Lecture 5. Cosmic Microwave Background (CMB) radiation

CONTENT

A G Polnarev. Mathematical aspects of cosmology (MAS347), 2009. Week 2. PART I. A non Mathematical Introduction. Lecture 5. Cosmic Microwave Background (CMB) radiation. 5.1. Discovery of CMB.5.2. Fluctuations in CMB.

5.1. Discovery of CMB

The CMB radiation was discovered in 1965. Penzias and Wilson shared the 1978 Nobel prize in physics for this discovery. The CMB is the relic radiation left over from the hot Big Bang. Its temperature,

$$T = 2.725 \text{ Kelvin}, \tag{1}$$

is extremely uniform all over the sky. The energy (or frequency) spectrum of this radiation corresponds to black-body radiation (Fig.5.1). At the present moment the error bars on the data points are so small that they can not be seen on the curve predicted by the Big Bang theory (see Fig. 5.2) and there is no alternative theory yet proposed which predicts the same energy spectrum, hence the measurement of the CMB spectrum is the test of the Big Bang theory of expanding Universe.

It is known that approximately 400,000 years after the Big Bang the temperature of the CMB dropped below $3000K$. Starting from this moment photons of the CMB had the average energy so small that they could not prevent protons and electrons from forming neutral hydrogen. Then the CMB photons interacted very weakly with neutral hydrogen. In other words, starting from this moment the Universe started to be opaque for the CMB photons. If we look at different directions over sky we can see back to this moment of time only. It seems that we see some sort of a surface which, as we know from the previous lecture, is called the surface of the last scattering since it was the last time most of the CMB photons scattered by free electrons. All maps of the temperature of the CMB can be considered as direct images of this surface of last scattering(Fig. 5.3). [See WMAP site).]

5.2. Fluctuations in CMB

For a long time after its discovery the CMB radiation did seem to be uniform over sky. When observational technology improved, dipole anisotropy was detected (seeFig.5.4). This anisotropy is related to the peculiar velocity of the Earth (the Sun), v with respect to the CMB, i.e. relative to the frame of reference in which the CMB has no dipole anisotropy:

$$\frac{\delta T_D}{T} \sim \frac{v}{c} \approx 10^{-3}, \tag{2}$$

Approximately 20 years later, in 1992, the Cosmic Background Explorer (COBE) satellite detected cosmological fluctuations in the microwave background temperature (see Fig.5.5).

Mather and Smoot received the 2006 Nobel Prize in Physics for their discovery of the black-body spectrum and the anisotropy of the CMB radiation using the Cosmic Background Explorer (COBE).

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Only very sensitive instruments, such as the COBE and even more sensitive the WMAP, can detect tiny fluctuations in the cosmic microwave background temperature. These fluctuations brings direct information about the physical conditions in the very early Universe, about the nucleosynthesis (i.e. origin of chemical elements) and the origin of galaxies and formation of the Large Scale Structure of the Universe, in order words, with the help of the CMB fluctuations one can determine the basic parameters of the Big Bang theory. It is possible to say that any map of the CMB temperature is a direct image of the remote past of our Universe (see lecture 1 about an astronomical time machine).
These small temperature variations (fluctuations), δT

$$\frac{\delta T}{T} \sim 10^{-5}, \tag{3}$$

contain extremely valuable information about the origin, evolution, and content of the universe. These cosmic microwave temperature fluctuations are believed to trace fluctuations in the density of matter in the early universe, as they were imprinted shortly after the Big Bang.

The "angular spectrum" of the fluctuations (obtained by the expansion of temperature field over spherical harmonics) in the WMAP full-sky map shows the relative brightness of the "spots" in the map vs. the size or multipole numbers l **in expansion of the temperature anisotropy over spherical functions. The shape of this curve contains important information about the history of the Universe (see Fig.5.6).**

Thus the CMB has a very exiting history [Fig.5.7.) But this is not the end of the story.

5.3. Polarization of CMB

A more detailed picture of the early Universe is obtained if we measure the polarization of the CMB. This polarization is unavoidably generated due to scattering of the CMB photons on free electrons during the epoch of highly ionized plasma. This polarization was measured first on the South Pole in 2002 (see Fig. 5.8).

The first map of polarization looks like that Fig. 5.9.
WMAP has produced polarization maps over the whole sky. See Fig. 5.10.
Colors indicate "warmer" (red) and "cooler" (blue) spots, the bars show the "polarization" direction of the CMB. The new information obtained with the help of polarization measurements and some theoretical models provides new clues about events which took place when the the age of the Universe was only tiny fraction of second.