Final Report on the

Measurement of the temperature of the Cosmic Microwave Background

Toward fulfilling the requirements of PHY 210

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In this report, I present the results of my investigations of the temperature of the cosmic microwave background using the apparatus developed for this purpose in the PHY 210 laboratories.

Background information

The CMB is a practically isotropic radiation in the microwave region that is observed almost completely uniformly in all directions. This radiation is understood to be the radiation emitted by the universe at an early period of its history. It then gives us a snapshot of the universe at this early period - only three hundred thousand years old. This is the time when the universe finally became cold enough for neutral atoms to form from their nucleons and electrons, about 3000 K. Before this time / temperature, any neutral atoms formed could immediately be re-ionized by the high-energy radiation. Once a low enough temperature is reached, ions and electrons can effectively combine to form neutral atoms. As such, the universe is no longer opaque to radiation – as atoms become neutral, matter and radiation decouple, so that photons no longer keep scattering off the ions. When we examine the CMB, we look back to the time when light last interacted significantly with matter. In other words, the microwave background is really the light off the last scatterings, and gives the so-called Surface of Last Scattering. As the universe expands and cools, the wavelength of this light increases by stretching out, so that the radiation is red-shifted, into the microwave region.

The isotropy of this radiation is quite remarkable – it exhibits a constancy of temperature to within one part in a thousand in all directions. Further, the spectrum corresponds almost perfectly to that of a blackbody at that temperature. As such, the first observations of the background lent strong support to the Big Bang picture of cosmology. More recently, attention has focused on measuring the anisotropy of the microwave background, which gives invaluable information on the conditions of the early universe, including its geometry, the fluctuations that eventually spawn today's galaxies, its expansion rate, nature of dark matter, and so on.

Black Body

It is useful here to elaborate somewhat on the theory of the Black Body.

A perfect black body is a perfect absorber of light, so that it reflects none of it. Following the general principle of good absorbers also being good emitters, such a black body also re-emits the absorbed energy. In steady state, the black body re-emits all the absorbed energy in a spectrum that depends only on the temperature of the black body. In particular, the wavelength of maximum intensity depends on the temperature, in a relation given by *Wein's Displacement Law*:

$$T\lambda_{max} = a, \; a = 0.29 \text{ cm K approx}$$

Hence, as the temperature of a body is raised it radiates energy as shorter and shorter wavelengths. It is important to note, that anisotropy notwithstanding, the CMB behaves as an almost perfect Black body. Indeed, it is a better approximation to the blackbody than any made in the lab.

Planck's Law:

A result of central importance in the theory of the black body is the celebrated *Planck's Law*, which relates the energy density to the temperature and the frequency. It is this formula that resolves the old problem of Black Body Radiation, viz. the apparently infinite energy that should be radiated.

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

here,

T – temperature, ν -- frequency, h – Planck's constant, c – Speed of Light, k – Boltzmann's Constant

A low temperature approximation of this formula consists of a leading order series expansion, giving

$$\rho(\nu, T) = \frac{8\pi k \nu^2}{c^3} T = K T$$

This approximation is sufficiently precise for our purposes: at 10 GHz, the frequency of our observations, the relative error of this approximation is ~ 0.0008 at 300 K, 0.06 at 4 K.

It is a matter of some concern that this relative error actually rises with the decrease of temperature; however, for our purposes this level of precision is tolerable. To reduce this effect of decreasing the temperature, observations can be made at a different frequency.

Experimental Procedure and Related Issues:

For this measurement of the CMB temperature, the equipment consists of a receiver for 10 GHz which receives the signal, a series of amplifiers that amplify the signal, which is then converted to a voltage reading (a few milli Volt typically) on screen.

Based on the approximation to Planck's Law derived above, we expect the voltage – temperature plot to be linear, so that the slope yields the change in voltage per rise in temperature. As such, by measuring the voltage readings for black bodies at different temperatures, we can obtain this line. Then, by obtaining the voltage reading for the microwave background, we can find the corresponding temperature from the best-fit line.

We use voltage readings for black bodies at room temperature, liquid nitrogen 77 K, and liquid helium at 4.2 K.

Absorbers: For this procedure to work, we need to 'see' the temperature spectra of a blackbody. As such, the receiver must be pointed at a black body at the different temperatures. For this purpose, we use different commercially available microwave absorbers. By maintaining these absorbers at a certain temperature, we can thus observe the black body spectrum at that temperature.

In this experiment we used three types of absorbers – an absorber that works at a broader range of frequencies and has low coefficient of reflection, one that is optimal for the 10 GHz but has a higher coefficient of reflection at glancing incidence, and an absorber of the same material as the first type but which is corrugated, reducing the angle of incidence and increasing the effective surface of absorber seen by the receiver.

It was observed that to the degree of precision attained by this experiment, the precise type of absorber had no significant effect. One assumes that the second absorber works better at 10 GHz but this effect is counterbalanced by its comparative ineffectiveness at glancing incidences.

Minimize external light: In addition to reducing reflection by using high quality absorbers, it is desirable to minimize the external light impinging on the system, so that the black body spectrum predominates. To this effect, the receiver-absorber setup was wrapped in reflecting aluminum foil. It is noted that the use of high quality commercial absorbers partially negates the need for such foil, though the foil still makes a measurable difference.

Reflection from container, liquid surface: The liquid nitrogen, helium readings are made in metal duvals containing the corresponding liquid. Both the container's walls and the liquid surface itself are reflective surfaces, which could interfere with the black body spectrum desired. The metal container must therefore not be 'seen' by the receiver. To this end, the container's walls were covered completely by the absorber. It was however noted that the liquid surface itself did not reflect appreciably enough to affect readings – readings made with the receiver above the surface of the liquid did not differ appreciably from those with the receiver immersed in the liquid.

Temperature dependence of apparatus: The apparatus used, in the form of the amplifiers, depends on its temperature. That is, the amplifier gain is a function of the temperature. Hence, when measuring the voltage for liquid nitrogen/helium followed by the readings for the sky, in one case the equipment is colder than in the other, leading to inaccuracy in readings. A feedback-loop related temperature control circuit to solve this problem was rejected as impractical given the comparatively large size of the apparatuses involved.

Eventually, to minimize this problem, readings of the sky, liquid helium were taken rapidly one after the other, so that the temperature of the measuring apparatus would not change appreciably during the measurement interval.

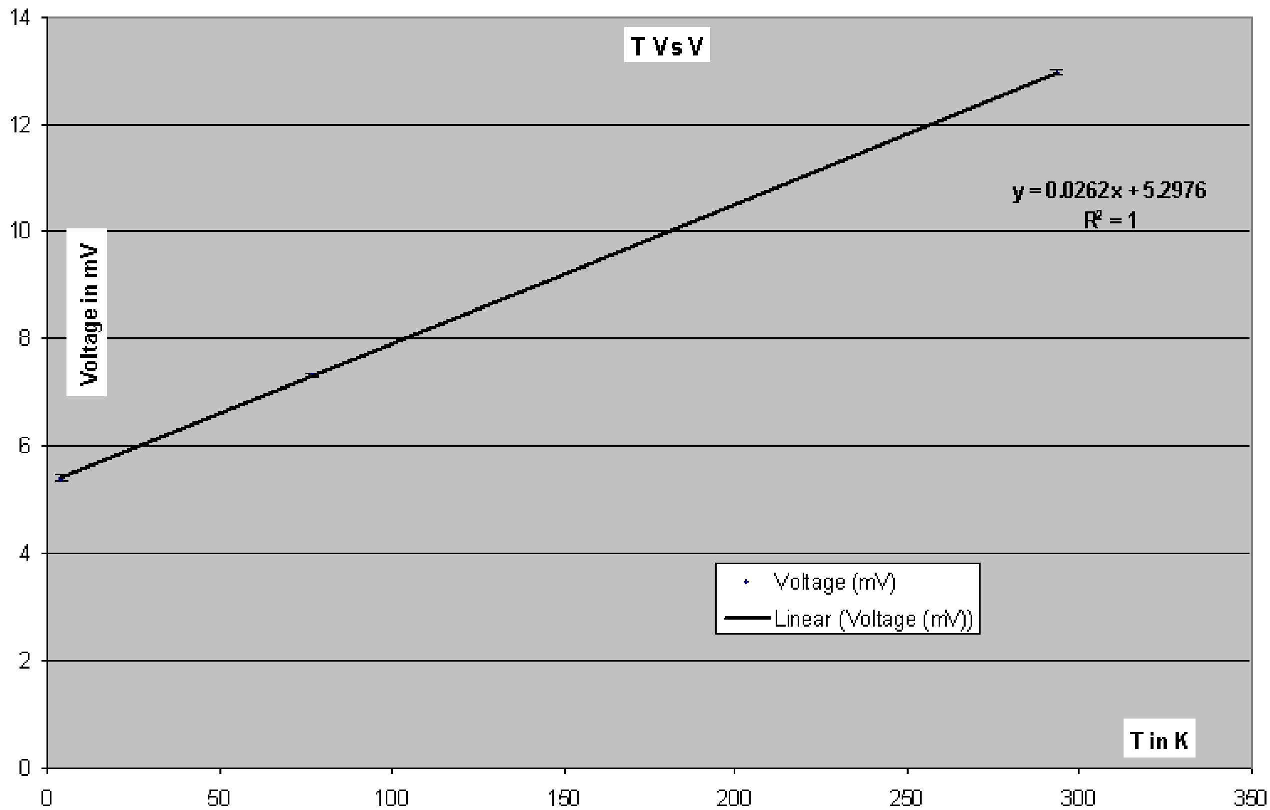
Variations in Amplitude Gain: An important source of random errors was the fluctuation of amplifier gain over the course of readings. This effect is minimized by the technique of taking multiple readings at the same temperature.

Observations: the final temperature readings obtained are:

Temperature	Voltage (mV)
293	12.98
77	7.32
4	5.4

An uncertainty of 0.05 V is estimated for each of the voltage readings. This translates into a temperature uncertainty of about 2 K. An unfortunate consequence of this is the inability of the setup to clearly distinguish the background temperature from the liquid helium temperature.

A plot of temperature versus voltage is given:



As we can see, the graph is almost exactly a straight line.

Conclusions

- The temperature of the background measures to 4 ± 2 K
- The accepted standard is 2.725 ± 0.001 K
- The two agree to within experimental uncertainty