Changing the Fundamental Parameters of the Universe

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Abstract

The aim of this project was learning about how the fundamental parameters affect our universe and creating information regarding this subject accessible to people outside of physics. In particular we studied how the speed of sound affects time frames such as the recombination period, the nucleosynthesis period and our everyday life today. The implications of these changes were studied in the cosmic microwave background (CMB), the formation of primordial elements and on Earth at present time. The sound speed in the CMB was indirectly varied by changing the physical baryonic density, and the change in speed of sound waves on Earth was studied in various scenarios. These visualisations and explanations will be made accessible to the public through a web page, to convey the influence of science on everyday life.

Contents

*Project in collaboration with Edzus Nakums

1 Introduction

This report will outline the basic theory behind the evolution of the universe, how we changed the speed of sound and in which specific time frames we changed the sound speed in. We also studied the implications these changes will have and finally what we plan to continue to study.

In this project the speed of sound was chosen to study as it is a phenomenon that is commonly experienced in everyday life and it plays a vital role both in our universe at present and in the early universe. Using the speed of sound to show the impact that physics has on general society would make learning about physics more relatable and accessible.

The speed of sound was first studied in the universe at present time, where the effects of raising the speed of sound were observed. It was found that if the speed of sound was changed in an instant of time, it would impact the way we hear in our everyday life and the kinetic energy of vibrating molecules. The basic equations of sound interactions were analysed and the speed of sound was raised and lowered in order to investigate the results. This analysis included coding simulations and mathematical examination.

The early universe was researched next, which included literature review of basic cosmological models, terms and history. Two time stages in the early universe were studied, including nucleosynthesis and the stage of recombination. Through these stages the implications of using the physical baryonic density to change the sound speed were examined.

Therefore, these changes to a common phenomenon we experience in everyday life will enable the public to learn further about physics. Additionally changing the fundamental parameters of our universe allows one to understand the limits and impact of these constants [1].

2 Evolution of the Universe

2.1 Structure of the Early Universe

The early universe consists of two important eras, called the radiation dominated era and the matter dominated era. These two eras were an important point of study within this project, in particular the nucleosynthesis period was studied along with the recombination period.

The radiation dominated era was the first era after the Big Bang, with 5 different epochs including the Planck, Grand Unified Theory, Quark, Lepton, and Nuclear epochs [2].

Summarising these 5 epochs, the Planck Epoch refers to the time from the Big Bang up to $10^{-43}s$ where it is incredibly difficult to hypothesise the physics.

During the Grand Unified Force Epoch it is postulated that the non-gravitational forces such as the strong force, the weak force and the electromagnetic force were all unified, however after $10^{-35}s$ the Quark epoch began and the strong force separated into its own characteristic behaviours [2]. The Quark epoch included the quark particles in a hot plasma, while the electroweak force began to separate into the electromagnetic force and the weak force before $10^{-5}s$.

After the Quark epoch the Lepton epoch started where hadrons started to form. After the Lepton epoch, the Nuclear Epoch was the time period from $100s$ to 50,000 years where light elements formed during the first $1000s$ and halted due to the cooling expansion of the universe [2]. The period of Big Bang Nucleosynthesis (BBN) occurred in between these epochs and refers to the period where the primordial light elements formed.

After the Nuclear epoch, the radiation dominated era transitioned into the matter dominated era, where matter started to dominate over radiation. The matter dominated era consists of 3 epochs including the atomic, galactic and stellar epoch. The recombination period in the transition from radiation to the matter dominated era was the studied as a time frame due to its formation of the cosmic microwave background (CMB).

2.2 Sound in the Early Universe

As mentioned previously the early universe was extremely hot and dense, which meant the medium throughout the early universe was a hot plasma. As the universe expanded the plasma contained perturbations caused by quantum fluctuations. These perturbations caused baryons within the plasma to gravitationally attract each other and create gravitational potential wells [3]. As more baryons are attracted, these wells become deeper and thus would start to attract photons. As photons fell into this well they would increase the temperature. The temperature changes would create pressure forces counteracting the gravitational forces. These counteracting forces produced oscillations known as Baryonic Acoustic Oscillations (BAO) [4].

The oscillations produced as a combination of gravitational and pressure forces within the plasma medium which counteract each other. These perturbations are comparable to sound waves and are referred to as baryonic acoustic oscillations (BAO) due to the fact that they oscillate the medium in a similar fashion to sound. These sound waves travel within the plasma until the recombination period, where the photons decouple and the distance they travel before recombination is referred to as the sound horizon ($\eta*$) [5].

The plasma that the BAO's occur in can itself be approximated as a perfect fluid in order to describe the relation between pressure and density called the equation of state [6],

$$p(t) = \omega\rho(t)c^2. \tag{1}$$

in this equation, $p(t)$ describes the time dependant pressure where t refers to time, $\rho(t)$ describes the time dependant density, c describes the speed of light and ω is the state parameter. The state parameter takes a value of 0 in a matter dominated state and 1/3 in a radiation dominated state.

The state parameter will allow us to find the speed of sound in the early universe in a state with contributions from both matter and radiation. This state would be seen in the transition between the radiation dominated era and the matter dominated era as the negatively charged electrons were coupled to the photons. This coupling meant that the photons and charged particles were in thermal equilibrium until the universe had sufficiently cooled down [7]. The state parameter describing the fluid will be related to the general speed of sound as shown below[8],

$$v_s^2 = \left(\frac{\partial P}{\partial \rho}\right)_s. \tag{2}$$

In this equation as stated before, P is the pressure and ρ is the density. Considering that there is both contributions of baryonic matter (ρ_b) and radiation (ρ_R) the density can be written as [6],

$$\rho = \rho_b + \rho_R \tag{3}$$

From the equation of state we can see that if ω is 0 for a matter dominated state, this means that pressure is also 0 within this state. Due to this relation, the pressure only has a contribution from the radiation state as described by [6],

$$P_R = \frac{c^2}{3}\rho_R \tag{4}$$

Relating this to equation 2, we can write the partial derivative as,

$$v_s^2 = \frac{\partial P_R}{\partial \rho_R}\frac{\partial \rho_R}{\partial \rho} = (\frac{c^2}{3})\frac{\partial \rho_R}{\partial \rho}. \tag{5}$$

This is taken from the pressure in a radiation state as previously mentioned in equation 4. Next the density is expanded into its separate contributions in order to simplify it further.

$$v_s^2 = (\frac{c^2}{3})(\frac{\partial \rho_R}{\partial \rho_R} + \frac{\partial \rho_b}{\partial \rho_R})^{-1}, \tag{6}$$

$$v_s^2 = (\frac{c^2}{3})(1 + \frac{\partial \rho_R}{\partial \rho_b})^{-1}. \tag{7}$$

The proportionality relation between the density of each state and the scale factor is derived from the conservation of energy and the Friedmann equations [6]. Thus we have the scaling factors as,

$$\rho_b \propto a^{-3}, \tag{8}$$

$$\rho_R \propto a^{-4}. \tag{9}$$

Using these relations we can write the density as shown below, where the subscript 0 refers to a certain time t [6].

$$\frac{\rho_R}{\rho_{R0}} = \frac{a^{-4}}{a_0^{-4}}, \tag{10}$$

$$\frac{\rho_b}{\rho_{b0}} = \frac{a^{-3}}{a_0^{-3}}. \tag{11}$$

These scaling factors can be used to solve for the partial derivative from equation 7 as shown,

$$\frac{\partial \rho_R}{\partial \rho_b} = \frac{\partial \rho_R}{\partial a}\frac{\partial a}{\partial \rho_b} = \frac{3\rho_b}{4\rho_R}. \tag{12}$$

This equation gives the final relation for the speed of sound in the early universe as described by equation 13,

$$v_s^2 = (\frac{c^2}{3})\left(\frac{1}{1 + \frac{3\rho_b}{4\rho_R}}\right). \tag{13}$$

This equation allows one to describe the sound speed in the early universe, which is essential to study the implications in the universe.

2.3 Nucleosynthesis

In the early universe, the Big Bang Nucleosynthesis (BBN) period lasted approximately $10s$ to 20 minutes after the Big Bang [9]. This period formed the first primordial elements in the universe. The primordial elements refer to the first elements formed in the universe which consisted of helium, hydrogen, deuterium and lithium [10].

As the universe cooled to a temperature through which deuterium could form but still hot and dense enough for fusion process' to occur, a small percentage of protons, neutrons and electrons formed light elements [10]. Although these elements were formed, it occurred at the time of the radiation dominated era. After approximately 20 minutes, the universe had expanded and cooled to a point where these elements stopped forming.

This nuclear process in the early universe is directly affected by the physical baryon density. Due to the fact that the density of the medium will affect the amount of primordial elements created, means that it will affect the light element fractions in the BBN period [10].

2.4 Cosmic Microwave Background (CMB)

The cosmic microwave background occurred during the transition from the radiation dominated era to the matter dominated era. During this process as the universe cooled to approximately 3000K, the protons and neutrons were able to form neutral atoms with the electrons [11]. The photons who interact with charged particles were able to decouple from the particles due to light elements being formed such as hydrogen and helium.

The photons which were previously scattered by Thomson scattering while the charged particles were separated caused the universe to appear opaque due to constant scattering of photons. As soon as particles started to recombine into neutral atoms, the photons would scatter for the last time due to Thomson scattering 380,000 years after the Big Bang. This is named the surface of last scattering due to the photons now being able to travel in longer mean free paths. These photons formed the image of the CMB that is seen today.

The image of the CMB which can be seen in Figure 1, shows the temperature imprint left on the sky by photons from the last surface of scattering. The CMB although being isotropic and homogeneous to a high degree, can also be observed to have temperature anisotropies $\left(\frac{\delta T}{T}\right)_{observed}$ which can be accounted for from intrinsic temperature variation $\left(\frac{\delta T}{T}\right)_{intrinsic}$ and the variation caused by the photons being red-shifted $\left(\frac{\delta T}{T}\right)_{red-shifted}$[12].

$$\left(\frac{\delta T}{T}\right)_{observed} = \left(\frac{\delta T}{T}\right)_{intrinsic} + \left(\frac{\delta T}{T}\right)_{red-shifted}. \tag{14}$$

The intrinsic perturbations refer to the primordial fluctuations which came from quantum fluctuations in the universe before the inflationary period in the radiation era [3]. As inflation occurred these fluctuations were macroscopically increased, and oscillations within the medium occurred. These oscillations are also referred to as baryonic acoustic oscillations. These perturbations can be seen affecting the cosmic microwave background as mentioned before in figure 1.

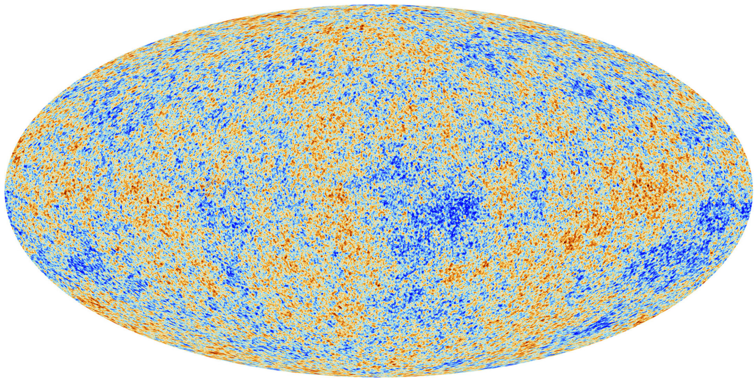


Figure 1: This figure shows a visualisation of the Cosmic Microwave Background as collected by the Planck Mission. The red spots in this diagram show the spots with a higher temperature than the mean temperature and the blue spots show the areas with lower temperature than the mean temperature [13].

The temperature anisotropies of the CMB are a function on a sphere and can be described using spherical harmonics. The temperature variation of the CMB can be expressed as a below,

$$\left(\frac{\delta T}{T}\right)(\theta,\phi) = \sum a_{\ell m} Y_{\ell m}(\theta,\phi). \tag{15}$$

The $Y_{\ell m}(\theta,\phi)$ represents the spherical harmonics being used to describe the temperature fluctuations, $\left(\frac{\delta T}{T}\right)(\theta,\phi)$ shows the variation of temperature from the mean and finally the coefficient term $a_{\ell m}$ represents the mean temperature deviation [12]. The subscripts of ℓ and m refer to the multipole number and azimuthal number respectively.

Theoretically, since the CMB anisotropy is due to primordial perturbations which have a nature of random fluctuations of Gaussian nature, the expected value of $a_{\ell m}$ would be 0 [12]. The variance would be represented as $\langle |a_{\ell m}|^2 \rangle$ and due to the isotropic nature of the fluctuations, the variance would depend only on the multipole number (ℓ) since m represents the orientation of direction [12]. C_ℓ refers to the angular power spectrum as defined below.

$$C_\ell = \frac{1}{2\ell+1}\sum_m \langle |a_{\ell m}|^2 \rangle. \tag{16}$$

Using this theoretical framework, the expectation values $\langle |a_{\ell m}|^2 \rangle$, would produce the anisotropies within the CMB, however as we observe the CMB only one set of a_{lm} can be observed, and thus the average of each these observed values is taken [12]. The observed angular power spectrum is defined as the average [12],

$$\widehat{C_\ell} = \frac{1}{2\ell+1}\sum_m |a_{\ell m}|^2. \tag{17}$$

The variance of the observed temperature anisotropy is the average over the celestial sphere, which is defined as [12],

$$\frac{1}{4\pi}\int \left(\frac{\delta T}{T}(\theta,\phi)\right)^2 d\Omega = \sum_\ell \frac{2\ell+1}{4\pi}\widehat{C_\ell}. \tag{18}$$

The value for the fluctuation of temperature or the angular power spectrum is seen on the y-axis of the angular power spectrum of the CMB as can be seen in figure 2.

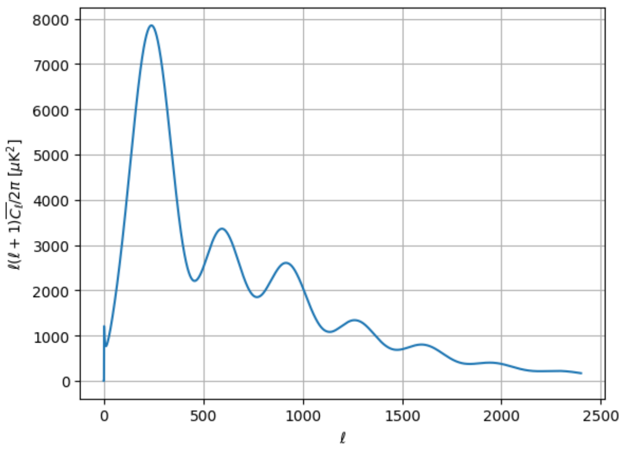


Figure 2: This figure shows the angular power spectrum for a theoretical cosmic microwave background. The data plotted was generated through the python package CAMB, for the observed cosmological parameters in the CMB.

The values on the x-axis of the angular power spectrum are the multipole number (ℓ). Small values of ℓ refer to large angular scales, and large values of ℓ refer to small angular scales.

The multipole numbers can be converted to angular scale by the relation below where the θ or k refer to the angular scale [12],

$$\theta = k = \frac{2\pi}{\ell} = \frac{360}{\ell}. \tag{19}$$

The amplitude and position of the peaks within the power spectrum itself contain information about the baryonic acoustic oscillations, the damping of these waves and the sound horizon.

The first peak of the angular power spectrum in Figure 2 refers to an increase in temperature fluctuations at a large angular scale. This peak shows the first maximum compression. This refers to the first gravitational potential well formed which attracted both light and baryonic matter and thus increased the temperature and pressure. The increased pressure and counteracting compression of gravity is what can be seen in the first peak at a large angular scale. As the gravity compresses the matter, the temperature fluctuations create a peak [5]. The position of the peak at a certain multipole number is affected by the sound horizon as the distance the acoustic waves travel affects the larger angular scales at which its fluctuations can be seen [5].

The second feature of the angular power spectrum is the first trough after the large peak. This trough represents the first rarefraction within the plasma created by the areas of significantly decreased density due to the baryonic matter being attracted towards the gravitational potential wells [5]. These areas of decreased density mean a decrease in temperature fluctuations and thus decrease in the power of temperature fluctuations.

The subsequent peaks in the graph represent the acoustic wave effects on different angular scales, and their positions are also affected by the sound horizon distance however they are much less sensitive to these changes. In addition the subsequent peaks are lower due to Silk damping of the photons before and after recombination [5]. These peaks are affected by the damping processes more due to the fact that they are at smaller angular scales.

Silk damping refers to the damping of photons travelling through the coupled photon-baryon fluid in the early universe before the recombination period [5]. As the acoustic waves travel through the plasma fluid, the photons would get redirected on their path and thus diffuse the acoustic wave and create resistance to the acoustic wave [5]. This diffusion would smooth the fluctuations created in the plasma and thus would have a more profound affect on smaller angular scales.

Along with this damping, there is a second damping process that occurs after the recombination period. This damping comes from the photons from the surface of last scattering or the free streaming photons. They are called free streaming photons because after they scatter for the last time they travel freely to the point in the universe where we can observe them [5]. The damping or the smoothing effect comes from the free streaming photons getting scattered from their path residing from the CMB. As they travel through the universe the path of all of the photons creates the CMB, and as they interact with free particles they get scattered from their path damping the fluctuations and pattern of the CMB.

This damping affects smaller angular scales since at smaller angular scales the amount the path changes by is more noticeable. Although both the damping processes affect all of the features in the angular power spectrum, the peaks at smaller angular scales are affected more and thus they are lower in amplitude.

This information taken from the CMB is important for analysing the universe and the angular scale determines how much of these features can be observed. The angular scale that can be reached by observation depends on the angular resolution of the equipment used. Since in this project we will be changing values theoretically the power spectrums, and the temperature fluctuations will be theoretical.

2.5 Sound in the Universe Today

The speed of sound is defined as the rate of change in pressure with respect to the density of a medium through which the sound is travelling. Sound is an acoustic wave of vibrations defined by the compressions and rarefractions of pressure within a medium [8]. The medium through which sound travelled in the early universe was a plasma, however in the universe today it depends on what we define as the medium.

Another important variable in evaluating the speed of sound in a material is to consider the temperature changes. As an area of a medium is compressed its temperature is raised and as it decompresses the temperature lowers [8]. If one makes an approximation that the wavelength is much longer compared to the mean free path, then the flow of heat from pressure regions is negligible, and the process can be modelled using an adiabatic variation as shown [8].

$$P = \alpha \rho^{\gamma}. \tag{20}$$

In this relation, P refers to the pressure, ρ refers to the density, α refers to a constant and γ refers to the adiabatic constant.

Furthermore equation 2 can be used to find the speed of sound in a medium in relation to the expression above as,

$$v_s^2 = \frac{P\gamma}{\rho}. \tag{21}$$

Finally using the ideal gas law, this can be simplified down further to equation 22 below in order to express the speed of sound in a gas where k is the Boltzmann constant , T is the temperature and m is the mass of each individual particle.

$$v_s^2 = \frac{\gamma kT}{m}. \tag{22}$$

Studying this equation, it is favourable for a gas to be less dense, or to have less massive particles in order to have a higher sound speed. This is due to the fact that gas particles weakly interact between one another and the less dense a gas is the less obstacles there are to move in order to have a higher speed of sound. Less massive particles also take less energy to move and thus the faster the speed of sound is.

The opposite is true for solids. In a solid, the particles are packed together tighter than a gas, which means that particle's interactions are stronger. As a sound wave travels through a solid, a more dense material is favourable due to particles being packed closer together. This means a molecule vibrated in a solid will pass on its energy to a neighbouring particle quicker and thus the vibrations from the acoustic wave will travel through quickly.

If one also considers the intermolecular force in a solid material, as a sound wave displaces a molecule in a material, the tighter the particles are packed the stronger the counteracting intermoleculer force will be in order to place the molecule back to its original unperturbed position [14]. This allows for an efficient process in order to have a molecule ready to oscillate again, and this increasing the speed at which the waves propagate [14].

3 Methodology

This project included studying three time frames that would be affected by the speed of sound such as the period of Big Bang Nucleosynthesis, 380,000 years after the Big Bang when the CMB formed and the universe at present time. While studying these time frames it was assumed that the speed of sound, or the baryonic density was changed instantly at that time frame.

During the BBN epoch, the baryonic density was changed in order to indirectly affect the speed of sound in the plasma medium. Next the baryonic density was changed to indirectly affect the sound speed at recombination, as the cosmic microwave background formed. Lastly the sound speed was increased in present day in order to understand what this would affect in present everyday life.

These values were changed through the CAMB python programming package, along with mathematically studying the formulae.

3.1 Big Bang Nucleosynthesis

During the period of Big Bang Nucleosynthesis, the critical baryon density was changed in order to study the implications of changing the sound speed within the plasma.

The critical baryon density with a scaling factor ($\Omega_b h^2$) was varied from 0.02 to 0.16 in 0.002 steps. The scaling factor h refers to the Hubble parameter divided by $100km/s/Mpc$, which in this case was chosen to be 0.7. This data was plotted and interpreted as part of studying the implications of changing the sound speed in the early universe.

Using CAMB the python package, the fraction of helium in the universe was found by inputting the critical baryonic density parameter. As mentioned previously this is directly related to the physical baryon density (ρ_b) through $\Omega_b \rho_c$. Once these parameters were inputted the results were calculated and the fraction of helium was extracted from the result parameters and plotted through python.

3.2 Period of Recombination

As mentioned previously, sound waves need a medium to travel in. In the early universe this medium was a hot and dense plasma and equation 13 describes this relation. Using equation 13, the physical baryon density ρ_b was varied using the definition of the critical baryon density as labelled in equation 23. The critical density ρ_c is defined below and has a value of 9.124×10^{-27} if the Hubble parameter is taken as 70km/s/Mpc.

$$\Omega_b = \frac{\rho_b}{\rho_c}, \tag{23}$$

$$\rho_c = \frac{3H^2}{8\pi G}. \tag{24}$$

Using the equations defined above, the critical density multiplied by the critical baryon density can change the speed of sound as described below,

$$v_s^2 = (\frac{c^2}{3}) \left(\frac{1}{1 + \frac{3\rho_c \Omega_b}{4\rho_R}} \right). \tag{25}$$

Using equation 25 the critical baryon density was varied from 0.05 to 1 in 0.025 steps. For each set of Ω_b a theoretical angular power spectrum was calculated using CAMB. From this point, the CMB plotting functions are used from the CMB Summer School created by the McMahon School of Cosmology.

The data from the angular power spectrum is first converted from $\ell(\ell+1)C_\ell/(2\pi)$ to C_ℓ. Next an array is initialised containing values from 0.5 to -0.5. This array is used to make an X dimension array and Y dimension array in the python code.

Since a flat sky approximation is being used in order to plot a portion of the sky ($10^\circ \times 10^\circ$) instead of the entire imprint, the k value which is related by equation 19 has an x and y component instead of one radial component k. Using the dimensions created above, the radial component k is calculated as shown below,

$$k = \sqrt{k_x^2 + k_y^2}. \tag{26}$$

A Fourier space is created, and a fast Fourier transform is carried out in order to move the data points into Fourier space. The values of the angular power spectrum are related to this space and multiplied by a Gaussian random initialisation to include the random nature of anisotropies within the temperature imprint. This data is applied to the two dimensional space and is fast Fourier transformed again in order to move back to real space. Next the points are plotted in order to show the temperature imprint.

For this project an additional piece of code was made in order to add a variable slider for the data in order to show how the speed of sound is varied, and how it would affect the CMB. The CMB code was also adapted in order to show the transition of the angular power spectrum and CMB temperature imprint as the critical baryon density is changed.

3.3 Universe at Present Time

For the universe at present time, the sound waves speed was increased to $3 \times 10^5 m/s$, and the implications of increasing the speed of sound was studied. First the effect was studied using the fundamental relationship between the frequency (f), velocity (v) and wavelength (λ) of a travelling wave.

$$v = f\lambda. \tag{27}$$

This equation is studied and by raising the speed of sound, one can understand the affect on the wavelength (λ). The general wave equation was also used to relate the frequency with the changing speed of a wave. Equation 28 was used in order to simulate a wave travelling at $300 m/s$ and $3 \times 10^5 m/s$.

$$y = Sin(2\pi x f). \tag{28}$$

In addition, to studying the physical changes of the travelling wave, the kinetic energy of an acoustic wave was studied. By using equation 22, the temperature effects could be studied in relation to raising the speed of sound.

4 Results and Discussion

4.1 Changes in the Nucleosynthesis Period

The nucleosynthesis period was a time frame which was studied in relation to changing the physical baryonic density. This change in baryonic density was made instantly at this point in time in the universe evolution. The baryonic density was changed in this time frame in order to investigate further whether a connection between the recombination period and nucleosynthesis is possible. This surface level study allows for the future possibility in connecting a change in baryonic density in the nucleosynthesis period to a change in the sound speed during the nuclear epoch.

As mentioned previously, the CAMB python package was used to simulate the results of changing the critical baryonic density and investigating what this change in density would affect. Unfortunately as the CAMB package only contains the change in the fraction of helium in the universe the various other primordial elements could not be studied in detail through python in CAMB.

Studying the change in the fraction of helium through CAMB, a serious of critical baryon densities were used as inputs. As the density was decreased in the nucleosynthesis period, the fraction of primordial helium also decreased which can be seen in figure 3. After a critical baryon density value of 0.04 the curve flattens and becomes constant.

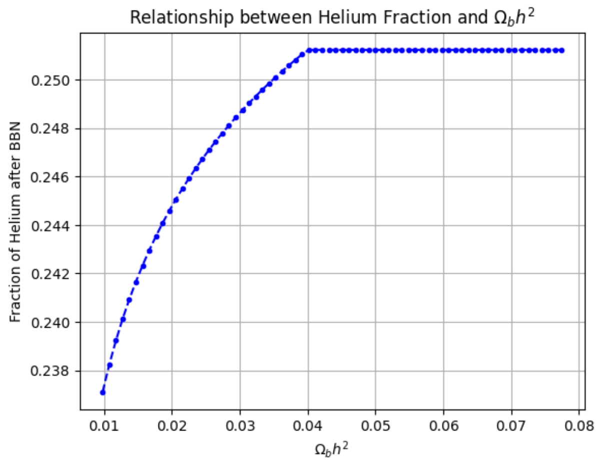


Figure 3: This figure shows the relationship between the $\Omega_b h^2$ and the fraction of helium in the universe created in the nucleosynthesis period. For reference the $\Omega_b h^2$ in our universe is approximately 0.022

This agrees with intuition as if you decrease the density of baryons, you would decrease the amount of neutrons and protons within the plasma. This would decrease the amount of reactions occurring and creating primordial helium. This however is not a linear relation of causation between the critical baryonic density and helium fusion production. There are more complicated factors stemming from nuclear physics involving cross sections that will not be introduced in this report.

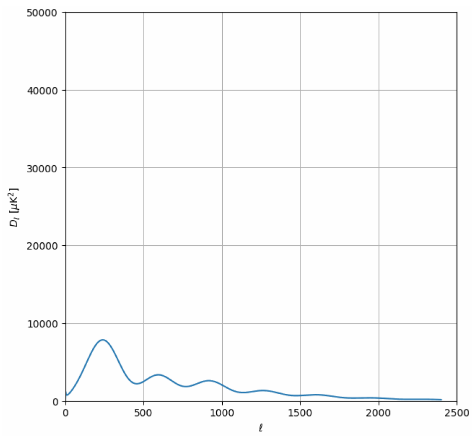
Since the python CAMB package will only handle the fraction of helium created in the universe, another program called Parthenope will be considered in the future analysis of primordial elements affected by critical baryonic density.

In relation to what will be studied next, there is a plan to study a change in the baryonic density in this time period which could be potentially connected to a change in the speed of sound in the nuclear epoch. If this change can be implemented and propagated through the universe, a value in the early universe can adopt a time dependant model which could explain a rise in baryonic density.

4.2 Changes in the Recombination Period

During recombination, the sound speed of the plasma fluid was studied in relation to varying the physical baryon density. From equation 25, it can be seen that as the baryon density increases, the sound speed within the plasma decreases. This change in density could be related to the change in Ω_b. Through this change the pattern of the CMB can be altered in order to visually display the affect of the speed of sound in the early universe.

Firstly the density increasing will be discussed in relation to the theoretical angular power spectrum of the cosmic microwave background. In the initial figure in Figure 4 it can be seen that the first peak is situated at a multipole number of ≈ 200.



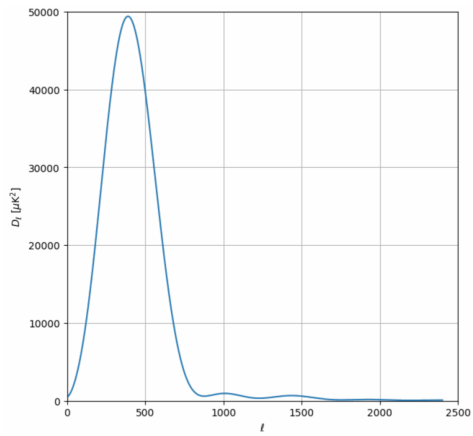


Figure 4: The figure on the left shows the initial power spectrum with a critical baryon density of 0.05. This power spectrum is also equivalent to Figure 2, with a different axis limit in order to convey clearly the large scale change that occurs when the baryon density is changed. The figure on the right shows the angular power spectrum with a critical baryon density of 1. These images are taken from a gif. file which can be accessed through the link here

As the baryon density increases, the speed of sound within the plasma decreases. This corresponds to a decrease in the sound horizon, which shifts the location of the peaks to smaller angular scales or larger multipole numbers. This shift in location can be seen between the two figures below.

The next noticeable difference in the angular power spectrums is the amplitude change. The first peak at the large angular scale is increased massively compared to the subsequent peaks. The raise in amplitude means a raise in temperature fluctuations as the baryon density is increased. This is in line with our expectations as if the baryon density is increased, the gravitational potential wells become deeper and attract more baryonic matter and thus more photons. As more photons are introduced into this gravitational potential well the temperature fluctuations increase. The gravitational potential wells attract more baryons causing the lower density areas to lose even more baryons and thus cause a significant decrease in temperature fluctuations.

However the difference in amplitude proportionality between the first peak and the subsequent peaks and troughs can be explained with damping. Since the sound horizon is decreased due to a decrease in speed, the first trough is at a smaller angular scale and is thus more affected by the damping interactions before and after recombination. The Silk damping and second damping process decreases the amplitude of the rest of the subsequent peaks.

The images in Figure 4 were taken from a gif file compiled in python. This gif can be viewed on the website linked here as mentioned previously.

The next change noticed during the recombination period is discussed with the temperature imprints formed from the angular power spectrum images in figure 5. These images were created through the python package CAMB.

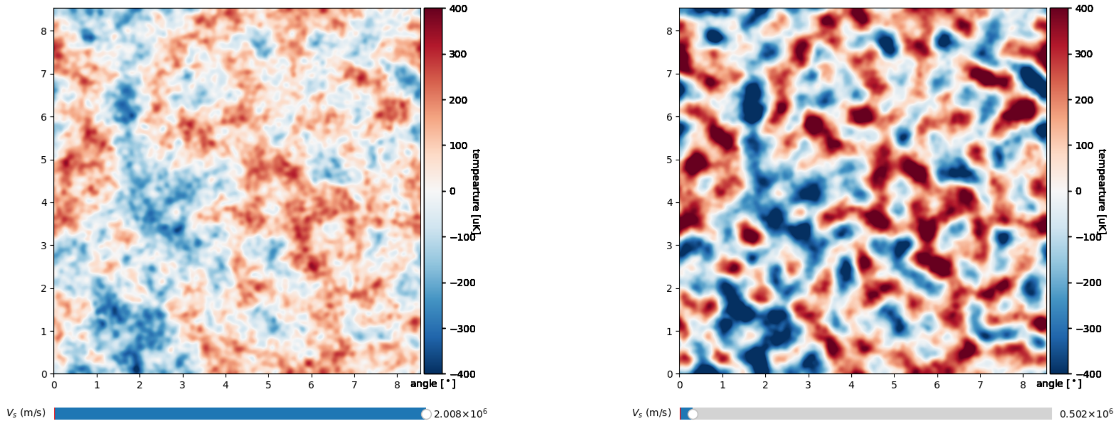


Figure 5: The figure on the left shows the initial CMB with a critical baryon density of 0.05. The figure on the right shows the angular power spectrum with a critical baryon density of 1. These images are taken from a gif file which can be accessed through the link here

Studying the images in figure 5, one can see that the first image on the left corresponds with the angular power spectrum image figure 2. This temperature image of the CMB corresponds to the highest speed and lowest critical baryon density. The red and orange spots indicate an area of higher density with more fluctuations, and the blue spots indicate areas of lower density with lower temperature fluctuations.

As the density of baryons is increased, the gravitational potential wells increase in depth. This causes the areas in the temperature imprint in the figure on the right hand side to look more intense in colour due to an increase in fluctuations in temperature in the over dense areas and a lower fluctuation rate in areas of lower density indicated in blue. The same logic as discussed above is used.

As well as these details, it can be seen in the temperature plots that the higher density CMB contains less small fluctuations between the varying areas of density. This is due to the damping effect which affects smaller angular scales greater than large angular scales. This damping effect is increased due to the decrease in the sound horizon and thus affected the smaller fluctuations in the CMB imprint making the large scale fluctuations more profound.

This project focused on creating information about changing the fundamental constants of the universe accessible to people outside of physics. With this goal in mind, gif files of the changes in the CMB were created. The changes in the CMB were also demonstrated through a slider changing the speed of sound in the early universe. This slider although not yet implemented on the website for accessible physics, is planned to be implemented in the future. The python code of for the slider is introduced in the Appendix section.

4.3 Changes in the Universe Today

For the changes made in the universe today, the speed of sound was studied as part of how it would affect everyday life. This information would be helpful for people outside everyday life to relate to physics.

The investigation about how changing the speed of sound would affect everyday life started with studying equation 22. Assuming the medium does not change and the mass of the particles do not change in the air, if the speed of sound is increased to $3 \times 10^5 m/s$ then the temperature in equation 22 increases. This increase would account for the traveling vibrations carrying more kinetic energy. As the acoustic waves travel the air would heat up to approximately $224,000,000K$ assuming we take the mass of an air particle to be $4.81 \times 10^{-26} kg$ and the adiabatic air constant as 1.4 [15].

Next the sound waves were studied in the context of how the wavelength would change. While a sound wave travels, if the medium does not change there is no reason for the frequency to change. However if the speed changes the wavelength will absorb this change in order to balance equation 27.

With this logic as the speed of sound increases, the wavelength will also increase. This change is simulated below through python in figure 6. This gif file is simulated and displayed on the website as linked here.

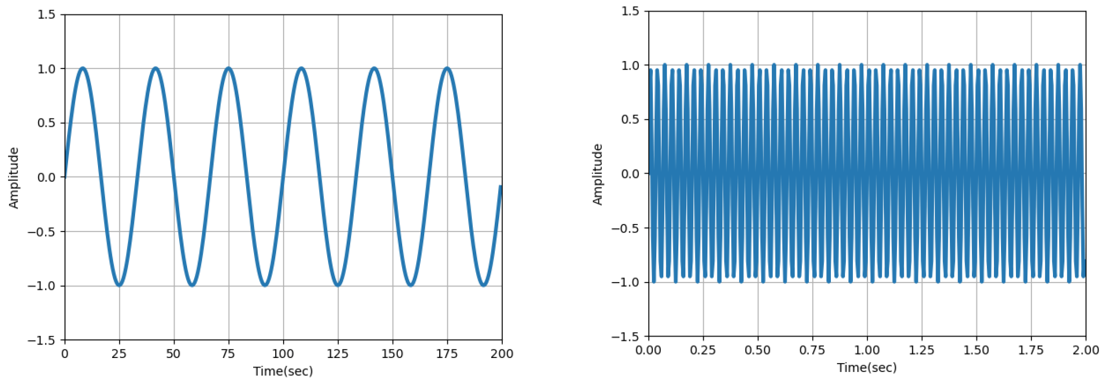


Figure 6: The figure on the left shows a sound wave in travelling at 300 m/s through a medium with frequency 10,000Hz. The figure on the right shows a sound wave in travelling at 300000 m/s through a medium with frequency 10,000Hz.

Assuming this change happens instantly, and frequency is responsible for pitch in acoustic waves the sound of these travelling waves can be studied. By calculating a wavelength from a frequency with speed $300m/s$, and finding the corresponding frequency from that wavelength with $3 \times 10^5 m/s$, we can find what this sound wave would hypothetically would sound like. If the range of frequencies that humans can hear is 20Hz to 20kHz, as soon as the speed of sound increases by a factor of 10^3 the only frequencies that could be potentially heard by humans would be 0Hz to 23Hz. This range of frequencies would include extremely low frequency sounds from mammals such as whales and elephants.

4.4 Further Implications and Looking Forward

As the baryonic density is changed, this would affect further constants in nature such as the curvature parameter Ω_k, the expansion of the universe and the amount of dark matter in our universe. These effects have not been studied yet in relation to the change in physical baryonic density however they plan to be studied further as the effort is made in order to connect these changes throughout the universe evolution

While studying the early universe every single one of the changes made to the speed of sound or the physical baryonic density was made instantly at that specific point in time. However a change could be made during one point in the nucleosynthesis period and propagated through the recombination era to study the change in the speed of sound while connecting the intricate relationships between all of the constants in the early universe.

Looking forward, for this project the information collected will first be made available on the website linked here. Once the information is made public, it is planned for the CMB slider to be implemented as part of the website. After this the connection between the time periods will be studied in an attempt to show how changes in the early universe can affect the stellar epoch and more.

5 Conclusion

The aim of this project was learning about how the fundamental parameters impact our universe. By constructing visualisations and explanations catered to people outside of physics we can demonstrate the impact physics has on everyday life.

During the project, three time frames were studied including the universe at present, early universe during the nucleosynthesis period and the recombination period. The implications of these changes were studied in relation to the primordial elements, the cosmic microwave background (CMB) and the Earth at present time. These changes were visually displayed and presented on the website as linked previously.

Looking forward, more of this information will be made publicly available on the website and more animations will be created. It is also planned for the CMB simulation including a slider controlling the speed of sound in the early universe to be implemented as part of the website.

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I would firstly like to express my gratitude towards my collaborator on this project Edzus Nakums and my supervisor Dr. Venus Keus. I had several discussions with them regarding the project and how topics could be approached and so many of the ideas developed over this project were created with their help. Without their support much of my understanding within this project would have been greatly limited.

Next I would like to say thank you to the creators of the CMB Planck Simulator as the idea to create a variable slider changing the speed of sound for the CMB was originally inspired from their project.

The help that the McMahon School of Cosmology and their resources within the summer school for learning about the CMB could not be understated in creating this project. Their functions and tutorials on creating the code for the CMB were essential to this project. The code also included using the CAMB python programming language which was an extremely important resource on investigating the cosmological parameters of the universe and creating theoretical data in order to use for the CMB simulations.

Lastly I would like to thank the Dublin Institute for Advanced Studies and the organisers of the DIAS internship projects 2023 Dr. Atri Dey and Dr. Saki Koizumi. As the organisers, they offered their continous support throughout the entirety of the project.

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Appendix

Python Code for the Nucleosynthesis Period

```
import numpy as np
import matplotlib.pyplot as plt
import camb
from camb.bbn import BBNPredictor

params = camb.CAMBparams()
params.set_cosmology(H0=70, ombh2=0.0245, omch2=0.05, mnu=0.06, omk=0, tau=0.06)
params.InitPower.set_params(ns=1, r=0)
params.Evolve_baryon_cs=True
params.Want_CMB=True

results = camb.get_results(params)

omega=np.arange(0.02,.16,.002)
omegah=omega*(.7)**2

hefrac=np.zeros([np.size(omegah)])

k=0
for i in omegah:
    params = camb.CAMBparams()
    params.set_cosmology(H0=70, ombh2=i, omch2=0.05, mnu=0.06, omk=0, tau=0.06)
    params.InitPower.set_params(ns=1, r=0)
    params.Evolve_baryon_cs=True
    params.Want_CMB=True

    results = camb.get_results(params)
    he=params.YHe
    hefrac[k]=he
    k+=1

plt.title('Relationship between Helium Fraction and $\Omega_b h^2$')
plt.ylabel('Fraction of Helium after BBN')
```

```
plt.xlabel('$\Omega_b h^2$ ')
plt.grid(True)
plt.plot(omegah,hefrac,'--bo',markersize=3)


plt.savefig(f'bbnhelium.png', format='png', bbox_inches='tight')
```

Python Code for the Recombination Period

```
import numpy as np
import matplotlib.cm as cm
import matplotlib.mlab as mlab
import matplotlib.pyplot as plt
from matplotlib.widgets import Slider
from matplotlib import animation
from matplotlib.animation import FuncAnimation
import imageio
## If using animation side of code make sure to use
#%plotting specific arguement below
#%matplotlib notebook
#If using slider within the code make sure to use
#%plotting arugument below
%matplotlib tk

Thank you to the The McMahon Cosmology Lab for
the CMB Course on plotting CMB: https://sites.google.com/uchicago.edu

/themcmahoncosmology
lab/cmb-summer-school?authuser=0

def load_funcOmB(vs_index):
    filename = f"cambB{vs_index}.txt"
    ell, DlTT = np.loadtxt(filename, usecols=(0, 1), unpack=True)
    #plt.plot(ell,DlTT)
    #plt.ylabel('$D_{\ell}$ [$\mu$K$^2$]')
    #plt.xlabel('$\ell$')
    #plt.grid(True)
    #plt.show()
    return ell, DlTT

#To calculae the physical baryon denisty
def bardenistycal(x):
    return x*(9.124e-27)

#To calculate the sound speed
def cscalca(y):
    c=3e8
    return c/(np.sqrt(3+(9*(y*9.124e-27)/(4*4.6e-32))))
```

```
omega=np.arange(0.05,1.05,.05)
omega=np.round(omega,4)
bary=bardenistycal(omega)
cs=cscalca(omega)
cs=np.round(cs,2)

def make_CMB_T_map(N, pix_size, ell, DlTT):

    "makes a realization of a simulated CMB sky map given an
    input DlTT as a function of ell,"
    "the pixel size (pix_size) required and the
    number N of pixels in the linear dimension."
    np.random.seed(100)
    # convert Dl to Cl
    ClTT = DlTT * 2 * np.pi / (ell*(ell+1.))
    ClTT[0] = 0. # set the monopole and the dipole of the Cl spectrum to zero
    ClTT[1] = 0.

    # make a 2D real space coordinate system
    onesvec = np.ones(N)
    inds  = (np.arange(N)+.5 - N/2.) /(N-1.)
    # create an array of size N between -0.5 and +0.5
    # compute the outer product matrix: X[i, j] = onesvec[i] * inds[j] for i,j
    # in range(N), which is just N rows copies of inds - for the x dimension
    X = np.outer(onesvec,inds)
    # compute the transpose for the y dimension
    Y = np.transpose(X)
    # radial component R
    R = np.sqrt(X**2. + Y**2.)

    # now make a 2D CMB power spectrum
    pix_to_rad = (pix_size/60. * np.pi/180.)
    # going from pix_size in arcmins to degrees and then degrees to radians
    ell_scale_factor = 2. * np.pi /pix_to_rad
    # now relating the angular size in radians to multipoles
    ell2d = R * ell_scale_factor
    # making a fourier space analogue to the real space R vector
    ClTT_expanded = np.zeros(int(ell2d.max())+1)
    # making an expanded Cl spectrum (of zeros)
    #that goes all the way to the size of the 2D ell vector
    ClTT_expanded[0:(ClTT.size)] = ClTT
    # fill in the Cls until the max of the ClTT vector

    # the 2D Cl spectrum is defined on the multiple
    #vector set by the pixel scale
    CLTT2d = ClTT_expanded[ell2d.astype(int)]
    #plt.imshow(np.log(CLTT2d))
    # now make a realization of the CMB with the
    #given power spectrum in real space
```

```
    random_array_for_T = np.random.normal(0,1,(N,N))
    FT_random_array_for_T = np.fft.fft2(random_array_for_T)
    # take FFT since we are in Fourier space

    FT_2d = np.sqrt(CLTT2d) * FT_random_array_for_T
    # we take the sqrt since the power spectrum is T^2
    plt.imshow(np.real(FT_2d))


    ## make a plot of the 2D cmb simulated map in
    Fourier space, note the x and y axis labels need to be fixed
    #Plot_CMB_Map(np.real(np.conj(FT_2d)*FT_2d*ell2d *

    (ell2d+1)/2/np.pi),0,np.max(np.conj(FT_2d)*FT_2d*ell2d *

    (ell2d+1)/2/np.pi),ell2d.max(),ell2d.max())  ###

    # move back from ell space to real space
    CMB_T = np.fft.ifft2(np.fft.fftshift(FT_2d))
    # move back to pixel space for the map
    CMB_T = CMB_T/(pix_size /60.* np.pi/180.)
    # we only want to plot the real component
    CMB_T = np.real(CMB_T)

    ## return the map
    return(CMB_T)

def Plot_CMB_Map(Map_to_Plot,c_min,c_max,X_width,Y_width):
    from mpl_toolkits.axes_grid1 import make_axes_locatable
    print("map mean:",np.mean(Map_to_Plot),"map rms:",np.std(Map_to_Plot))
    fig=plt.gcf()
    im = plt.imshow(Map_to_Plot, interpolation='bilinear',

    origin='lower',cmap=cm.RdBu_r)
    im.set_clim(c_min,c_max)
    ax=plt.gca()
    divider = make_axes_locatable(ax)
    cax = divider.append_axes("right", size="5%", pad=0.05)

    cbar = plt.colorbar(im, cax=cax)
    #cbar = plt.colorbar()
    im.set_extent([0,X_width,0,Y_width])
    plt.ylabel('angle $[^\circ]$')
    plt.xlabel('angle $[^\circ]$')
    cbar.set_label('tempearture [uK]', rotation=270)

    plt.draw()
    return(0)
```

```
#initial file and parameters
fig, axis = plt.subplots(figsize=(7, 7))
fileinitial=f"cambB0.05.txt"
ell, DlTT = np.loadtxt(fileinitial, usecols=(0, 1), unpack=True)

## variables to set up the size of the map
N = 2**10  # this is the number of pixels in a linear dimension
            ## since we are using lots of FFTs this should be a factor of 2^N
pix_size  = 0.5 # size of a pixel in arcminutes

## variables to set up the map plots
c_min = -400  # minimum for color bar
c_max = 400   # maximum for color bar
X_width = N*pix_size/60.  # horizontal map width in degrees
Y_width = N*pix_size/60.  # vertical map width in degrees


CMB_T = make_CMB_T_map(N, pix_size, ell, DlTT)
Plot_CMB_Map(CMB_T, c_min, c_max, X_width, Y_width)

#Slider for Sound Speed
ax=plt.sca(axis)
slider_axCS = plt.axes([0.2, 0.001, 0.6, 0.05])
# Position of the slider
# Set the range and initial value
slidercs = Slider(slider_axCS, '$V_s$ (m/s) ',
valmin=449070.8,valmax=2008177.42, valinit=.025,valstep=cs,
                  dragging=True)


def updateB(val):
    axes=plt.sca(axis)
    index = np.where(cs == slidercs.val)[0][0]# Get the current slider value
    slider_value=omega[index]
    data1 = load_funcOmB(slider_value) # Generate new heatmap data
    ell= data1[0]
    DlTT=data1[1]# Update the heatmap with new data
    CMB_T = make_CMB_T_map(N, pix_size, ell, DlTT)
    return Plot_CMB_Map(CMB_T, c_min, c_max, X_width, Y_width)

slidercs.on_changed(updateB)

plt.show()

##Making a GIF for CMB Code Manually

Refernce for this code:
https://towardsdatascience.com
/how-to-create-a-gif-from-matplotlib-plots-in-python-
```

```
6bec6c0c952c#:~:text=You%20can%20create%20a%20GIF,

Into%20a%20GIF%20with%20imageio

fig, axis = plt.subplots(figsize=(7, 7))
N = 2**10  # this is the number of pixels in a linear dimension
            ## since we are using lots of FFTs this should be a factor of 2^N
pix_size  = 0.5 # size of a pixel in arcminutes

    ## variables to set up the map plots
c_min = -400  # minimum for color bar
c_max = 400   # maximum for color bar
X_width = N*pix_size/60.  # horizontal map width in degrees
Y_width = N*pix_size/60.  # vertical map width in degrees

slider_value=omega[20]
data1 = load_funcOmB(slider_value)

ell= data1[0]
DlTT=data1[1]

CMB_T = make_CMB_T_map(N, pix_size, ell, DlTT)
Plot_CMB_Map(CMB_T, c_min, c_max, X_width, Y_width)
plt.savefig(f'cmb{omega[20]}.png', format='png', bbox_inches='tight')

fig, axis = plt.subplots(figsize=(7, 7))
N = 2**10  # this is the number of pixels in a linear dimension
            ## since we are using lots of FFTs this should be a factor of 2^N
pix_size  = 0.5 # size of a pixel in arcminutes

    ## variables to set up the map plots
c_min = -400  # minimum for color bar
c_max = 400   # maximum for color bar
X_width = N*pix_size/60.  # horizontal map width in degrees
Y_width = N*pix_size/60.  # vertical map width in degrees
plt.ylabel('$D_{\ell}$ [$\mu$K$^2$]')
plt.xlabel('$\ell$')
plt.grid(True)
plt.xlim(0,2500)
plt.ylim(0,50000)

slider_value=omega[20]
data1 = load_funcOmB(slider_value)
ell= data1[0]
DlTT=data1[1]
plt.plot(ell,DlTT)
plt.savefig(f'cmb{omega[20]}.png', format='png', bbox_inches='tight')

frames1 = []
for t in omega:
```

```
    image = imageio.v2.imread(f'cmb{t}.png')
    frames1.append(image)

imageio.mimsave('cmbangpowerspectransition.gif', # output gif
                frames1,          # array of input frames
                duration=2,loop=0)      #loop indefintely
```

Python Code for Universe Today

```
import numpy as np
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D
from matplotlib import animation
from matplotlib.animation import FuncAnimation
from IPython.display import HTML
import ffmpeg

References:
http://louistiao.me/posts/notebooks/embedding-
matplotlib-animations-in-jupyter-notebooks/

fig = plt.figure()
axis = plt.axes(xlim =(0, 2),
                ylim =(-1.5, 1.5))
plt.grid(True)
plt.xlabel('Time(sec)')
plt.ylabel('Amplitude')
line, = axis.plot([], [], lw = 3)

def init():
    line.set_data([], [])
    return line,

# initializing empty values
# for x and y co-ordinates
xdata, ydata = [], []

# animation function
def animate(i):
    # t is a parameter which varies
    # with the frame number
    t = 0.005 * i

    x = t
    #creating a wave equation with speed 3e5 and frequency 1e4
    y = np.sin(2*np.pi*x*(3e5/1e4))
    xdata.append(x)
    ydata.append(y)
    line.set_data(xdata, ydata)
```

```
    return line,

anim = FuncAnimation(fig, animate, init_func=init,
                        frames=400, interval=20, blit=True)

anim.save('wave3e5.gif')
#anim.save('wave3e5.mp4')

fig = plt.figure()
axis = plt.axes(xlim =(0, 200),
                ylim =(-1.5, 1.5))
plt.grid(True)
plt.xlabel('Time(sec)')
plt.ylabel('Amplitude')
line, = axis.plot([], [], lw = 3)
# what will our line dataset
# contain?
def init():
    line.set_data([], [])
    return line,

# initializing empty values
# for x and y co-ordinates
xdata, ydata = [], []

# animation function
def animate(i):
    # t is a parameter which varies
    # with the frame number
    t = 0.5 * i
    L = 1e4
    v=300
    x = t
    #creating a wave equation with speed 300 and frequency 1e4
    y = np.sin(2*np.pi*x*(v/L))
    xdata.append(x)
    ydata.append(y)
    line.set_data(xdata, ydata)

    return line,

anim = FuncAnimation(fig, animate, init_func=init,
frames=400, interval=20, blit=True)

anim.save('wave300.gif')
#anim.save('wave300.mp4')
```