KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Advanced information on the Nobel Prize in Physics 2006

# Cosmology and the Cosmic Microwave Background

## Cosmology and the Cosmic Microwave Background

The Universe is approximately about 13.7 billion years old, according to the standard cosmological Big Bang model. At this time, it was a state of high uniformity, was extremely hot and dense was filled with elementary particles and was expanding very rapidly. About 380,000 years after the Big Bang, the energy of the photons had decreased and was not sufficient to ionise hydrogen atoms. Thereafter the photons "decoupled" from the other particles and could move through the Universe essentially unimpeded. The Universe has expanded and cooled ever since, leaving behind a remnant of its hot past, the Cosmic Microwave Background radiation (CMB). We observe this today as a 2.7 K thermal blackbody radiation filling the entire Universe. Observations of the CMB give a unique and detailed information about the early Universe, thereby promoting cosmology to a precision science. Indeed, as will be discussed in more detail below, the CMB is probably the best recorded blackbody spectrum that exists. Removing a dipole anisotropy, most probably due our motion through the Universe, the CMB is isotropic to about one part in 100,000. The 2006 Nobel Prize in physics highlights detailed observations of the CMB performed with the COBE (COsmic Background Explorer) satellite.

### *Early work*

The discovery of the cosmic microwave background radiation has an unusual and interesting history. The basic theories as well as the necessary experimental techniques were available long before the experimental discovery in 1964. The theory of an expanding Universe was first given by Friedmann (1922) and Lemaître (1927). An excellent account is given by Nobel laureate Steven Weinberg (1993).

Around 1960, a few years before the discovery, two scenarios for the Universe were discussed. Was it expanding according to the Big Bang model, or was it in a steady state? Both models had their supporters and among the scientists advocating the latter were Hannes Alfvén (Nobel prize in physics 1970), Fred Hoyle and Dennis Sciama. If the Big Bang model was the correct one, an imprint of the radiation dominated early Universe must still exist, and several groups were looking for it. This radiation must be thermal, i.e. of blackbody form, and isotropic.

The discovery of the cosmic microwave background by Penzias and Wilson in 1964 (Penzias and Wilson 1965, Penzias 1979, Wilson 1979, Dicke et al. 1965) came as a complete surprise to them while they were trying to understand the source of unexpected noise in their radio-receiver (they shared the 1978 Nobel prize in physics for the discovery). The radiation produced unexpected noise in their radio receivers. Some 16 years earlier Alpher, Gamow and Herman (Alpher and Herman 1949, Gamow 1946), had predicted that there should be a relic radiation field penetrating the Universe. It had been shown already in 1934 by Tolman (Tolman 1934) that the cooling blackbody radiation in an expanding Universe retains its blackbody form. It seems that neither Alpher, Gamow nor Herman succeeded in convincing experimentalists to use the characteristic blackbody form of the radiation to find it. In 1964, however, Doroshkevich and Novikov (Doroshkevich and Novikov 1964) published an article where they explicitly suggested a search for the radiation focusing on its blackbody characteristics. One can note that some measurements as early as 1940 had found that a radiation field was necessary to explain energy level transitions in interstellar molecules (McKellar 1941). Following the 1964 discovery of the CMB, many, but not all, of the steady state proponents gave up, accepting the hot Big Bang model. The early theoretical work is discussed by Alpher, Herman and Gamow 1967, Penzias 1979, Wilkinson and Peebles 1983, Weinberg 1993, and Herman 1997.

Following the 1964 discovery, several independent measurements of the radiation were made by Wilkinson and others, using mostly balloon-borne, rocket-borne or ground based instruments. The intensity of the radiation has its maximum for a wavelength of about 1 mm where the absorption in the atmosphere is strong. Although most results gave support to the blackbody form, few measurements were available on the high frequency (low wavelength) side of the peak. Some measurements gave results that showed significant deviations from the blackbody form (Matsumoto et al. 1988).

The CMB was expected to be largely isotropic. However, in order to explain the large scale structures in the form of galaxies and clusters of galaxies observed today, small anisotropies should exist.  Gravitation can make small density fluctuations that are present in the early Universe grow and make galaxy formation possible. A very important and detailed general relativistic calculation by Sachs and Wolfe showed how three-dimensional density fluctuations can give rise to two-dimensional large angle ($> 1°$) temperature anisotropies in the cosmic microwave background radiation (Sachs and Wolfe 1967).


Because the earth moves relative to the CMB, a dipole temperature anisotropy of the level of $\Delta T/T = 10^{-3}$ is expected. This was observed in the 1970's (Conklin 1969, Henry 1971, Corey and Wilkinson 1976 and Smoot, Gorenstein and Muller 1977). During the 1970-ties the anisotropies were expected to be of the order of $10^{-2} – 10^{-4}$, but were not observed experimentally. When dark matter was taken into account in the 1980-ties, the predicted level of the fluctuations was lowered to about $10^{-5}$, thereby posing a great experimental challenge.

### *The COBE mission*
Because of e.g. atmospheric absorption, it was long realized that measurements of the high frequency part of the CMB spectrum (wavelengths shorter than about 1 mm) should be performed from space. A satellite instrument also gives full sky coverage and a long observation time. The latter point is important for reducing systematic errors in the radiation measurements. A detailed account of measurements of the CMB is given in a review by Weiss (1980).

The COBE story begins in 1974 when NASA made an announcement of opportunity for small experiments in astronomy. Following lengthy discussions with NASA Headquarters the COBE project was born and finally, on 18 November 1989, the COBE satellite was successfully launched into orbit. More than 1,000 scientists, engineers and administrators were involved in the mission. COBE carried three instruments covering the wavelength range 1 μm to 1 cm to measure the anisotropy and spectrum of the CMB as well as the diffuse infrared background radiation: DIRBE (Diffuse InfraRed Background Experiment), DMR (Differential Microwave Radiometer) and FIRAS (Far InfraRed Absolute Spectrophotometer). COBE's mission was to measure the CMB over the entire sky, which was possible with the chosen satellite orbit. All previous measurements from ground were done with limited sky coverage. John Mather was the COBE Principal Investigator and the project leader from the start. He was also responsible for the FIRAS instrument. George Smoot was the DMR principal investigator and Mike Hauser was the DIRBE principal investigator.

For DMR the objective was to search for anisotropies at three wavelengths, 3 mm, 6 mm, and 10 mm in the CMB with an angular resolution of about 7°. The anisotropies postulated to

explain the large scale structures in the Universe should be present between regions covering large angles. For FIRAS the objective was to measure the spectral distribution of the CMB in the range 0.1 – 10 mm and compare it with the blackbody form expected in the Big Bang model, which is different from, e.g., the forms expected from starlight or bremsstrahlung. For DIRBE, the objective was to measure the infrared background radiation. The mission, spacecraft and instruments are described in detail by Boggess et al. 1992. Figures 1 and 2 show the COBE orbit and the satellite, respectively.

COBE was a success. All instruments worked very well and the results, in particular those from DMR and FIRAS, contributed significantly to make cosmology a precision science. Predictions of the Big Bang model were confirmed: temperature fluctuations of the order of $10^{-5}$ were found and the background radiation with a temperature of 2.725 K followed very precisely a blackbody spectrum. DIRBE made important observations of the infrared background. The announcement of the discovery of the anisotropies was met with great enthusiasm worldwide.
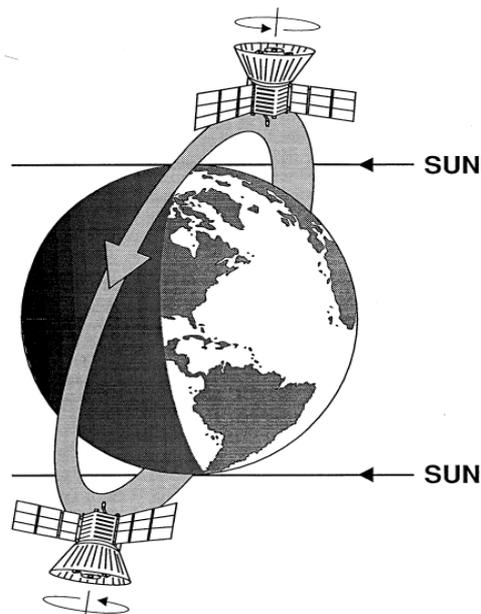


Fig. 1. Schematic view of COBE in orbit around the earth. The altitude at insertion was 900 km. The axis of rotation is at approximately 90° with respect to the direction to the sun. From Boggess et al. 1992.
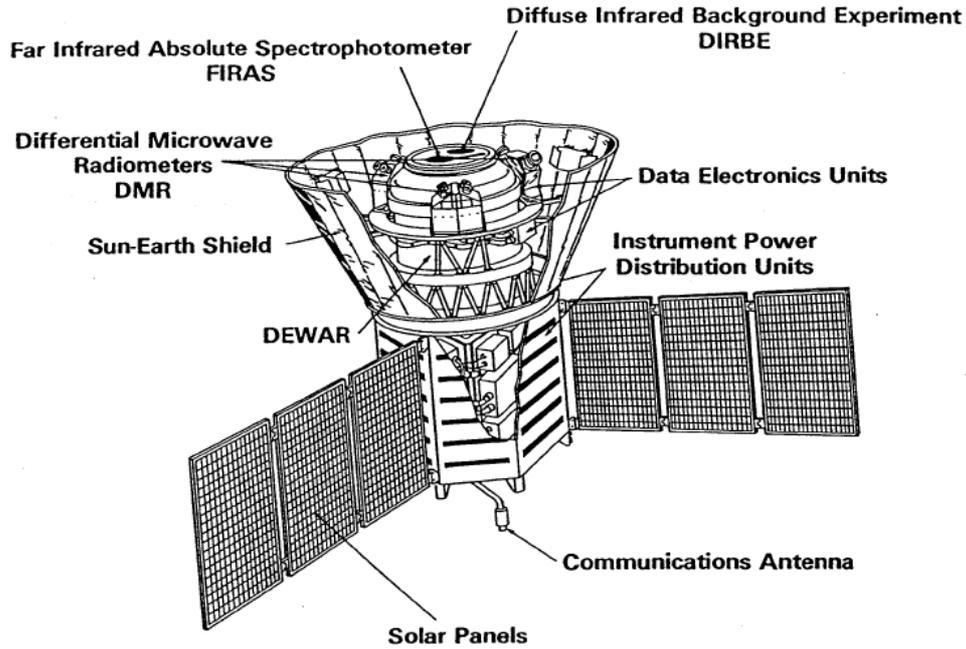
Fig. 2. The COBE satellite with the three instruments DIRBE, DMR and FIRAS. Width with solar panels deployed 8.5 m, height 5.5 m and weight 2,300 kg. FIRAS and DIRBE were cooled to 1.8 K using liquid helium. From Boggess et al. 1992.

The DMR collected the flux by corrugated horns aimed at parts of the sky 60° apart. Dicke-switched (see Dicke 1946) differential microwave radiometers measured the brightness difference in these two directions. The DMR signal flow is shown in figure 3. A detailed account of the DMR instrument can be found in Smoot et al. 1990.
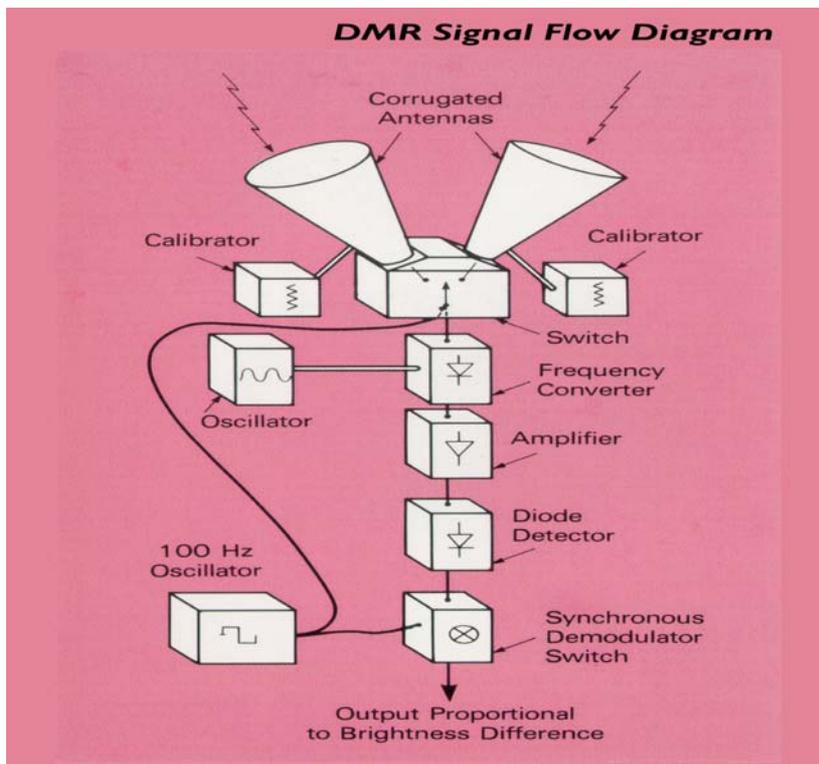


Fig. 3. The DMR signal flow diagram. There were six differential radiometers, two for each wavelength. Each pair had detectors separated by 60°. From lambda.gsfc.nasa.gov/product/cobe
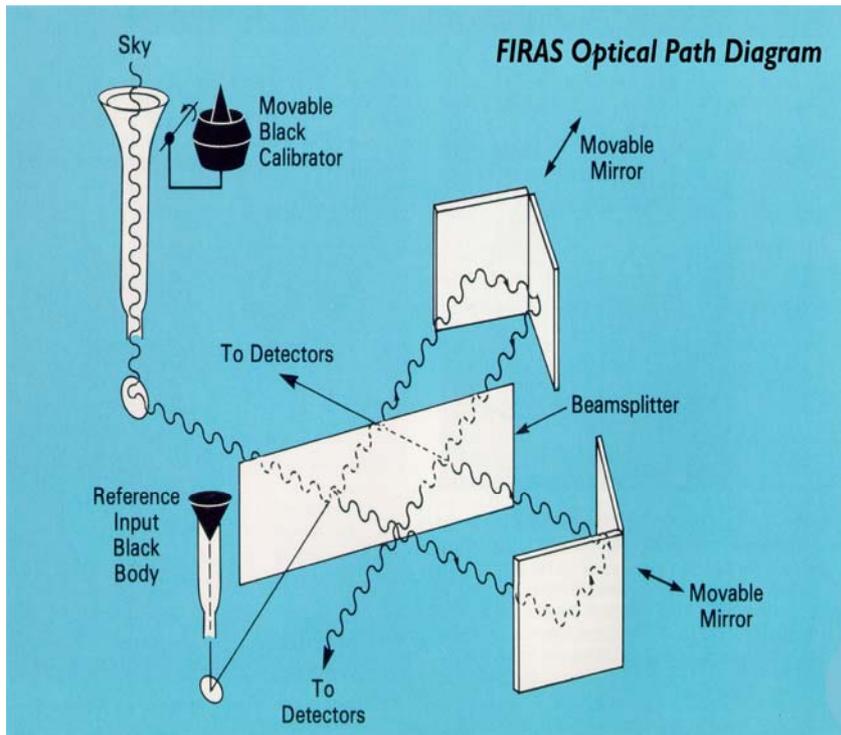
Fig. 4. The FIRAS optical path diagram. From lambda.gsfc.nasa.gov/product/cobe

FIRAS had two separate interferometers measuring the difference between the sky signal and an on-board blackbody calibrator (Mather 1982). The flux was collected by a flared horn. The FIRAS path diagram is shown in figure 4.

## *Anisotropies*

The DMR instrument (Smoot et al. 1990) measured temperature fluctuations of the order of $10^{-5}$ for three CMB frequencies, 90, 53 and 31.5 GHz (wavelengths 3.3, 5.7 and 9.5 mm), chosen near the CMB intensity maximum and where the galactic background was low. The angular resolution was about 7°. After a careful elimination of instrumental background, the data showed a background contribution from the Milky Way, the known dipole amplitude $\Delta T/T = 10^{-3}$ probably caused by the Earth's motion in the CMB, and a significant long sought after quadrupole amplitude, predicted in 1965 by Sachs and Wolfe. The first results were published in 1992.The data showed scale invariance for large angles, in agreement with predictions from inflation models.

Figure 5 shows the measured temperature fluctuations in galactic coordinates, a figure that has appeared in slightly different forms in many journals. The RMS cosmic quadrupole amplitude was estimated at $13 \pm 4$ μK ($\Delta T/T = 5\times10^{-6}$) with a systematic error of at most 3 μK (Smoot et al. 1992). The DMR anisotropies were compared and found to agree with models of structure formation by Wright et al. 1992. The full 4 year DMR observations were published in 1996 (see Bennett et al. 1996). COBE's results were soon confirmed by a number of balloon-borne experiments, and, more recently, by the 1° resolution WMAP (Wilkinson Microwave Anisotropy Probe) satellite, launched in 2001 (Bennett et al. 2003).
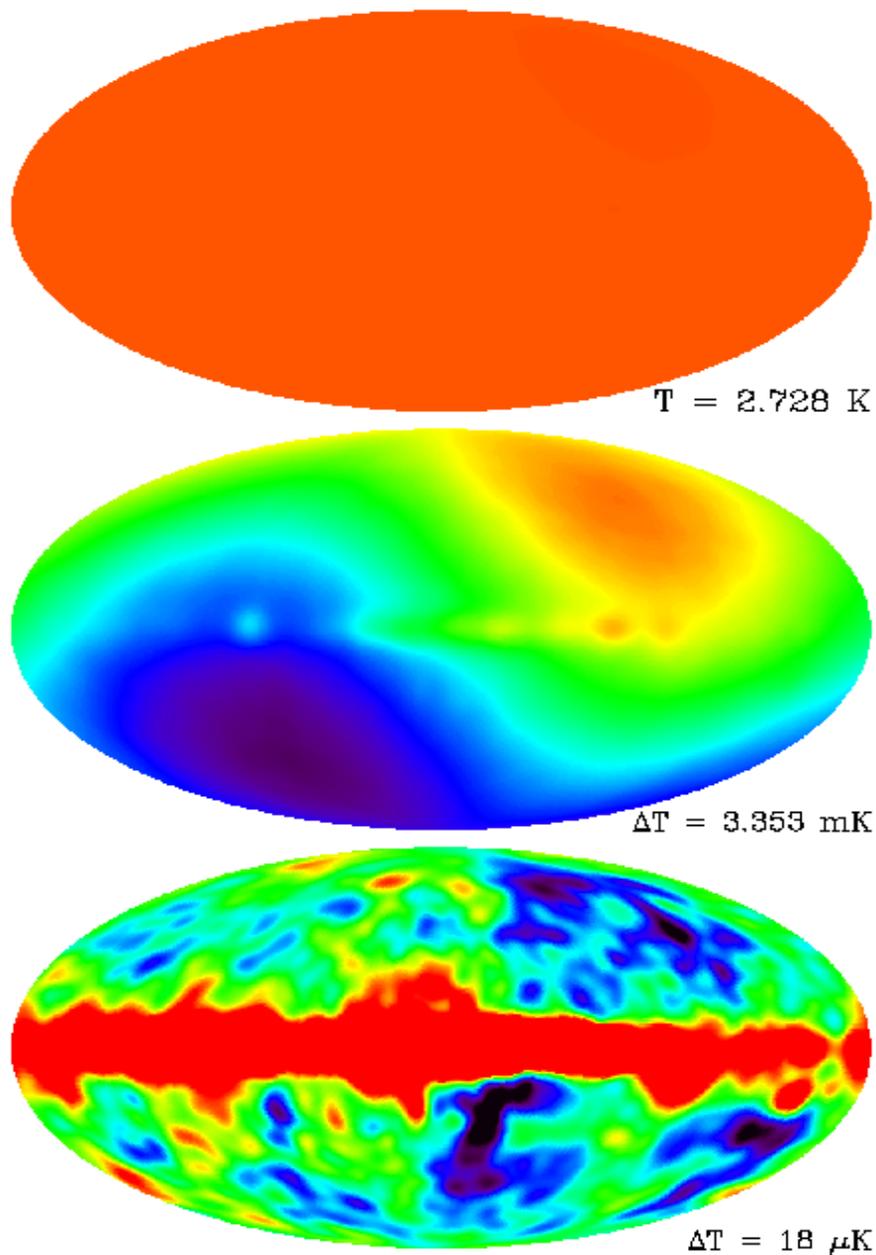
Fig. 5. DMR results (Smoot et al. 1992, http://lambda.gsfc.nasa.gov/product/cobe/ ) in galactic coordinates (horizontally longitude from + 180° to -180°, vertically latitude from + 90° to -90°, centre approximately on the Milky Way centre. The data from the 53 GHz band (6 mm wavelength) showing the near uniformity of the CMB (top), the dipole (middle) and the quadrupole and higher anisotropies with the dipole subtracted (bottom). The relative sensitivities from top to bottom are 1, 100 and 100,000. The background from the Milky Way, not following a blackbody spectrum (visible as a horizontal red band in the bottom panel), has not been subtracted.

Most models for structure formation predict that the temperature variations should follow a Gaussian distribution for large angles (corresponding to the DMR measurements). In inflation based models the Gaussian distribution originates from primordial quantum fluctuations. COBE's DMR data showed Gaussian, near scale-invariant temperature fluctuations and in that sense provides support for inflation models (Kogut et al. 1996).

## *Blackbody spectrum*

The FIRAS instrument (Mather et al. 1982) measured the CMB spectrum in the wavelength range 0.1 – 10 mm and proved it to follow a blackbody form with high precision. Figure 6 shows the first FIRAS results in the wavelength range 0.5 – 5 mm (Mather et al. 1990), obtained after only nine minutes. The data follow perfectly a blackbody spectrum with the temperature $2.735 \pm 0.060$ K. At the time this was a surprising discovery, because of earlier measurements (e.g. Matsumoto et al. 1988 at 0.5 and 0.8 mm) that had shown very significant departures from a blackbody form and thereby cast doubt on the Big Bang model.

Figure 7 shows the deviations from a blackbody spectrum with a temperature of $2.726 \pm 0.010$ K published 1994 (Mather et al. 1994). After careful studies of errors caused by the FIRAS calibrator (figure 4), the CMB temperature was finally given as $2.725 \pm 0.002$ K (Mather et al. 1999) with deviations from a blackbody spectrum less than 1 part in $10^5$.
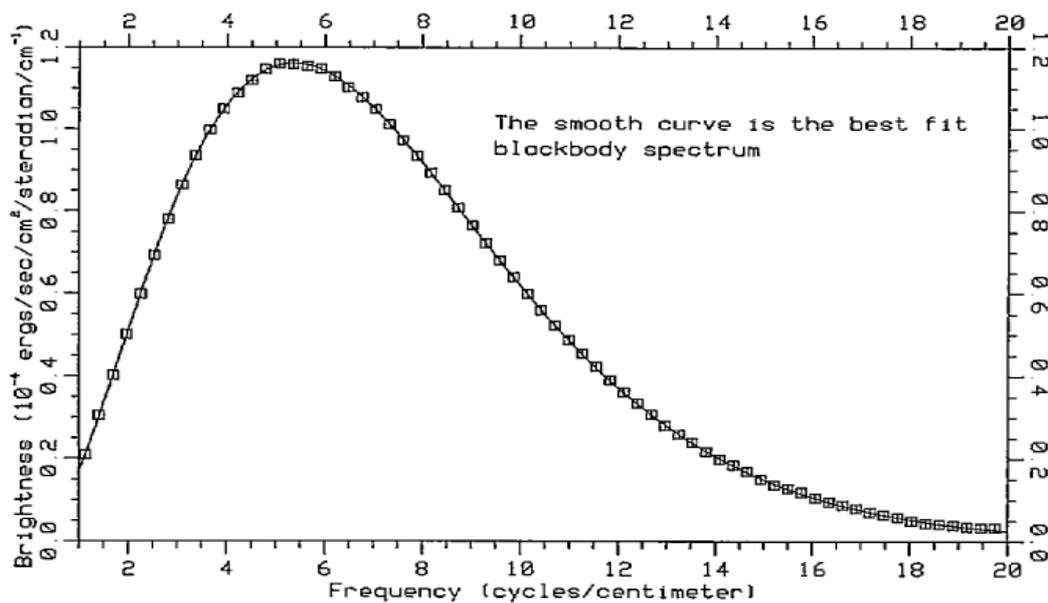


Fig. 6. The first FIRAS result (Mather et al. 1990). Data had been accumulated during nine minutes in the direction of the northern galactic pole. The small squares show measurements with a conservative error estimate of 1%. The unit along the vertical axis is erg (cm s sr)$^{-1}$. The relation to SI units is 1 MJy sr$^{-1}$ = $2.9979 \cdot 10^{-7}$ erg (cm s sr)$^{-1}$. The full line is a fit to the blackbody form.
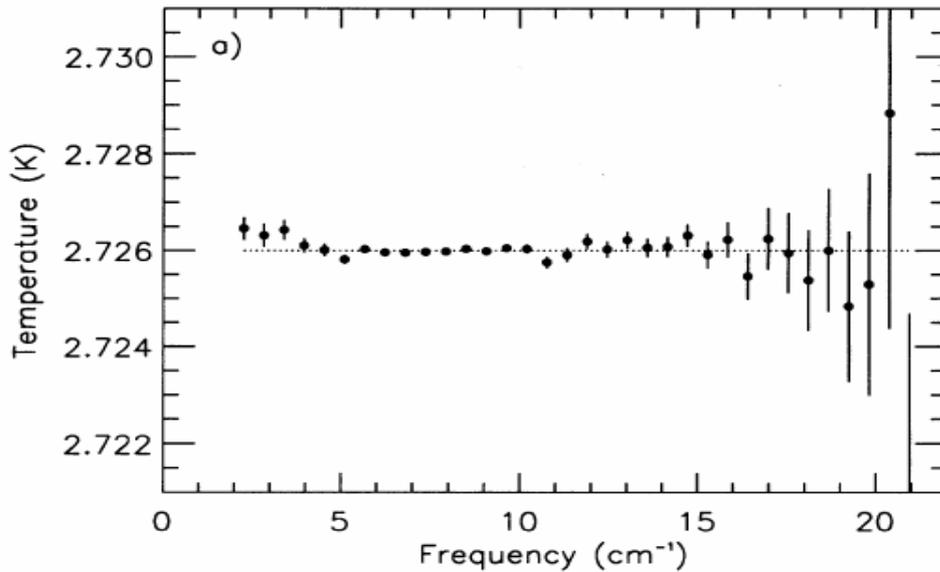
Fig. 7. Results from FIRAS published 1994 (Mather et al. 1994). Data points show deviations from a blackbody spectrum with the temperature 2.727 K (final result for the temperature is 2.725 ± 0.002 K, Mather et al. 1999). Largest deviations were 0.03% of the maximum radiation. From Mather et al.1994.

In the early Universe, matter and radiation were in thermal equilibrium and the blackbody form was unaffected by the expansion provided that energy was not released (e.g. photons from particle decays or from small black holes). The observed very precise blackbody form gives strong limits on such energy release (Wright et al. 1994). The absolute value of the blackbody temperature is one of the best determined cosmological parameters.

## *Outlook*

The 1964 discovery of the cosmic microwave background had a large impact on cosmology. The COBE results of 1992, giving strong support to the Big Bang model, gave a much more detailed view, and cosmology turned into a precision science. New ambitious experiments were started and the rate of publishing papers increased by an order of magnitude.

Our understanding of the evolution of the Universe rests on a number of observations, including (before COBE) the darkness of the night sky, the dominance of hydrogen and helium over heavier elements, the Hubble expansion and the existence of the CMB. COBE's observation of the blackbody form of the CMB and the associated small temperature fluctuations gave very strong support to the Big Bang model in proving the cosmological origin of the CMB and finding the primordial seeds of the large structures observed today.

However, while the basic notion of an expanding Universe is well established, fundamental questions remain, especially about very early times, where a nearly exponential expansion, *inflation*, is proposed. This elegantly explains many cosmological questions. However, there areother competing theories. Inflation may have generated gravitational waves that in some cases could be detected indirectly by measuring the CMB polarization. Figure 8 shows the different stages in the evolution of the Universe according to the standard cosmological model. The first stages after the Big Bang are still speculations.
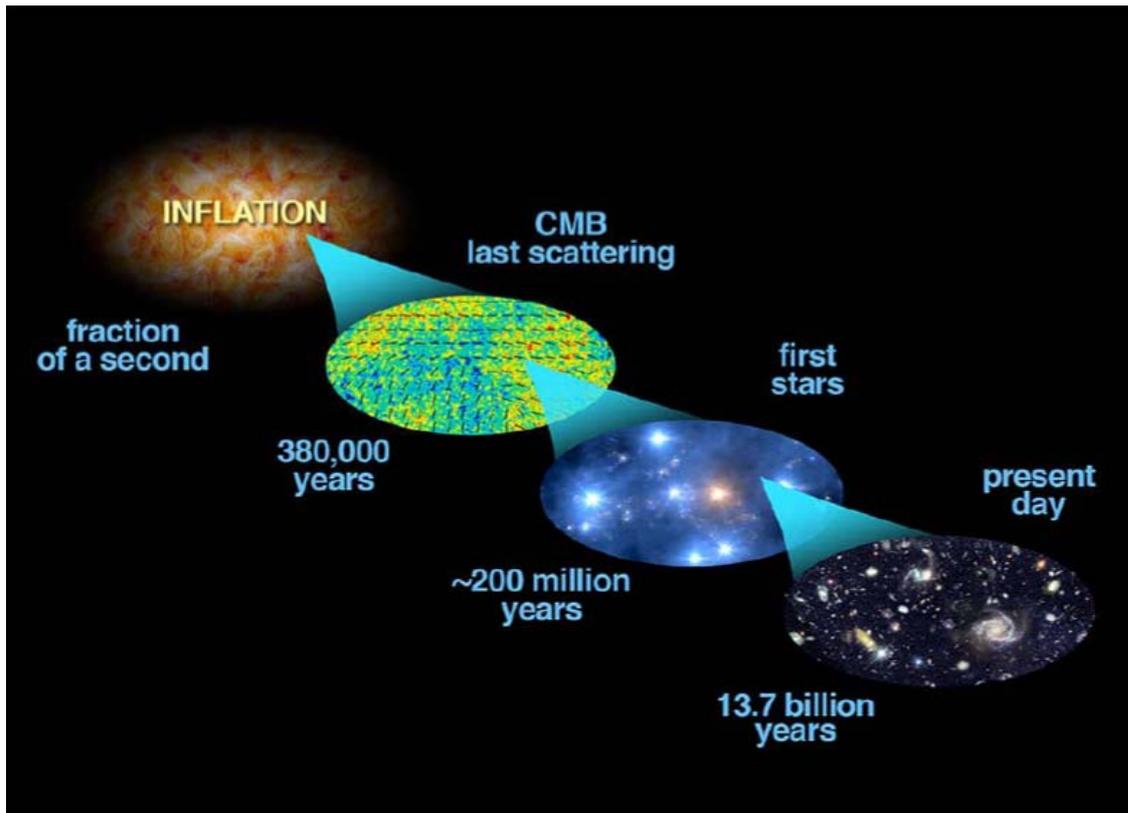
Fig. 8. Stages in the evolution of the Universe. From Task Force On Cosmic Microwave Background Research, National Academies 2005.

The observations of the CMB by many experiments, including the WMAP satellite with a much better angular resolution than COBE, have yielded a wealth of cosmological information. When combined with other experiments, one may be able to estimate the amount of dark matter in the Universe. Here there is a strong link with particle physics, and in particular the Large Hadron Collider accelerator at CERN which may soon show evidence for new particles, such as supersymmetric particles that can account for the dark matter, created in the very early Universe.

## *References*

http://lambda.gsfc.nasa.gov/product/cobe/
Mather, J.C. and Boslough, J. 1996: *the very first light* (BasicBooks 1996)
Smoot, G. and Davidson, K. 1993: *Wrinkles In Time* (Little, Brown and Company, London 1993)

Alpher R.A. & Herman R.C. 1949 Phys. Rev. 75, 1089
Alpher R.A., Herman R.C. & Gamow G. 1967 Proc. Nat. Sci. USA 58, 2179
Bennett, C.L. et al. 1996, Astrophys. J.(Letters) 464, 1 (4-year cobe DMR results)
Bennet, C.L. et al. 2003, Astrophys. J. Suppl. 148, 1
Boggess, N.W. et al. 1992, Astrophys. J. 397, 420
Conklin, E.K. 1969, Nature 222, 971
Corey, B.E. and Wilkinson, D.T. 1976, BAAS 8, 351
Dicke, R.H. 1946, Rev. Sci. Instr. 17, 268
Dicke, R.H. et al. 1965, Astrophys. J. (Letters) 142, 414
Doroshkevich, A.G. and Novikov, I.D. 1964, Sov. Phys. Doklady 9, 111.

Fixsen, D.J. et al. 1996, Astrophys. J.473, 576, [astro-ph/9605054]

Friedmann, A. 1922, Z. Phys. 10, 377

Gamow G. 1946, Phys. Rev. 70, 572

Henry, P.S. 1971, Nature 231, 561

Herman, R. 1997 The Prediction of the Cosmic Microwave Background Radiation in
Proc. of the George Gamow Symposium, George Washington University 12 April 1996 (Ed.
E. Harper et al., Astronomical Society of the Pacific Conference Series no. 129) p. 71

Kogut, A. 1996, Astrophys. J (Letters) 464, 29

Lemaître, G. 1927, Annales de la Société Scientifique de Bruxelles, Tome XLVII, série A, 49

Mather, J.C. 1982, Opt. Eng. 21, 769

Mather, J.C. et al. 1990, Astrophys. J. (Letter) 354, 37

Mather, J.C. 1994, Astrophys. J. 420, 440

Mather, J.C. et al. 1999, Astrophys. J 512, 511

Matsumoto T. et al. 1988, Astrophys. J. 329, 567

McKellar, A.1941, Publ. Dominion Astrophys. Obs. 7, 251

Penzias, A.A. 1979 The Origin of Elements, Les Prix Nobel, 444

Penzias, A.A. and Wilson, R.W. 1965, Astrophys. J (Letters) 142, 419

Sachs, R.K. and Wolfe, A.M. 1967, Astrophys. J. 147, 73

Smoot, G.F., Gorenstein, M.V. and Muller, R.A. 1977, Phys. Rev. Lett. 39, 898

Smoot, G. et al. 1990 Astrophys. J 380, 685

Smoot, G. et al. 1992 Astrophys. J (Letters) 396, 1

Tolman, R.C. 1931, Phys. Rev. 37, 1639

Weinberg, S. 1993: The First Three Minutes, 2nd edition (BasicBooks 1988&1993)

Weiss, R. 1980 Ann. Rev. Astron. Astrophys. 18, 490

Wilkinson, D.T. and Peebles, P.J.E. 1983, in Serendipitous Discoveries in Radio Astronomy
(National Radio Astronomy Observatory, Green Bank WV 1983) s. 175.

Wilkinson, D.T. and Peebles, P.J.E. 2000, Proceedings of Nobel Symposium 109, Enköping
1998, (Eds. L. Bergström, P. Carlson and C. Fransson) Physica Scripta T85,136

Wilson, R.W. 1979 The Cosmic Microwave Background Radiation, Les Prix Nobel, 463

Wright, E.L. et al. 1992, Astrophys. J. (Letters) 396, 13

Wright, E.L. et al. 1994, Astrophys. J. 420, 450