15.2: Implications of the CMB Temperature and Spectrum

Learning Objectives

- You will understand why the CMB supports the Big Bang Theory

What Do You Think: Evidence for the Big Bang Theory

One piece of evidence in support of the Big Bang theory is the **Hubble expansion**. On average, we see galaxies moving away from each other as the space between them stretches. Extrapolating this expansion back to earlier times in the history of the Universe, the Big Bang theory predicts that the Universe was once much denser, and as a result, hotter. The Big Bang theory naturally explains the CMB as the glow left over from the hot, dense early state of the Universe.

At about 380,000 years after the Universe came into existence (more exactly 375,000 ± 3000 years according to current best estimates), the temperature everywhere was about 3000 K. The entire Universe was still a fairly dense soup of simple nuclei, free electrons, and photons. The photons before this time could not get very far because they were constantly running into electrons and being scattered, similar to the way water droplets scatter light in a fog. The electrons were still separate from the nuclei because in the high temperature conditions they had too much energy to stay bound. As the temperature dropped, however, the electrons were eventually able to bind to nuclei, forming neutral atoms, mostly hydrogen and helium. Neutral hydrogen and helium gas do not interact strongly with 3000 K photons, and so the Universe became mostly transparent at this time. The light could travel freely for great distances without interacting with anything. The CMB is the light that was set free at this time, and it has been traveling across the Universe for nearly 13.8 billion years—perhaps only stopping when it hits the antenna on your television. When we are looking at an image of the CMB, such as that observed by the Planck satellite in Figure 15.5, we are seeing a *direct* picture of the Universe in its infancy.

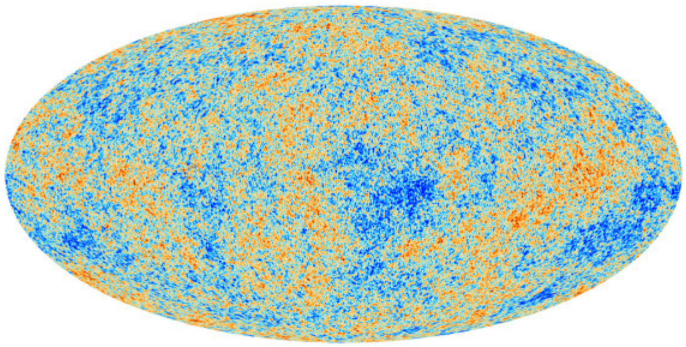

Figure 15.5: Map of the CMB as measured by ESA's Planck Satellite in 2013. This radiation was emitted when the Universe was 375,000 years old. The contrast has been enhanced compared to the CMB map in Figure 15.2 such that the red spots are slightly hotter than the blue spots by about 1/10,000th of a degree Kelvin . The map is shown in the Mollweide projection so that all positions on the sky can be seen at once. Credit: ESA and the Planck Collaboration

The temperature of the Universe at the time when photons from the CMB were set free (about 3000 K) corresponds to infrared light, since it is blackbody radiation. The expansion of the Universe has caused the light to redshift to a wavelength more than 1000 times longer. That is why we see it as microwave light today.

In an expanding Universe, the wavelength of a photon will be stretched along with the space in which it is embedded. The scale factor of the Universe is related to the redshift:

$$\frac{\lambda_o}{\lambda_e} = 1 + z = \frac{S_o}{S_e}$$

where λ_o is the wavelength of CMB photons, z is the redshift, and S is the scale factor of the Universe. The subscript e describes when light was emitted and the subscript o describes when we observe it today. Using the relationship between wavelength and temperature for a blackbody spectrum ($T = 2.9 \times 10^{-3} / \lambda_e$), we can also relate the scale factor and redshift to temperature:

$$\frac{\lambda_o}{\lambda_e} = 1 + z = \frac{S_o}{S_e}$$

where T is the temperature of the CMB. This means that at early times, when the scale factor is smaller, the Universe is hotter.

In the following activity, we will determine how much the Universe has stretched since light from the CMB was emitted and how the temperature has changed.

The Redshift of the Cmb and the Temperature of the Universe

Observations of the CMB tell us that it formed at a redshift of z = 1100. The observed temperature of the CMB today is 2.73 K.

Worked Examples:

1. By what factor has the Universe stretched since light from the CMB was emitted?

- Given: z = 1100
- Find: S_o/S_e
- Concept: S_o/S_e = 1+z
- Solution: S_o/S_e = 1101 times

This means the Universe has stretched by a factor of 1101 since light from the CMB was emitted.

2. How much hotter was the temperature of the Universe when light from the CMB was emitted?

- Given: z = 1100
- Find: T_e/T_o
- Concept: T_e/T_o = 1+z
- Solution: T_e/T_o = 1101 times hotter

3. What was the temperature of the Universe when light from the CMB was emitted?

- Given: $z = 1100$, $T_o = 2.73$ K
- Find: T_e
- Concept: $T_e/T_o = 1+z$
- Solution: $T_e = (T_o)(1+z) = (2.73\text{ K})(1101) = 3006$ K

Now compare these temperatures and stretch factors to those for some of the objects you learned about previously.

Questions:

1.

2.