CMB space mission, [WMAP](http://en.wikipedia.org/wiki/WMAP), to make much more precise measurements of the great scale anisotropies over the full sky. The first results from this mission, disclosed in 2003, were detailed measurements of the angular power spectrum to below degree scales, tightly constraining various cosmological parameters. The results are broadly consistent with those expected from [cosmic inflation](http://en.wikipedia.org/wiki/Cosmic_inflation) as well as various other competing theories, and are available in detail at NASA's data bank for Cosmic Microwave Background (CMB) (see links below). Although WMAP provided very accurate measurements of the great angular-scale fluctuations in the CMB (structures about as broad in the sky as the moon), it did not have the angular resolution to measure the smaller scale fluctuations which had been observed by former ground-based [interferometers](http://en.wikipedia.org/wiki/Interferometer).

A third space mission, the [Planck Surveyor](http://en.wikipedia.org/wiki/Planck_Surveyor), launched in May, 2009. Planck employs both [HEMT](http://en.wikipedia.org/wiki/HEMT) radiometers as well as [bolometer](http://en.wikipedia.org/wiki/Bolometer) technology and will measure the CMB on smaller scales than WMAP. Unlike the previous two space missions, Planck is run by the [ESA](http://en.wikipedia.org/wiki/European_Space_Agency) (the European Space Agency). Its detectors got a trial run at the Antarctic [Viper telescope](http://en.wikipedia.org/wiki/Viper_telescope) as ACBAR ([Arcminute Cosmology Bolometer Array Receiver](http://en.wikipedia.org/wiki/Arcminute_Cosmology_Bolometer_Array_Receiver)) experiment—which has produced the most precise measurements at small angular scales to date—and at the [Archeops](http://en.wikipedia.org/wiki/Archeops) balloon telescope.

Additional ground-based instruments such as the [South Pole Telescope](http://en.wikipedia.org/wiki/South_Pole_Telescope) in Antarctica and the proposed [Clover](http://en.wikipedia.org/wiki/Clover_%28telescope%29) Project, [Atacama Cosmology Telescope](http://en.wikipedia.org/wiki/Atacama_Cosmology_Telescope) and the [QUIET telescope](http://en.wikipedia.org/wiki/QUIET_telescope) in Chile will provide additional data not available from satellite observations, possibly including the B-mode polarization.

**Data reduction and analysis**

Raw CMBR data coming down from the space vehicle (i.e., WMAP) contain foreground effects that completely obscure the fine-scale structure of the Cosmic Microwave background. The fine-scale structure is superimposed on the raw CMBR data but is too small to be seen at the scale of the raw data. The most prominent of the foreground effects is the dipole anisotropy caused by the Sun's motion relative to the CMBR background. The dipole anisotropy and others due to Earth's annual motion relative to the Sun and numerous microwave sources in the galactic plane and elsewhere must be subtracted out to reveal the extremely tiny variations characterizing the fine-scale structure of the CMBR background.

The detail analysis of CMBR data to produce maps, an angular power spectrum, and ultimately cosmological parameters is a complicated, computationally difficult problem. Although computing a power spectrum from a map is in principle a simple [Fourier transform](http://en.wikipedia.org/wiki/Fourier_transform), decomposing the map of the sky into [spherical harmonics](http://en.wikipedia.org/wiki/Spherical_harmonics), in practice it is hard to take the effects of noise and foreground sources into account. In particular, these foregrounds are dominated by galactic emissions such [free-free](http://en.wikipedia.org/wiki/Bremsstrahlung), [synchrotron](http://en.wikipedia.org/wiki/Synchrotron_radiation#synchrotron_radiatiom_in_astronomy), and [dust](http://en.wikipedia.org/wiki/Dust#dust_in_other_contexts) that emit in the microwave band; in practice, the galaxy has to be removed resulting in a CMB map that is not a full-sky map. In addition, point sources like galaxies and clusters represent another source of foreground which must be removed lest they distort the short scale structure of the CMB power spectrum.

Constraints on many cosmological parameters can be obtained from their effects on the power spectrum, and results are often calculated using [Markov Chain Monte Carlo](http://en.wikipedia.org/wiki/Markov_Chain_Monte_Carlo) sampling techniques.

**CMBR dipole anisotropy**

From the CMB data it is seen that our local group of galaxies (the galactic cluster that includes the Solar System's Milky Way Galaxy) appears to be moving at 627±22 km/s relative to the **reference frame of the CMB** (also called the **CMB rest frame**) in the direction of galactic longitude *l* = 276±3°, *b* = 30±3°. This motion results in an anisotropy of the data (CMB appearing slightly warmer in the direction of movement than in the opposite direction). The standard interpretation of this temperature variation is a simple velocity redshift and blueshift due to motion relative to the CMB, but alternative cosmological models can explain some fraction of the observed dipole temperature distribution in the CMB.

**Low multipoles and other anomalies**

With the increasingly precise data provided by WMAP, there have been a number of claims that the CMB suffers from anomalies, such as very great-scale anisotropies, anomalous alignments, and non-Gaussian distributions. The most longstanding of these is the low-*l* multipole controversy. Even in the COBE map, it was observed that the [quadrupole](http://en.wikipedia.org/wiki/Quadrupole) (*l*=2 spherical harmonic) has a low amplitude compared to the predictions of the big bang. Some observers have pointed out that the anisotropies in the WMAP data did not appear to be consistent with the big bang picture. In particular, the quadrupole and octupole (*l*=3) modes appear to have an unexplained alignment with each other and with the [ecliptic plane](http://en.wikipedia.org/wiki/Plane_of_the_ecliptic), an alignment sometimes referred to as the *axis of evil*. A number of groups have suggested that this could be the signature of new physics at the greatest observable scales. Ultimately, due to the foregrounds and the [cosmic variance](http://en.wikipedia.org/wiki/Cosmic_variance) problem, the greatest modes will never be as well measured as the small angular scale modes. The analyses were performed on two maps that have had the foregrounds removed as best as is possible: the "internal linear combination" map of the WMAP collaboration and a similar map prepared by [Max Tegmark](http://en.wikipedia.org/wiki/Max_Tegmark) and others. Later analyses have pointed out that these are the modes most susceptible to foreground contamination from [synchrotron](http://en.wikipedia.org/wiki/Synchrotron_radiation#synchrotron_radiation_in_astronomy), dust, and [free-free](http://en.wikipedia.org/wiki/Bremsstrahlung) emission, and from experimental uncertainty in the monopole and dipole. A full [Bayesian analysis](http://en.wikipedia.org/wiki/Bayesian_analysis) of the WMAP power spectrum demonstrates that the quadrupole prediction of [Lambda-CDM cosmology](http://en.wikipedia.org/wiki/Lambda-CDM_model) is consistent with the data at the 10% level and that the observed octupole is not remarkable. Carefully accounting for the procedure used to remove the foregrounds from the full sky map further reduces the significance of the alignment by ~5%.