15.1: Observations of the CMB Spectrum

Learning Objectives

- You will know that the CMB is nearly uniform and coming from all directions
- You will know that the CMB spectrum is a 3K blackbody

What Do You Think: Temperature of the Universe

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We can use the light from astronomical objects to measure their temperatures. The CMB is coming from every direction in the sky, so we can use this light to take the temperature of the Universe as a whole. But first, what exactly is the cosmic microwave background?

Arno Penzias and Robert Wilson did not set out to discover the CMB. They were working with a new kind of detector at Bell Labs in New Jersey in 1964. In the course of making very careful measurements and re-checking their equipment, they realized they had detected a source of "noise" in their antenna. It was coming from all directions in the sky and could not be attributed to any known source.

Neither Penzias nor Wilson knew what to make of their antenna noise. But then Arno Penzias learned of a paper by Robert Dicke, Jim Peebles, and David Wilkinson, all cosmologists at nearby Princeton University. In the paper, which was still in draft form, they discussed relic radiation that should have been created in the early stages of a hot dense Universe. After reading the paper, Penzias invited the Princeton scientists to come to Bell Labs and have a look at the antenna (Figure 15.1), along with his and Wilson's results. Together they decided to publish simultaneous papers announcing the discovery of the background radiation predicted by the Big Bang theory. The Princeton group would write about the theoretical underpinnings of the radiation, and the pair from Bell Labs would write about their discovery. The papers were published back-to-back in *Astrophysical Journal Letters* in 1965. Penzias and Wilson won the 1978 Nobel Prize in physics for the discovery.

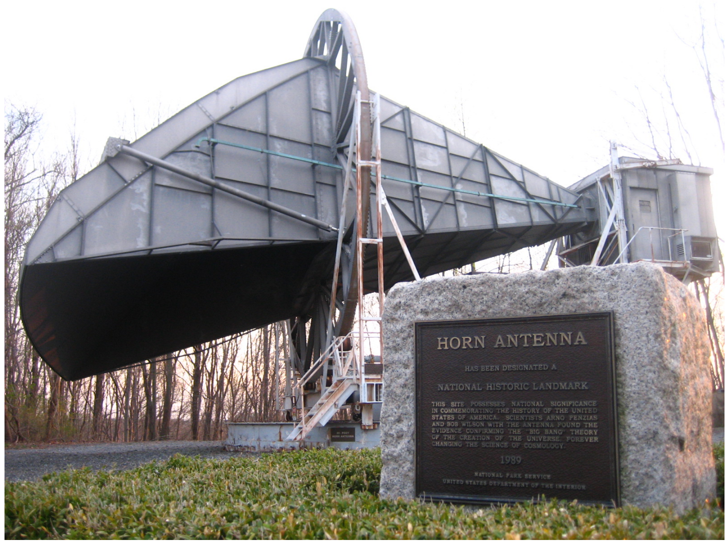

Figure 15.1: This horn antenna was used by Penzias and Wilson at Bell Labs in their discovery of the CMB. Credit: Wikimedia Commons

At first glance the CMB is an almost completely uniform glow in the entire sky as seen in microwaves. It is similar to the blue glow seen in the sky on a cloudless day; there are almost no discernible features. Figure 15.2 illustrates the uniformity of the temperature of the CMB across the entire sky compared to a map of temperatures on Earth. Since the CMB is observed with microwave telescopes rather than visible light, color is typically used to represent temperature, not wavelength, in maps of the CMB. Furthermore, CMB maps are usually shown in the Mollweide projection so that all positions on the sky can be seen at once. An example of what a map of Earth would look like in a Mollweide projection is shown in Figures 15.2 (bottom panel) and 15.3.

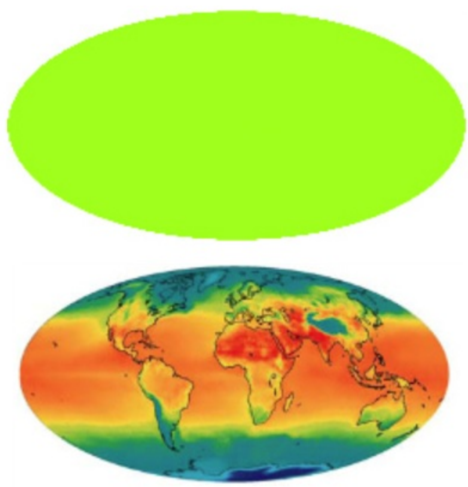

Figure 15.2: The uniformity of the temperature of the CMB (top panel) compared with a map of Earth on the same temperature scale (bottom panel). The temperature of the CMB is much more uniform than the temperature across Earth. Both maps use a projection such that the entire sphere of the sky (in the case of the CMB) or globe (in the case of the Earth) can be represented at once (as in Figure 15.3). Credit: NASA/WMAP Science Team

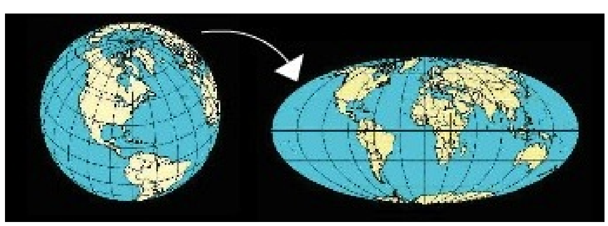

Figure 15.3: A Mollweide map projection of Earth. The advantage to this projection is that it allows all positions on the globe to be seen at once. There are still distortions relative to a spherical globe, but they are less than those of a rectangular (Cartesian) map. Credit: NASA/WMAP Science Team

Recall that we can measure the temperature of an object from its spectrum—a plot of wavelength (horizontal axis) vs. their intensity of emission (vertical axis) at that wavelength. The most common type of continuous spectrum is called a blackbody spectrum (or Planck spectrum) and it has a characteristic shape. We also learned that the peak wavelength of the blackbody spectrum corresponds to the temperature: the hotter the object, the shorter the wavelength at the peak and the higher the curve at all wavelengths.

In 1989, the COBE satellite was launched, with a goal of measuring the spectrum of the CMB over the entire sky. The COBE team included dozens of scientists and engineers. Hundreds of other people helped make the mission a success. The team leaders for the project, John Mather and George Smoot, won the Nobel Prize in 2006 for discoveries made by the COBE team.

COBE contained an instrument called the **Far-InfraRed Absolute Spectrophotometer**, or FIRAS. The FIRAS instrument measured the intensity of the CMB at multiple wavelengths and determined that it has a blackbody spectrum with a temperature of 2.725 ± 0.002 K. This is the best example of a blackbody spectrum that we know of in the Universe; it is a more perfect blackbody than any oven, charcoal briquet, or lamp we have ever created. Figure 15.4 shows the spectrum of the CMB, as measured by FIRAS. The data and the model agree to high precision; the uncertainty in the data points is smaller than the width of the line used to plot the model fit.

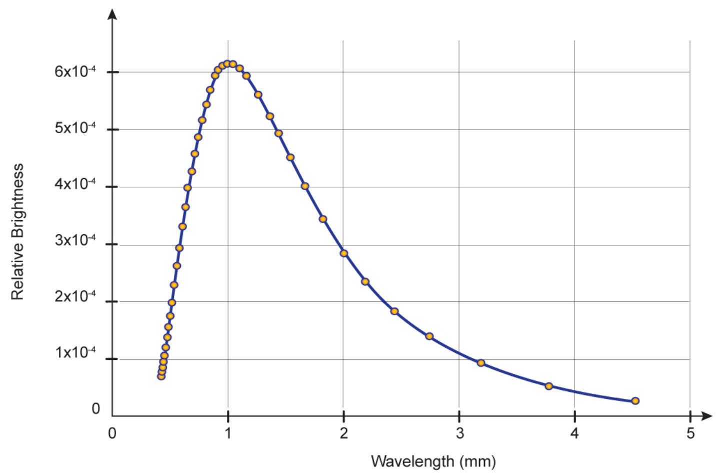

Figure 15.4: Spectrum of the CMB as measured by the FIRAS instrument on the COBE satellite. The CMB is the most perfect blackbody known. It has a temperature of about 3 degrees above absolute zero, which corresponds to a peak wavelength of about a millimeter. Theory and observation agree to better than the width of the line in the graph. Credit: NASA/SSU/Aurore Simonnet based on COBE/FIRAS data

Taking the Temperature of the Universe

In this activity you will use the COBE/FIRAS data to determine the temperature of the Universe. The COBE scientists fit the entire curve, but you will try to estimate only the position of the peak. It is not as accurate this way, but it gives the gist of how the temperature is measured.

1. First you will measure the peak wavelength of the blackbody (Planck) curve from the data. To do this, use the following graph:

USE GRAPH

a.

2.

Since the CMB is radiation coming from everywhere in the sky, you have just measured the overall temperature of the Universe!