

THE COSMIC MICROWAVE BACKGROUND

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ABSTRACT

The early Universe left us a message. About 300,000 years after the Big Bang, it became transparent. From then on, the electromagnetic radiation which originated in the Big Bang could travel almost freely and spread information on the early state of the Universe. We receive this radiation today, substantially cooled, in form of microwaves, which reach us from all directions on the sky in almost equal intensity. The structures seeded in the early Universe were imprinted on the cosmic microwave background. These fine patterns, comparable to tiny waves on the ocean of the background radiation, provide a wealth of information on the state of the early Universe, its evolution and its present geometry. Numerous experiments, among them the ambitious satellite projects *MAP* and *Planck*, will observe the microwave background with high accuracy in the near future and thereby help answer many cosmological questions definitively, but they will also confront us with challenges of a new scale. This article describes the main physical processes which imprinted structure on the microwave background, and the expectations raised in particular towards the satellite experiments.

THE BIG BANG AND ITS ECHO

The theory of the Big Bang is a widespread and well founded picture of the origin of our Universe. It holds that the entire Universe originated ten to 15 billion years ago in a very hot and dense state.

It had been recognised several decades ago that this picture has unique observational consequences. A multitude of elementary particles must have formed in the very hot, early phase of the Universe, among them the particles of light, the photons. Some 300,000 years after the Big Bang, the cosmic material became transparent, where upon photons could travel almost freely.

At that time, they had a spectrum which was determined solely by the temperature of the cosmic material. It is named Planck spectrum after its discoverer. The photons maintained the form of that spectrum, hence their population can completely be described by a single temperature value up until this day. As cosmological expansion proceeded, the temperature dropped to reach 2.73 Kelvin today. This means that the cosmic radiation background shines in the regime of microwaves; hence the term cosmic microwave background.

It was discovered by Penzias and Wilson in 1964, but they did not recognise it as such. A group of cosmologists around Robert Dicke in Princeton, however, knew immediately what Penzias and Wilson had really measured. The discovery of the cosmic microwave background was and is one of the central pillars of modern cosmology, because its existence follows from Big Bang theory, and Big Bang theory in turn explains it in the simplest way.

SEARCH FOR IRREGULARITIES

The cosmic microwave background immediately created a new problem. The fact that there is structure in the Universe implies that the temperature of the microwave background must not be *exactly* equal in all directions, but it has to display a faint direction dependence, an anisotropy. This expectation motivated the search for anisotropy in the microwave background immediately after its discovery.

For twenty-seven years, from 1965 to 1992, this search remained unsuccessful. During that time, the expectations on the magnitude of the anisotropy kept being corrected by both the-

ory and experiment. In much the same way as the spectrum of the microwave background can be characterised by a single temperature value, the anisotropy can be described as a temperature fluctuation depending on the direction on the sky. During those 27 years, the expectation on the amplitude of the temperature fluctuations dropped from 10% to 0,001% of the mean temperature of 2.73 Kelvin, because it was recognised that dark rather than luminous matter played the dominant role in the Universe.

THE BREAK-THROUGH: COBE AND THE CONSEQUENCES

Severe doubt had been raised about our picture of the origin of structure in the Universe when the American satellite *Cosmic Background Explorer* (COBE) was launched. Within very short time, COBE transmitted two fundamental cosmological results to Earth: Firstly, the spectrum of the cosmic microwave background follows a Planck spectrum to extreme precision, as required by the Big Bang theory. Secondly, COBE finally found the fluctuations in the microwave background that had been searched for so long.

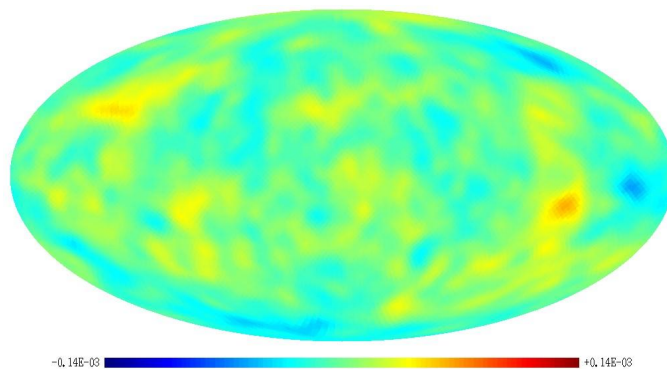


FIG. 1.—Simulated full-sky map of the temperature fluctuations in the cosmic microwave background, imaged with COBE's angular resolution of 7 degrees. Blue regions have lower, red regions higher temperature than the mean. The unit on the colour scale is Kelvin.

Numerous experiments were undertaken after COBE to establish the existence of the temperature fluctuations and to measure their amplitude on smaller angular scales. From the ground, this

is only possible to a very limited degree because the atmosphere veils the microwave background. Therefore, such experiments have to be performed in places which are high up, dry, and cold, like for instance the South Pole. Even better suited are balloon experiments which observe from stratosphere. While the successes of these experiments are spectacular, even better results are expected from satellite experiments. Two such satellites are currently being planned and built, the American *Microwave Anisotropy Probe (MAP)* and the European *Planck* satellite.

With the existence of the irregularities in the microwave background firmly established, the question arises as to why further experiments are necessary to measure the tiny temperature fluctuations in ever closer detail? To answer this question, we must have a look at where the fluctuations came from, i.e. from what physical processes they originated.

WHEN THE FOG LIFTED

As mentioned before, the microwave background shows the Universe as it was when it became transparent. This happened when the particles of the cosmic plasma could combine to form atoms. This “recombination” did not happen instantly, but took some 30,000 years, in which the Universe transformed from its initially opaque to the transparent state. Perhaps this procedure can be compared to how the fog lifts on an autumn morning. What happened during this transition period?

Three main physical effects must be taken into account:

1. The *Sachs-Wolfe effect*: The structures which we can observe today in our cosmic neighbourhood must already have been seeded when the recombination commenced. Otherwise, they would not have been able to evolve into the pronounced objects that we see today. When recombination set in, there were already over- and under-densities in the cosmic material. Photons which were hosted by over-densities when they became free had to spend part of their energy to leave the overdense regions, because their gravity exceeded that of the surroundings. This loss of energy implies an increase in wavelength, which can be described as a decrease in photon temperature. Conversely, those photons are a little hotter which came from under-dense regions. This effect is named Sachs-Wolfe effect after its discoverers.
2. *Acoustic oscillations*: Because of its still rather high temperature, the cosmic mixture of plasma and photons had a pressure which counteracted gravity. Overdense matter clouds, which should have contracted because of their self-gravity, expanded and cooled because of the gas pressure until gravity could dominate the pressure again, collapsed until pressure dominated, and so forth; in other words: The interplay between gravity and pressure caused oscillations in the cosmic plasma.

Only sufficiently small matter clouds could oscillate. This is because pressure waves travel at the finite sound speed, hence it takes them a finite time to propagate from one side of the cloud to the opposite, so that the pressure builds up the slower the larger the cloud is.

It is crucial for the consequences of this effect that the finite sound-crossing time and the finite age of the Universe cause the oscillations in matter clouds of equal size to synchronise. Consider a cloud which is small enough for sound waves to cross it in the time span between the Big Bang and the onset of recombination. Before the onset of recombination, pressure can build up in it which slows the collapse. Smaller matter clouds oscillate already, while larger

clouds still don't. It is important that at any given time before recombination, matter clouds of equal size are in the same oscillation phase, because they could start oscillating at the same time. Since these oscillations are comparable to sound waves, they are called acoustic oscillations.

3. *Silk damping*: As long as there are charged particles in the cosmic gas, i.e. as long as the recombination has not fully completed, the photons interact strongly with the plasma. They tend to drive forming matter clouds apart. This effect is unimportant for clouds which are large and therefore massive enough to collapse despite this “photon wind”. Smaller matter clouds are destroyed, or “damped away”. This effect is called *Silk damping*, again after its discoverer.

ANALYSIS OF SKY MAPS

It became apparent in the previous section that the temperature fluctuations in the microwave background should have typical properties dependent on their size. How can these temperature fluctuations be described as a function of size?

Usually, the technique of Fourier transformation is used for such purposes. It decomposes the quantity investigated into sine and cosine waves of all possible lengths and determines which wave length is required how often to describe the original quantity.

The analysis of sky maps proceeds in nearly the same manner, but instead of the sine and cosine functions of the Fourier transform, so-called spherical harmonic functions are used. As with the Fourier transform, the result is a “spectrum” which quantifies how strongly structures of a given size are represented in the sky map. Of course, “size” here refers to the angular extent of the structures. To discriminate this spectrum from the electromagnetic spectrum, the term “power spectrum” is used.

Based on the preceding discussion on the physical processes responsible for temperature fluctuations in the cosmic microwave background, we can now estimate qualitatively how its power spectrum should look like.

Very large structures in the microwave background can only have been produced by the Sachs-Wolfe effect. For if the structures were larger than the length that sound could travel between the Big Bang and the recombination, the pressure could not exert any influence, and Silk damping sets in only on very much smaller scales.

Sufficiently small structures can oscillate driven by the interplay between pressure and gravity. Oscillations of structures of a given size were synchronised. They led to compressions and rarefactions of the cosmic material and to accelerated and decelerated motion. In that way, they caused temperature fluctuations in the microwave background which appear as a characteristic wave pattern in the power spectrum. Physically not entirely correctly, the maxima are called “Doppler peaks”.

Towards even smaller structures, Silk damping sets in and suppresses them. This means that virtually no very small structures are expected in the cosmic microwave background. The power spectrum therefore drops steeply (exponentially) towards very small structures.

A typical example for a possible power spectrum of the cosmic microwave background is shown by Fig. 2.

COSMOLOGICAL PARAMETERS

If one compares power spectra expected for different combinations of cosmological parameters, it turns out that the position of the maxima and minima, their separation from each other, their

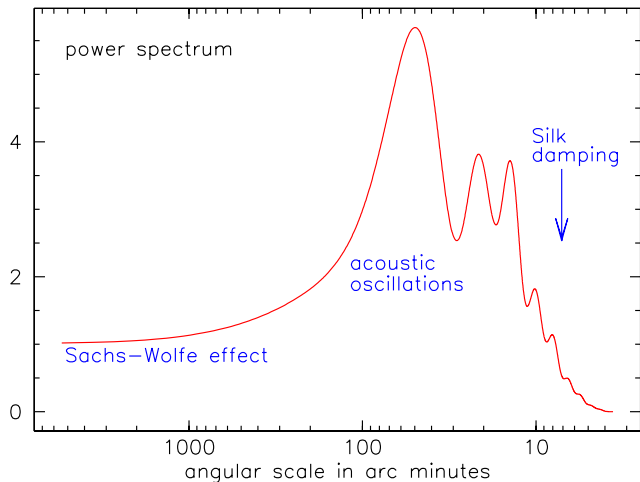


FIG. 2.—Example for a possible power spectrum of the cosmic microwave background. The abscissa indicates the size of structures in arc minutes, the ordinate is arbitrarily scaled. Following the convention, the size of the structures decreases from left to right. The flat part of the curve at large structures is caused by the Sachs-Wolfe effect. Between some ten and some 100 arc minutes, the acoustic oscillations produce the characteristic sequence of maxima and minima, which are suppressed towards even smaller scales by Silk damping. COBE observed at 420 and more arc minutes, hence in the pure Sachs-Wolfe part of the power spectrum.

absolute height and the depth of the valleys between them depend sensitively on the cosmological parameters. This means in turn that the cosmological parameters can be very accurately determined if only the power spectrum of the cosmic microwave background can be measured sufficiently precisely.

This fact is one of the main driving forces behind the modern experiments on the cosmic microwave background. Most of the cosmological parameters are not very accurately known today. Uncertainties of several ten per cent are common, and this situation is very unsatisfactory because virtually all cosmological theories depend on the cosmological parameters. As long as they are not accurately known, the predictive power and the testability of the theories remains limited.

The accuracy of cosmological parameters determinations based on the power spectrum depends critically on how many maxima and minima in the power spectrum are accessible to an experiment. The decisive quantity is the angular resolution of the observation, which is the smallest angular size which an experiment can identify and measure. Figures 2 and 3 imply that an angular resolution of a few arc minutes is enough to cover the entire region of acoustic maxima and minima. Towards even smaller angular scales, Silk damping suppresses the structures. In the microwave regime, an angular resolution of a few arc minutes is fantastically good. As mentioned, COBE had an angular resolution of seven degrees! In addition to a high angular resolution, the coverage of as much as possible of the sky is a crucial goal for present and future experiments.

MICROWAVE FOREGROUNDS

The cosmic microwave background is the oldest and most distant source on the sky which can be observed at all. Accordingly, its light had to cross the entire observable Universe before it could reach us. On this long way, a lot could happen to the photons of the microwave background, and photons of other types of source could mix with them.

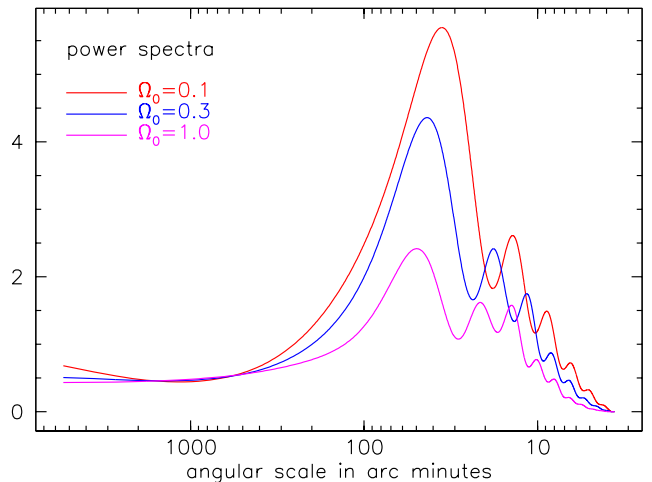


FIG. 3.—Power spectra of the cosmic microwave background for different values of the cosmic density parameter Ω_0 . The axes are identical to those of Fig. 2. With decreasing cosmic density, i.e. decreasing Ω_0 , the amplitude of the acoustic oscillations increases, and the maxima of higher order (to the right of the highest maximum) shift towards smaller angular size.

One example for such sources of “secondary” microwave radiation are distant galaxies, which emit a major fraction of their light in the infrared spectral range. Because of the expansion of the Universe, the wave length of the infrared radiation is stretched into the microwave regime before it finally reaches us. The distant galaxies are superimposed on the cosmic microwave background as point-like sources.

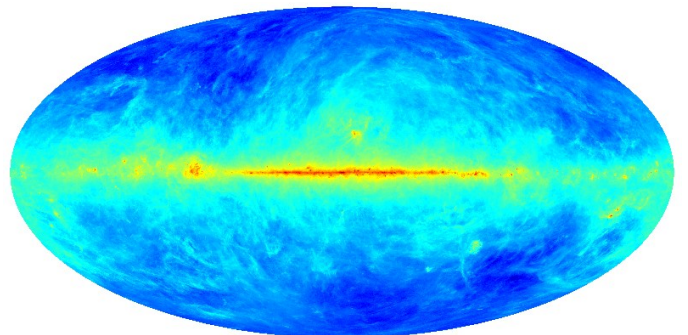


FIG. 4.—Infrared emission from warm dust in the Milky Way. The largest part of the emission comes from the plane of the Galactic disk, but dust is also observed at comparatively high Galactic latitudes.

Our Galaxy, the Milky Way, also emits microwave radiation. Three physically different process contribute to that, so that the appearance of the Milky Way in the microwave regime depends strongly on the frequency or wave length of the observation. Examples are given in Figures 4 and 5. Bodies in the Solar System also emit microwave radiation, for instance the Sun, the Moon, and the major planets.

On their way to us, the photons of the microwave background occasionally cross galaxy clusters which, apart from numerous galaxies, contain a large amount of hot gas. For cosmology, they are as important as index fossils because their evolution depends sensitively on the properties of the Universe. The hot gas in the galaxy clusters interacts with the photons of the microwave background through an effect called *Sunyaev-Zel'dovich effect* after its discoverers. It allows galaxy clusters to be identified even at large distance.

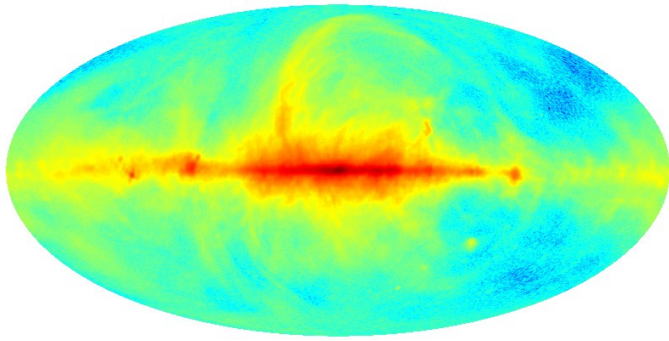


FIG. 5.—Radio emission by electrons in the Galactic magnetic field.

Of course, the microwave foregrounds and the cosmic microwave background must be separated from each other as carefully as possible in order to be able to analyse the different components separately. For that, it is very important that the spectra of the individual components are substantially different, so that the result of their mixing changes significantly with the frequency of the observation. For present and future observations of the microwave background, it is therefore very important that they not only cover as much of the sky as possible with high angular resolution, but also bridge as broad a spectral range as possible.

THE PLANCK SATELLITE

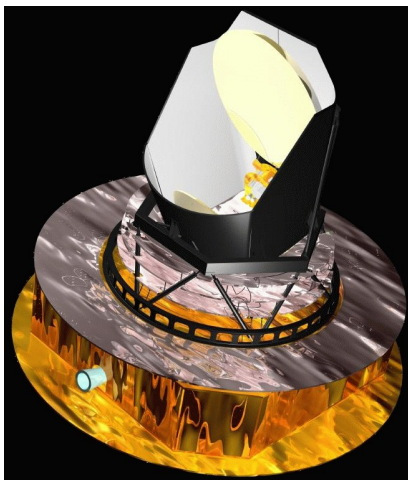


FIG. 6.—Schematic drawing of the *Planck* satellite. The primary mirror of the telescope can be seen above the centre; to its lower left is the secondary mirror. Right below the primary mirror is the focal plane, where both instruments are located. The total diameter of the satellite is just short of three metres.

The most ambitious current project to survey the microwave sky is the European *Planck* project. Its goal is to launch a satellite in 2007 which will observe the entire sky twice within two years. During that time, it will produce maps of the microwave background in nine different frequencies between 30 and 857 GHz, whose angular resolution approaches five arc minutes and whose relative accuracy reaches two parts per million. The sky maps to be produced by *Planck* will thus be 50 times more detailed and ten times more accurate than those COBE was able to supply. Even the angular resolution and the sensitivity of the American *MAP* satellite will be increased by *Planck*

by at least a factor of two. Moreover, *MAP* will observe in the frequency range between 22 and 90 GHz only.

EXPECTATIONS

The two satellite experiments *MAP* and *Planck* are faced with particularly far-reaching expectations. *MAP* will be launched in summer 2001 and will measure above all how the power spectrum of the cosmic microwave background behaves between the first and the third maximum. The relative locations and amplitudes of these three maxima will, among other things, reveal whether the so-called inflationary cosmology is correct.

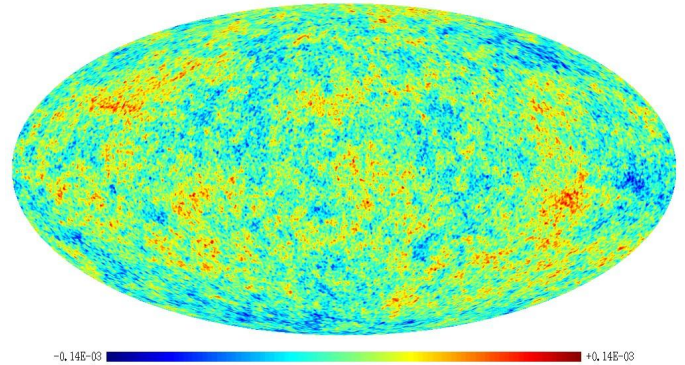


FIG. 7.—Simulated sky map of the temperature fluctuations in the cosmic microwave background at an angular resolution of 30 arc minutes.

Owing to its high angular resolution, *Planck* will be able to cover the entire power spectrum of the microwave background up to the scales which are suppressed by Silk damping. It will then be possible to measure all relevant cosmological parameters with accuracies close to a few parts in a thousand, which will mark an unprecedented progress compared to current knowledge.

Moreover, *Planck* will detect some ten thousand galaxy clusters and about the same number of active galaxies at large distances, i.e. in the still rather young Universe. *Planck* will provide exact maps of the dust, the magnetic field and the hot gas in the Milky Way, measure the microwave emission from the Solar System and possibly even detect asteroids and comets due to their microwave signals. There is currently one big unobserved gap in the complete electromagnetic spectrum between gamma rays and radio waves, and *Planck* will close it.

Besides exact cosmological information, *Planck* will provide a wealth of information which will substantially influence almost all branches of extragalactic research. Since *Planck* will close the last wide gap in the observed electromagnetic spectrum, there will be many surprises and new puzzles. It could of course also happen that the power spectrum of the cosmic microwave background turns out totally different from what we expect today. Even more interesting: Then, our entire picture of how structures form and evolve in the Universe would have to be thought over again. What ever *MAP* and *Planck* are going to reveal will cause a revolution in cosmology and extragalactic astrophysics.