The Cosmic Microwave Background

Harshda Saxena

26 March 2020

1 Introduction

Remember the good ol' days when people used to watch television? Not Netflix no, I mean the cable TV, which when did not get a proper signal used to show static? That static also includes certain signals, some of which are a remnant of our universe's early stages, what we will discuss today as a part of this article on The Cosmic Microwave Background(CMB)(No prerequisites to join me on this wild ride!).
American cosmologist Ralph Apher first predicted the CMB in 1948 while working on the Big Bang nucleosynthesis(the production of nuclei from pre-existing protons and neutrons).

However, the CMB was first accidentally discovered in 1965, when two researchers with Bell Telephone Laboratories (Arno Penzias and Robert Wilson) were creating a radio receiver, and were puzzled by the noise it was picking up. They initially thought it was pigeon poop on the antenna (not kidding, look it up) but after realizing that it was an actual signal coming from everywhere uniformly throughout the sky, they finally realized that the CMB had been discovered (for which they got the Nobel Prize, of course). [1]
So what is this Background radiation that I speak of, how did it originate and how does it help us to understand the early stages of our universe?

2 Origin of the CMB

Rewinding time back to the early stages of the universe when it was just one-hundred-millionth the size it is today and its temperature was around 273 million degrees above absolute zero, the conditions were so extreme that no stable atoms could be formed.[2]
This ionized soup of matter is called plasma, and like all objects, it was emitting something known as a blackbody spectrum, which is just a thermal distribution of electromagnetic waves(we can call it a black body since, all the light emitted by it was effectively reabsorbed by the plasma). The black body spectrum, which is basically the pattern of the intensity of the radiation over a range of wavelengths or frequencies, is emitted by all bodies due to the thermal energy

they possess. Fun fact- Analysis of this spectrum shows that the universe in its early stages was orange (Orange is the new Black!).

However, this radiation emitted by constituent particles of the plasma couldn't travel very far, before it hit an electron and ricocheted, still trapped within the plasma . As space expanded and cooled further, around the 3000K mark(around 38,0000 years after the big bang), neutral atoms could finally form. The light emitted by the plasma just before it neutralized, could now freely stream through the universe.
As the universe expanded, these photons underwent something called a cosmological redshift(a phenomenon where electromagnetic radiation from an object undergoes an increase in wavelength due to the expansion of space, causing them to decrease in energy), as a result, the orange light was redshifted to the microwave part of the spectrum, invisible to the human eye(thank god otherwise everywhere we would look we would have been seeing orange light, not fun at all!).

Hence, the CMB is just electromagnetic radiation filling all space, giving us a snapshot view of when atoms were formed in the early stages of the universe. First, a brief discussion of how it was measured and studied about.

3 Measurements of CMB

Precise measurements of the CMB are critical to cosmology, since any proposed model of the universe must explain this radiation, which helps us to understand how the early universe was formed.

While portions of the CMB were mapped in the coming decades after its discovery, the first full-sky map came from NASA's Cosmic Background Explorer (COBE) mission, which launched in 1989. It took measurements of the CMB(between 1cm to 1 um), which provided experimental confirmation to the Big Bang model of the origin of the universe.[4]

Inspired by the initial COBE results of an extremely isotropic(similar in all directions) and homogeneous background, a series of ground- and balloon-based experiments tried probing further, and found CMB anisotropies(the spectral radiance at different angles of observation in the sky contains small anisotropies, or irregularities, which vary with the region examined) over the full sky on smaller angular scales.[4]

In June 2001, NASA launched a second CMB space mission, WMAP (Wilkinson Microwave Anisotropy Probe), to make much more precise measurements of these anisotropies.
WMAP used symmetric, rapid-multi-modulated scanning, rapid switching radiometers to minimize non-sky signal noise. The results of this pegged the

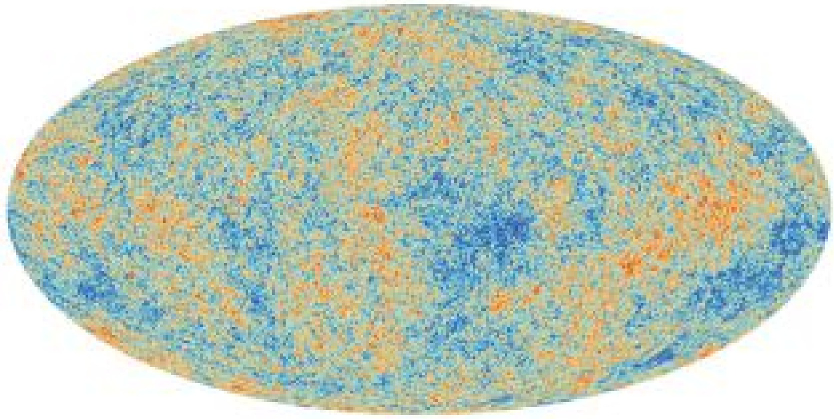

Figure 1: The Cosmic Microwave Background temperature fluctuations from the 7-year WMAP data seen over the full sky[3].

universes age at around 13.7 billion years and revealed that stars started shining around 200 million years after the big bang, much earlier than predicted.[4]

A third space mission, the ESA (European Space Agency) Planck Surveyor, was launched in May 2009 and performed an even more detailed investigation until it was shut down in October 2013, measuring the CMB at a smaller scale than WMAP.

On 21 March 2013, the European-led research team behind the Planck cosmology probe released the mission's all-sky map of the CMB. The map suggests the universe is slightly older than researchers expected. According to the map, subtle fluctuations in temperature were also imprinted on the CMB which reflects ripples that arose early in the universe.
The 2013 data opened a lot of answers about the composition of the universe, the age and much more. For example, it revealed that the universe contains 4.9 % ordinary matter, 26.8 % dark matter and 68.3 % dark energy(What dark mater and dark energy truly are is another rabbit hole to go down into and for another day). It also pegged the age of the universe at around 13.799 billion years old and the Hubble constant(a unit that tells us how fast space is expanding, a very important feature to help us understand the evolution of the universe) was measured to be 67.74 (km/s)/Mpc. [4]

4 Data Analysis Time

Now we go, dare I say, to the real part of Astronomy, unlike the ones which have inspired common men for generations, like "looking up", now we are going to briefly discuss the data obtained from said activity.

Raw CMBR data, even from space vehicles such as WMAP or Planck, contain many effects that completely obscure the fine-scale structure of the cosmic microwave background. These errors are mostly due to relative motion of the sun and earth with respect to the CMBR(CMB appearing slightly warmer in the direction of movement than in the opposite direction) and have to be removed through many complicated procedures to find the actual small changes in the CMBR in different angular distances. [5]

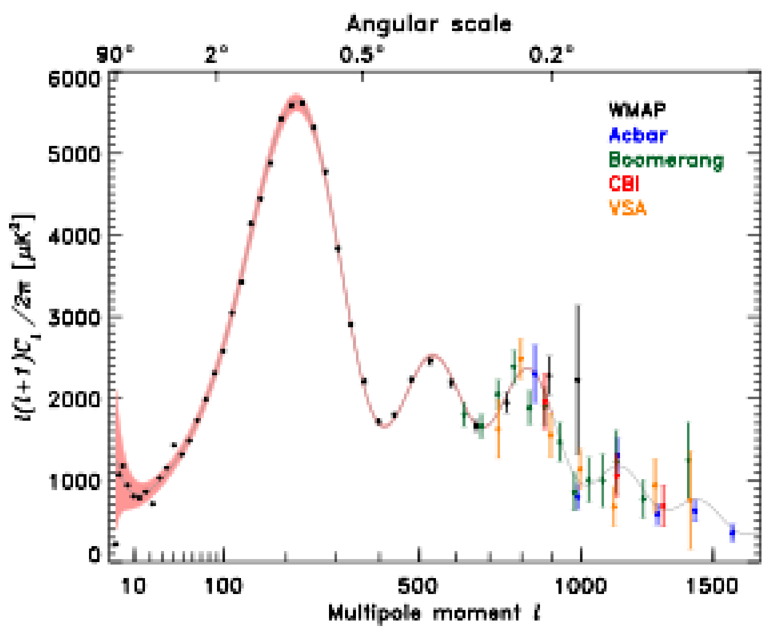

Figure 2: Power Spectrum of the CMB, where multipole moment is just angular distance, and the y axis is fluctuations in CMB temperature[6].

Most of the cosmological information we get from the CMB is found by studying its power spectrum, a plot of the amount of fluctuation in the CMB temperature spectrum at different angular scales on the sky.

These fluctuations are of 2 types- primary anisotropy, due to effects that occur at the surface of last scattering and before(that is changes within the plasma, or at the instant when it cooled enough for recombination); and secondary anisotropy, due to effects such as interactions of the background radiation with hot gas or gravitational potentials, which occur between the last scattering surface and the observer at this instant.

The shape of this power spectrum is determined by oscillations in the plasma of the early universe, and the frequencies and amplitudes of these oscillations are determined by its composition. Hence, we can compute the properties of the plasma by studying the positions and relative sizes of these peaks.
The position of the first peak, for example, tells us about the curvature of the universe (and hence how much total stuff there is in it according to The General Theory of Relativity, again a rabbit hole for another time), while the ratio of heights between the first and second peaks tells us how much of the matter is ordinary matter(baryonic matter, to be more precise, that is, made up of protons and neutrons, but not electrons and neutrinos). The third peak is used to get information about the dark matter densities in the universe.[6]

Analysis of Data also shows that CMB is polarized and broadly classified into 2 types- E polarized due to scattering in the primordial plasma and B polarized due to gravitational lensing (basically bending due to the effects of gravity) of E polarized. Due to the expansion of the universe, the CMB is constantly redshifting and will become too small to detect after a time(more incentive to study it now!).

5 Summary

TLDR- The Cosmic Microwave Background is an electromagnetic radiation as a remnant from the early stages of the universe, which was created around 400,000 years after the big bang, when the universe became cool enough to allow formation of atoms. This let the thermal radiation from the plasma escape, which finally was redshifted due to the expansion of the universe and entered the microwave band of the spectrum forming the CMB we see today.

As a result of a lot of commendable work done by many scientists throughout the world, the CMB spectrum has become the most precisely measured black body spectrum in nature and hence has opened many windows into the in-depth understanding of our universe and its origins.

References

[1] *Cosmic Microwave Background: Remnant of the Big Bang* https://www.space.com/33892-cosmic-microwave-background.html

[2] *Tests of the Big Bang* https://map.gsfc.nasa.gov/universe/bb_tests_cmb.html

[3] https://www.nasa.gov/images/content/735683main_pia16873-full_full.jpgl

[4] *Cosmic Microwave Background* https://en.wikipedia.org/wiki/Cosmic_microwave_background#Microwave_background_observations

[5] *Cosmic Microwave Background* https://en.wikipedia.org/wiki/Cosmic_microwave_background#Data_reduction_and_analysis

[6] Jeff Filippini, UC Berkeley Cosmology Group (August 2005) *The Cosmic Microwave Background* http://cosmology.berkeley.edu/Education/CosmologyEssays/The_Cosmic_Microwave_Background.html