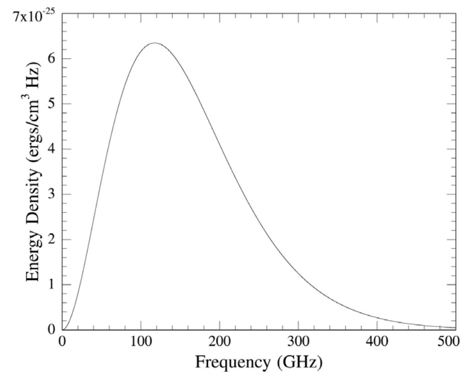
PHYS 210
Spring 2006
Experimental Cosmology

The goal of Cosmology is to understand the physical history of our Universe, how it formed and developed, why does it have certain characteristics and how will it evolve in the future. Cosmology draws heavily on particle physics and astronomical observations. We will discuss just one such observation, the Cosmic Microwave Background (CMB).

1. Black Body Radiation

Black body radiation is a simple consequence of equipartition of thermal energy. At a temperature *T* each degree of freedom, including each quantum mode of electromagnetic field, has an average thermal energy equal to *kT*/2. It can be shown that the energy density as a function of temperature is given by

$$u(\nu, T) = \frac{8\pi h \nu^3}{c^3} \frac{1}{e^{h\nu/kT} - 1}.$$



The spectrum of the radiation is shown on the right for a temperature of 2 K. The frequency of the maximum energy density depends linearly on the temperature, $\nu_{max} = 59\,\text{GHz}\,T(K)$. For example, at room temperature (~300 K) the maximum occurs at about 2×10^{13} Hz or wavelength of 17 μm, in the far infrared and at 6000 K, which is the temperature of the Sun, the peak is in the visible range. At low frequencies, when $h\nu/kT \ll 1$, the energy density is proportional to the temperature. As the name suggests, the black body radiation is only emitted by "black", i.e. not transparent objects, which absorb and emit the radiation in equilibrium with their own temperature. The black body radiation can be used for non-contact temperature measurements. Infrared thermometers based on this principle are easily available.

2. Evolution of the Universe

The universe started in a very hot and dense state immediately after the Big Bang. In this state photons as well as all other particles were thermal equilibrium. Eventually the Universe expanded and cooled until the electrons and protons combined into neutral atoms and the Universe became transparent to light. The black body radiation photons that existed at that time, about 390,000 years after the Big Bang, continued to propagate freely through the Universe. As the Universe continued to expand the wavelength of the photons increased and their temperature dropped. Today, after 13.7 billion years, the temperature of the cosmic black body radiation is 2.7K. The radiation is nearly uniform in all directions, but not perfectly so. Small temperature fluctuations, about 1 part in 10^4, exist due to initial density fluctuations that eventually developed into stars and galaxies that we see today. In fact, the spectrum of these fluctuations, recently measured with exquisite precision by the Wilkinson Microwave Anisotropy Probe constructed at Princeton, tells us a lot about the properties of our Universe.

3. Measurement of the microwave radiation

Radiation in this range is measured using electronic technology. However, because the wavelength of the radiation is very short (millimeters to centimeters), great care is needed in construction of the electronics. Every piece of wire becomes an inductor or an antenna. Fortunately, microwave technology is fairly mature and compact amplifiers, filters and other components are easily available commercially. We will use a simple combination of these components to measure the energy density of the radiation at 10 GHz. At this frequency, the energy is directly proportional to the temperature. However, one has to take into account the amplifier noise, reflection of microwaves and other systematic uncertainties. By careful calibration of the detector at several temperatures one can make an absolute measurement of the present temperature of the Universe.