

CMB Fluctuation Dependence on Matter and Dark Energy Density Fraction

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Introduction

The early structure of the universe as seen in the Cosmic Microwave Background (CMB) can be represented by an angular power spectrum (as in Figure 1), a plot that shows how the temperature in the young universe varies over smaller and smaller patches of the sky.

A power spectrum is a very good way to understand and calculate various cosmological parameters related to the universe, and this anisotropy spectrum depends on these parameters. We should first become familiar with the cosmological terms used. For the symbols below, fractional means that the density is divided by the critical matter-energy density for a flat universe, about 10^{-29}g/cm^3 .

Ω_k = curvature parameter

Ω_{cdm} = fractional dark matter density

Ω_b = fractional baryon density

Ω_Λ = fractional dark energy density

H_0 = Hubble constant = $(100 \text{km/s/Mpc})h$, h is called the Hubble parameter; current best $h \approx 0.7$

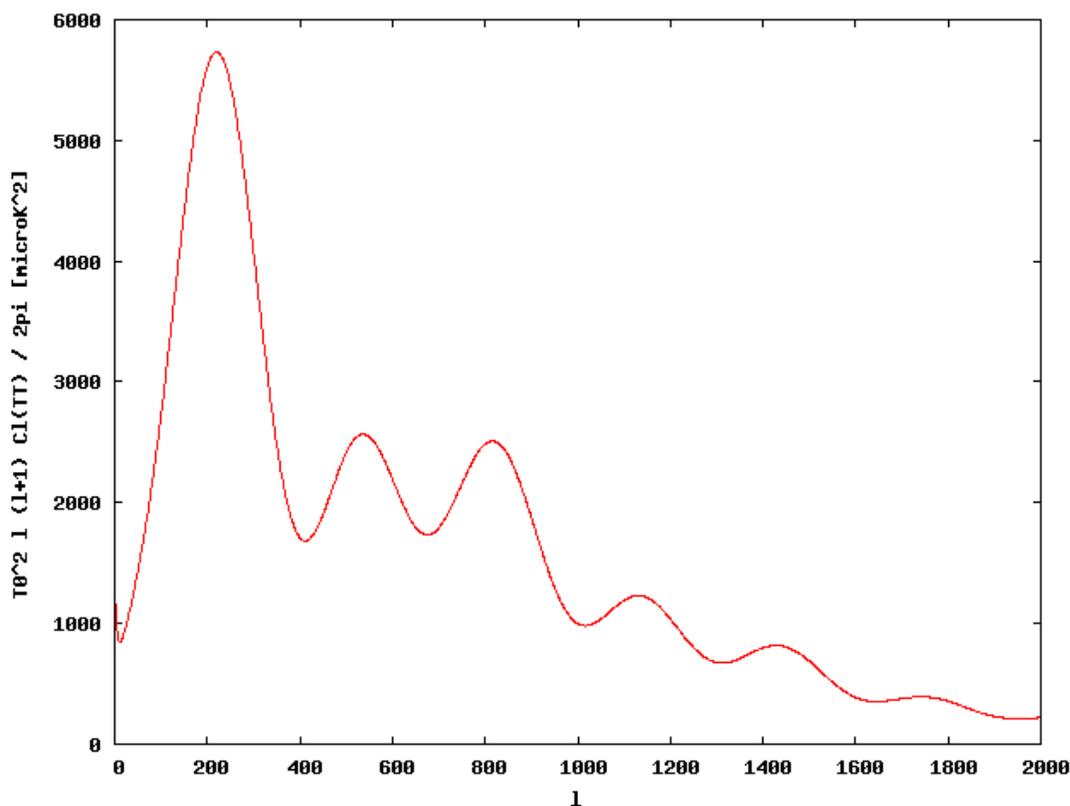


Figure 1. Angular power spectrum of CMB temperature fluctuations. Plot of temperature fluctuation vs. l -value (a measure of angular scale).

The vertical axis in the diagram above shows the temperature fluctuation and the horizontal axis shows the l -value of the spectrum. The l -value is related to the angular scale of fluctuations. In the table below fill in the l -value and the corresponding angular scale.

	First peak	Second peak	Third peak
l -value at spectrum peak			
$(180^\circ/l)$ = angular scale of fluctuations			

Question 1. What happens to the angular scale of the temperature fluctuation when the l -value is increased?

The Big Bang Theory that explains the creation, contents, and evolution of the universe is a scientific theory, a theory that can be proved wrong. The overwhelming evidence, however, is that the theory is a correct description of the universe.

In the very early universe there were no atoms; charged electrons and protons scattered light continuously as the universe expanded and cooled. Eventually, 380,000 years after the Big Bang, the universe cooled enough for neutral atoms (H and He) to form and light no longer scattered. But light that scattered just as the neutral atoms were formed continued travel, virtually unimpeded, and it is observed today as microwaves of temperature 2.7 K (-454.8°F) along with the temperature fluctuations ($\sim 10^{-5}$) due to the scattering. Studying the temperature fluctuations help to draw conclusions about the shape and contents of the universe.

Early Universe Contents

Using 2012 Wilkinson Microwave Anisotropy Probe (WMAP) data, cosmologists find that about 4.6% of the universe is made up of visible matter, i.e. electrons, protons and neutrons. The rest of the 95.4% of the universe is made up of dark matter and dark energy. About 24% of the universe is made up of dark matter and 71.4% is made up of dark energy. Photons (particles of light) and neutrinos (almost massless particles) comprise less than 1% of the universe. Dark matter is a form of matter that is invisible but is observed as the gravitational force needed to hold together galaxy clusters. Dark matter is weakly interacting at best, so once dark matter collapses due to gravitational attraction, it does not generate collisions, heat, or pressure; it stays in place. Until 47,000 years after the Big Bang, radiation was the dominant form of energy. Then matter became the dominant form of energy until 9 billion years after the Big Bang when dark energy dominated over matter. Dark energy is a form of energy that cannot be seen and produces force that opposes gravity and is the cause of the accelerating expansion of the universe. In this lab we ignore the dark energy because the universe was matter dominated when neutral atoms were formed.

Early Universe Physics

The power spectrum tells us about temperature fluctuations of the young universe. The power spectrum observed today is from the time when matter dominated the universe. In any given volume of space, there

was more energy in the form of matter than in the form of radiation or dark energy. The CMB tells us about the matter density of the early universe.

Matter in the form of protons and neutrons are called baryons. (To simplify early universe terminology, electrons are also called baryons by cosmologists although, technically speaking, they are not because of their small mass.) Very soon after the universe begins expansion, dark matter begins to cluster and attract baryons and photons gravitationally. The baryon clustering is opposed by photon pressure pushing the baryons away from the dark matter. The alternate compression and expansion cause the baryon-photon mixture to oscillate just as the alternate compression and expansion of air oscillates to create a sound wave. But the baryon-photon oscillation is better described as an acoustic wave, since no sound is created.

In the diagrams below, Fig. 2(a) shows the baryons being attracted towards dark matter due to gravity. Fig. 2(b) shows the baryons being compressed as photon pressure builds to push them away from dark matter. Fig. 2(c) shows the baryons expanding away from the dark matter. The expansion is due to photons pushing the baryons away.

Fig. 2 can be viewed as being on the scale of 89.3Mpc (=291Mly) of today's universe, from Fig. 3. The pressure exerted on baryons by photons causes expansion, but the dark matter's gravity tends to keep the baryons compressed. Oscillation of the photons and baryons is reflected in the acoustic peaks of Fig. 1, as will be explained below.

Power Spectrum Physics

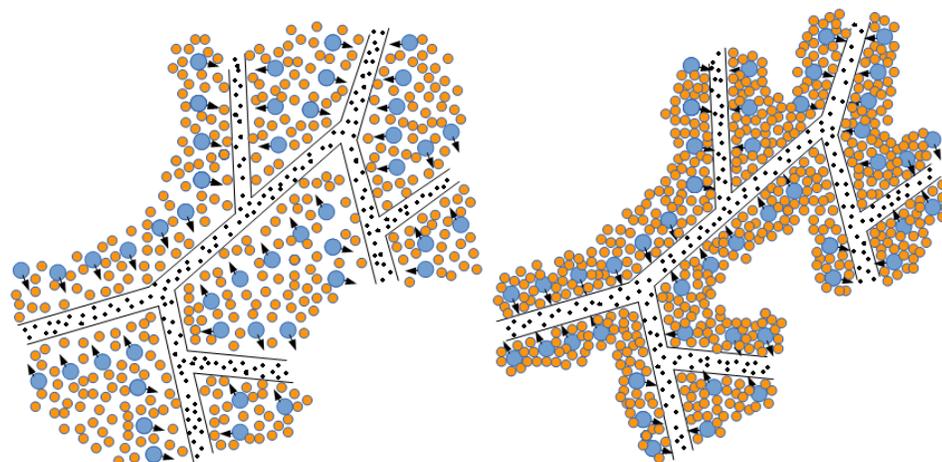
The horizon is the farthest distance over which acoustic waves, analogous to sound waves, have had a chance to travel during a certain time. The first peak in the power spectrum of Fig. 1 is the result of compression over the farthest distance, i.e. 380,000 years of sound travel. Other peaks in the power spectrum are due to expansion (for even numbered peaks) and compression (for odd numbered peaks) over distances less than 380,000 years of sound travel. Now consider the chronology for formation of the peaks.

Third Peak. Baryons are compressed within a comparatively small horizon (see Fig. 4(a)) at an early time in the universe. Then photons cause the baryons to expand, and afterwards they compress again due to the gravity of dark matter, as illustrated in Fig. 2. The arrows in Fig. 4(a) indicate oscillating baryons and photons. At the instant of the last baryon compression, 380,000 after the Big Bang, light scatters from the compression region (triple-vector lines in Fig. 4(d)) to form the third peak of Fig. 1, and atoms become neutral so the scattered light reaches us with limited re-scattering.

Second Peak. Baryons are compressed within the growing horizon, (see Fig. 4(b)) comparatively larger than the horizon in Fig. 4(a). The photons cause the baryons to expand, against the gravitational force of dark matter as illustrated in Fig. 2. The arrows in Fig. 4(b) indicate oscillating baryons and photons. At the instant of last baryon expansion, 380,000 years after Big Bang, light scatters from the expanded region (double-vector lines in Fig. 4(d)), to form the second peak of Fig. 1, as atoms become neutral so the scattered light reaches us with limited re-scattering.

First Peak. Baryons are compressed within a comparatively larger, growing horizon (see Fig. 4(c)). The gravity of dark matter causes baryons to compress, as illustrated in Fig. 2. This is the largest scale of compression. At the instant of this compression, 380,000 years after Big Bang, light scatters from the

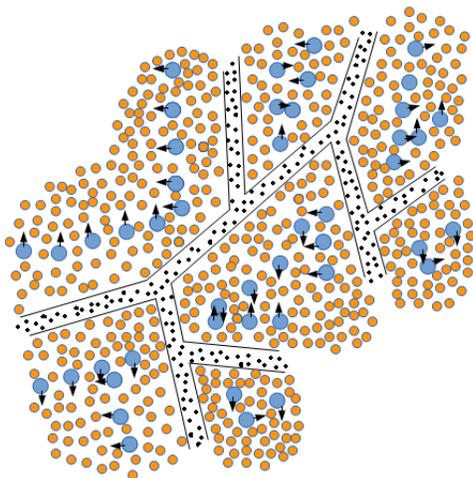
compressed region (single-vector lines in Fig. 4(d)) to form the first peak of Fig. 1 and, like before, atoms become neutral so the scattered light reaches us with limited re-scattering.



● Baryons
● Photons
• Dark matter

(a)

(b)



(c)

Figure 2. Oscillating charged baryons (protons) and photons. (a) Baryons attracted by gravitational force of dark matter. (b) Baryons being compressed due to the gravitational force of dark matter. (c) Baryons rebounding due to the photon pressure, pushing the baryons away from dark matter.

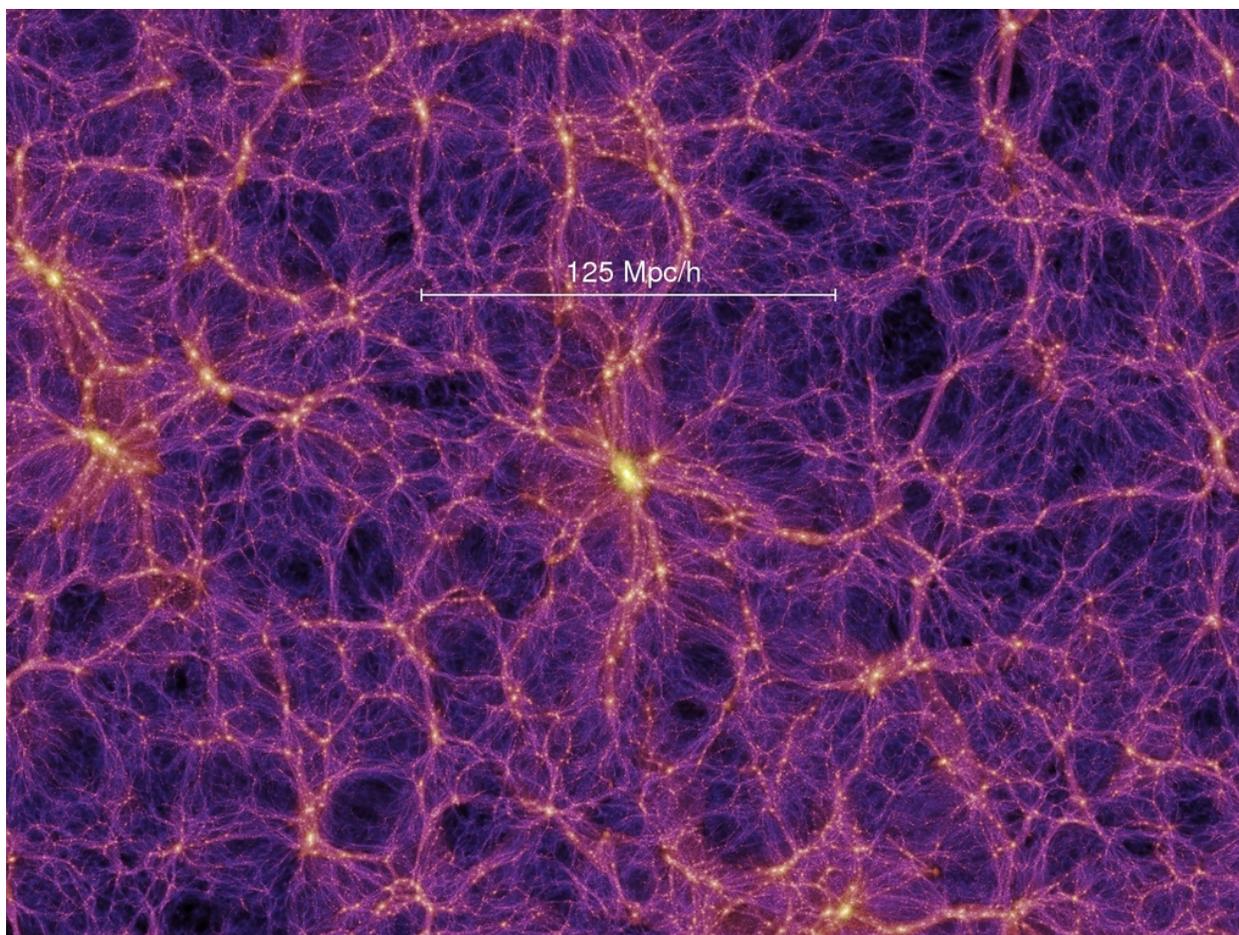


Figure 3. Simulation of the universe after 13.6Gyr from the Millennium Simulation Project. Scale is 125Mpc/h=179Mpc=582Mly
[\(http://www.mpa-garching.mpg.de/galform/virgo/millennium/\)](http://www.mpa-garching.mpg.de/galform/virgo/millennium/)

All peaks, first, second and third, are formed at the same time; the figures clarify the meaning of horizon and the scale of fluctuation of baryons and photons for different peaks. From Fig. 4(d), we see that all the light waves arrive at the CMB observer at the same time. Fig. 5 shows the different horizon sizes and oscillation of baryons and photons. There are three different sized ellipses in the diagram. The largest ellipse represents the largest horizon from which light scatters to form the first peak. Similarly the second largest ellipse and the smallest ellipse represent horizons from which light scatters to give the second and third peaks. Of course the oscillations do not occur horizontally or vertically; the oscillations occur in random orientations. Figure 5 is just a crude representation of the real universe.

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- Is your finding for the 1st peak also true for the 2nd peak?

- How does the height of the first peak change as the dark energy density increases?

- How does increasing the dark energy density affect the age of universe?

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References

Duncan, T. and Tyler, C., 2009, *Your Cosmic Context* (San Francisco, California)