Title: Cosmic Microwave Background (CMB)

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Abstract:

The cosmic microwave background (CMB) has revolutionized astrophysics. My paper describes its importance to high school students. CMB was first recorded by the Cosmic Background Explorer (COBE), a spacecraft launched to obtain CMB data. The first time the CMB was analysed in temperature, it was all the same, but reducing the fraction to 1/100,000 in temperature fluctuations showed us the current CMB anisotropies we see today(“CMB Introduction,” n.d.). This also answered the question of how galaxies and nebulas were formed. With the discovery of CMB anisotropies and using quantum fluctuations, scientists came up with a theory of acoustic oscillations; by combining data from other satellites they created the power spectrum, which is a graphical representation of the relationship between multipole and temperature fluctuations. Using CMB monopole cooling, scientists were able to calculate Hubble’s Constant, which encompasses the rate at which the universe is expanding in Megaparsec (Mpc) (1 Mpc = 3.24×10^{20} km). With this paper, I want the readers to be inspired to pursue and unveil more secrets of our universe.

Introduction:

When you look up at the sky, do you wonder what is out there in the distance? Does it ever occur to you how, and what, are the reasons the universe is the way it is? Well, some of the most unnoticeable things have answers to our biggest questions—for example, the cosmic microwave background (CMB).

The universe is a vast plane consisting of many observables and phenomena. The CMB is one of those observables found in the universe. During the Big Bang, a lot of heat was emitted in the universe, which had enough energy to split hydrogen atoms to its constituent protons and electrons. After 300,000 years, the universe started cooling down, which resulted in the formation of hydrogen and helium atoms; the energy and photons released due to the formation is known as CMB.

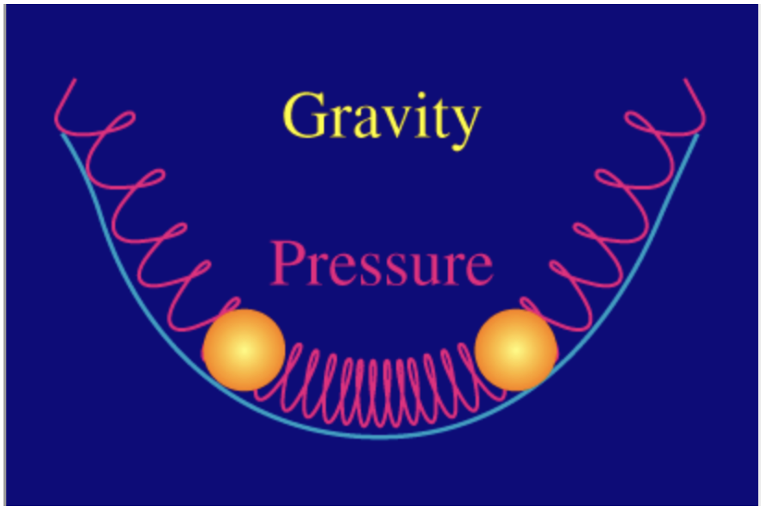
The first time CMB was recorded and measured was by the Cosmic Background Explorer (COBE), which was launched by NASA on November 18, 1989 (Brian Dunbar, n.d.). The discovery of CMB by COBE was groundbreaking, as it opened up a new chapter in astrophysics and cosmology. The CMB helped in answering a lot of questions as well as bringing up new ones.

Using CMB, we were finally able to answers to big and unknown questions about our universe. This paper is directed towards high school students, to inspire them to pursue the line of astrophysics/ astronomy and educate them on CMB, as it is important for high school students to know what's beyond our home planet.

How does CMB help us detect concentrations of matter

CMB anisotropy maps help us detect concentrations of matter, as the CMB anisotropy maps depict fluctuations in energy which was released during recombination. The pattern formed in anisotropy maps depicts sound waves, due to what we call acoustic oscillations. In the early universe, when the CMB was hotter than 3000K, the universe consisted of photon-baryon fluid. Gravity here tries to compress the photon baryon fluid and create a high density region, which results in the radiation pressure counteracting the forces.

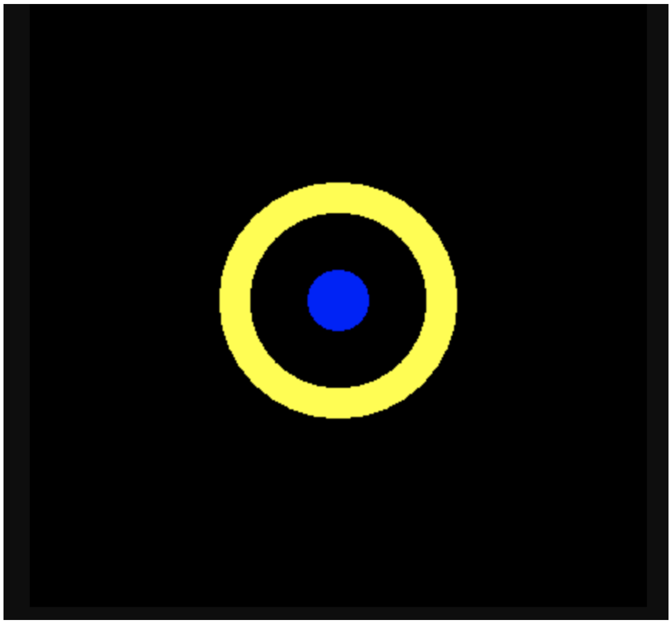
(Diagram 1)



(The strings here represent the radiation pressure and the yellow balls represent the photons. CMB Introduction. http://background.uchicago.edu/~whu/intermediate/gravity.html)

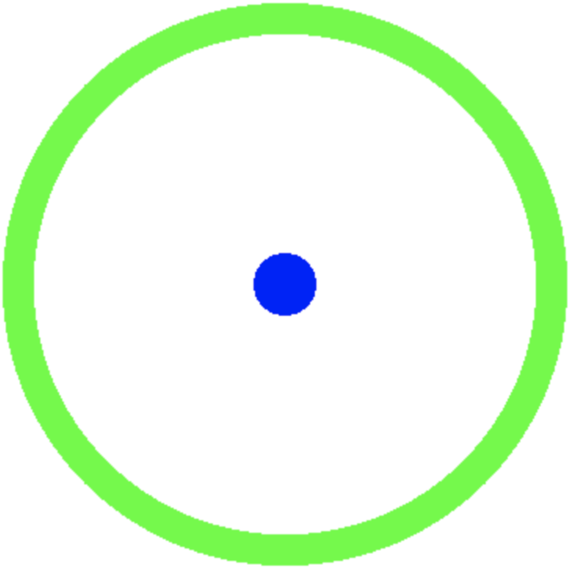
This interaction between the photon-baryon fluid and gravity is what we refer to as acoustic oscillations. Although these oscillations were between the photon baryon fluid and gravity, the potential hills and wells created showed characteristics of longitudinal waves or sound waves. The potential wells (areas containing high densities of photon-baryon plasma)starts expanding in spherical shape and oscillates like a sound wave due to intense pressure created by concentration of the photon baryon fluid. The sound wave, before recombination/decoupling, would contain dark matter at its centre with the photon-baryon fluid expanding, right after recombination the photons exit the fluid at the speed of light and the fluid left behind leaves an imprint at where it oscillated last. This phenomenon is also called freeze-frame, as seen in the picture below(“Baryon Acoustic Oscillation Cosmology,” n.d.).

(Diagram 2)



(An image of the photon-baryon plasma(in yellow) and dark matter(in blue) before recombination)

(Diagram 3)

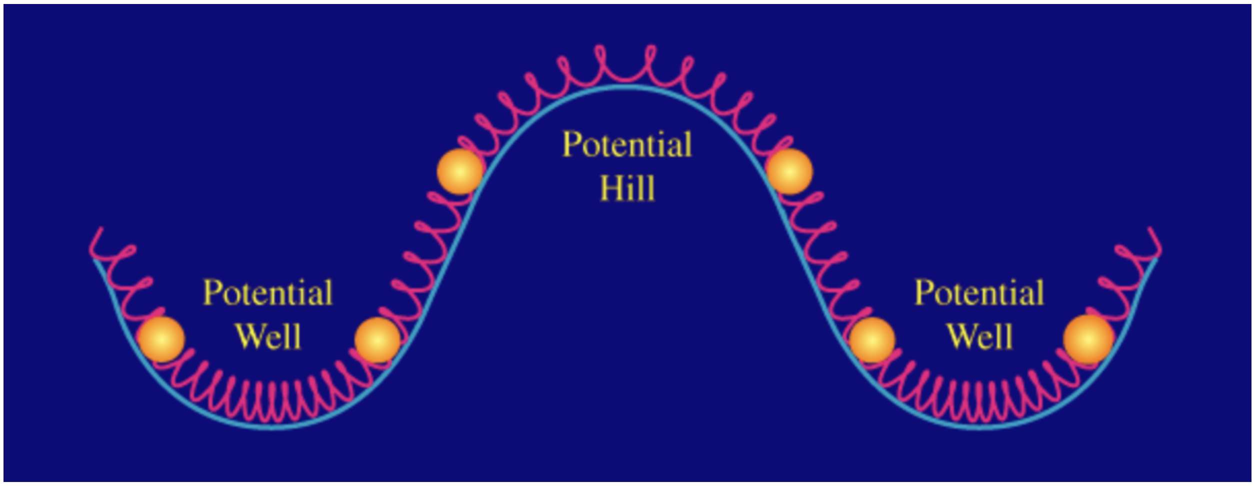


(An image of just the baryon plasma(in green) and the dark matter(in blue) during recombination. The green ring freezes at the position when the photons exit the plasma. Baryon Acoustic Oscillation Cosmology. https://www.astro.ucla.edu/~wright/BAO-cosmology.html)

After decoupling, the photon exits the photon-baryon fluid. In the two diagrams, the dark matter is blue, baryons are green, and photons are red. Before decoupling, the photon baryon fluid was in a high intensity region and was expanding spherically as seen in Diagram 1 (red and green makes yellow). After the decoupling, the photon exits the spherical shape created, shown in Diagram 2 (the yellow circle turns green). Now the leftover baryon fluid surrounds the dark matter. This sound wave travels till recombination and therefore distances covered by this fluid (around 450,000 light years before recombination) expand with the Universe and stretch to almost 50 million light years and continue expanding(“Baryon Acoustic Oscillation Cosmology,” n.d.). During recombination, when the oscillations stop occurring and photons exit the fluid at the speed of light, this instant is called freeze-frame and the perimeter covered by the fluid before recombination is where matter starts depositing and continues to expand with the perimeter, while the other areas have little to no matter. The area with little to no matter keeps on expanding with the universe.

CMB anisotropy maps helps us determine where matter is concentrated and where little to no matter would be present. The CMB is an observable which shows us the past. During the freeze-frame, the oscillations, which froze during their extrema, would create the most temperature fluctuations. In the early universe (before recombination), quantum fluctuations would create areas of high and low density. Similarly to what I mentioned before about what would happen to the fluid due to high density, due to quantum fluctuations there were regions of low density. Now in the regions of low density, potential hills would form and similarly in the regions of high density, potential wells would form. Now, when the freeze-frame occurred, the protons which exited the oscillation during their extrema (during compression or rarefaction) had the most temperature fluctuations("CMB Introduction," n.d.).

(**Image 4)**



(This image shows how the universe consisted of quantum fluctuations consisting of either potential hills or potential wells. *CMB Introduction*. (n.d.). http://background.uchicago.edu/~whu/intermediate/planewave.html)

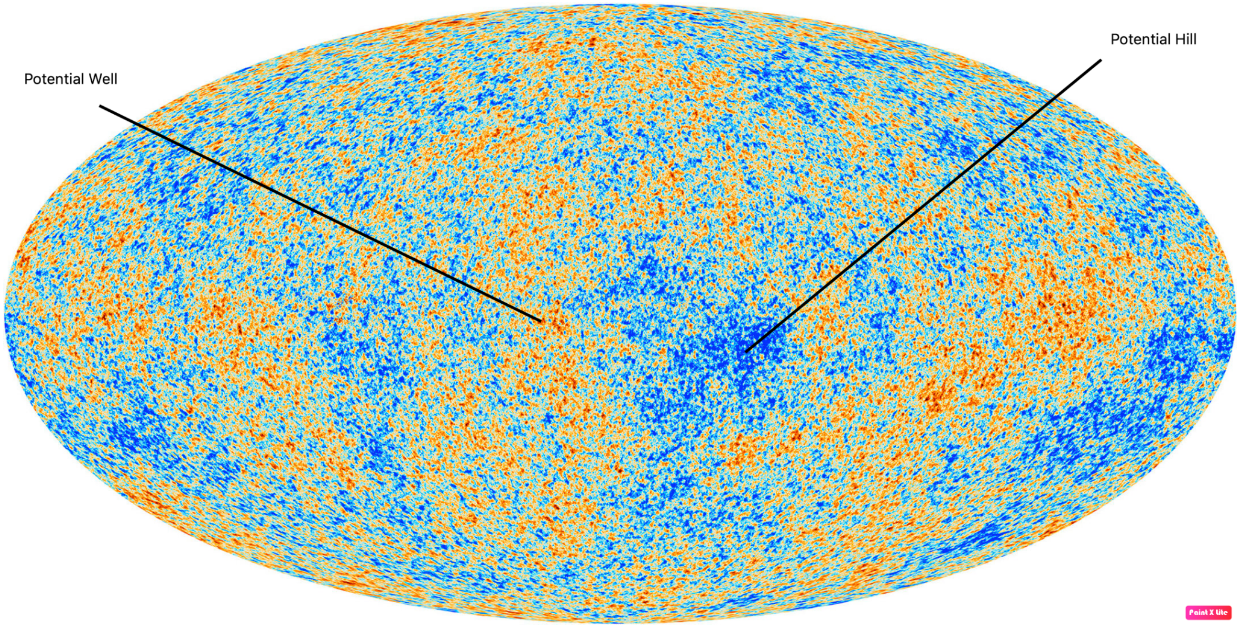
During the freeze-frame, the protons which exited the oscillation during their extrema (during compression or rarefaction) had the most temperature fluctuations. Areas of high temperature in the CMB anisotropies are considered as potential wells as

- $density = mass/area$
- Density here is taken in a 2-dimensional space rather than the usual 3-dimensional space.
- If the density is larger, hence the area is smaller and the probability of particles colliding also increases.
- $pressure = force/area$
- As the area is smaller, the pressure would increase and hence the force would also increase.

- $Work = Energy = Force \times v$
- As force is greater, hence the energy is greater too.

Similarly, when the oscillation froze during a rarefaction, the temperature is significantly less.

(Image 5)



(A CMB anisotropy map created by the *Planck* Team, the angular scale of this CMB anisotropy is ~0.08°. *Planck CMB*. (n.d.). https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB)

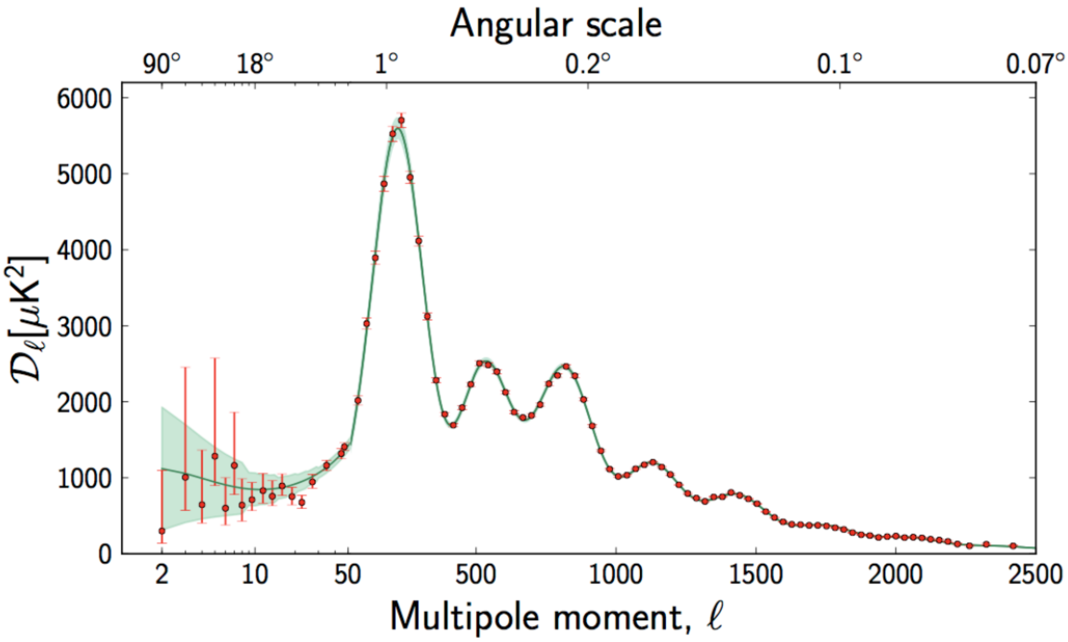
The image above is a CMB anisotropy map created by the *Planck* Satellite launched by the European Space Agency. This is a picture depicting the Universe when it was only 380,000 years old at scales of $\sim 0.08^\circ$. As we can see, there are regions of dark red, red, orange, blue, and dark blue. Now, this can only be seen at 1 part per 100,000 of deviation from the mean temperature (2.73K). The areas where a potential well/ region of high density occurred during the acoustic oscillation period is shown as dark red/ the coolest region, this is because, CMB anisotropies are footprints of the universe before recombination and hence the dark red region/

cold region is a potential well, which means that gravity will try to impede the photon from escaping. Thus, due to the excess energy used to escape the gravitational force , the CMB photon loses its energy it gained during recombination, hence showing as a dark red region. Similarly, the bright blue region/the hottest region indicates the potential hill. This is because, rather than the gravitation pushing the photon-baryon fluid down, it was pushing it up; hence the photons retain the same amount of energy during their escape to the fluid during recombination (*Do Hot Spots in the CMB Anisotropy Map Actually Correspond to Denser or Less Dense Regions?*, n.d.).

How CMB helps us determine the shape in which the universe is expanding

At recombination, the fluid which was oscillating froze while the photons emitted moved at the speed of light. Now, using the CMB anisotropies at different scales, we create the CMB power spectrum. In simple terms, the CMB power spectrum shows us the temperature fluctuations at different angular scales in radians and using these we can discern the scales of fluctuations.

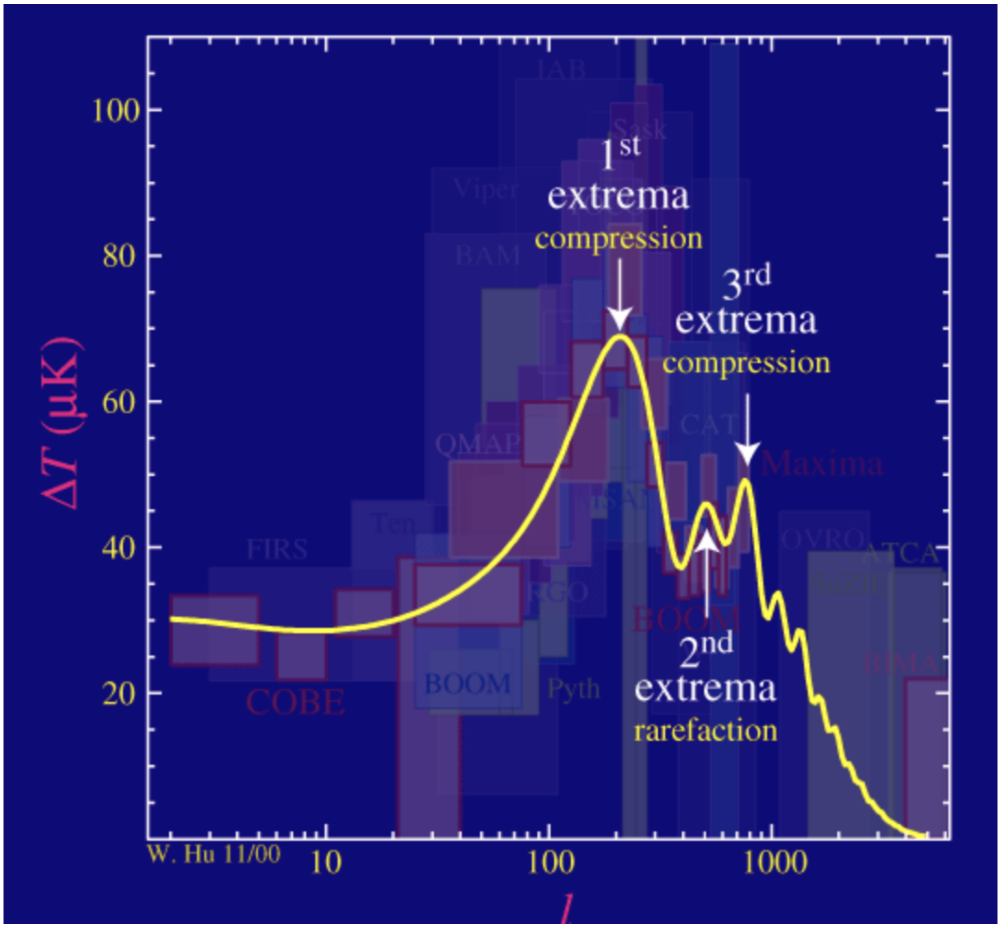
(Image 6)



(This image is a graph showing the relationship between temperature fluctuations and the multipole moment. *NivGK.png (1094×652)*. (n.d.). https://i.stack.imgur.com/NivGK.png)

This image is a graph representing the relationship between deviation in temperature in microKelvin squared (μK^2) and the angular scale in degrees and the multipole moment. The relationship between the multipole moment and the angular scale is approximately given by $\theta = \frac{180}{l}$; hence, the greater the angle, the smaller the multipole moment. This graph shows us how at different angular scales there is a deviation of temperature. This graph was created using data from multiple sources such as the COBE, *Planck* etc.

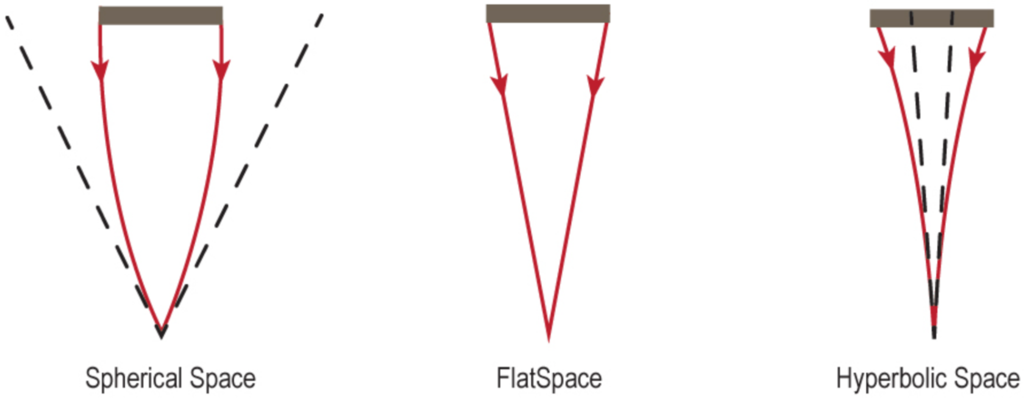
(Image 7)



(This image shows the multiple data extracted from different spacecrafts, where the data was averaged to make this graph. *CMB Introduction*. (n.d.). http://background.uchicago.edu/~whu/intermediate/score1.html)

Now the question arises: how does the universe expand? Does it expand in a straight line or not? The universe was said to be a bubble before the big bang. According to astrophysicists, mass, and energy in the Universe can bend spacetime. Now, the universe can curve in multiple ways, but we can always decipher it by how light travels. The light travelling will always follow the curvature of space-time, i.e., travel along a geodesic. A geodesic is the shortest path along any curve, and this can be seen in the image below.

(Image 8)

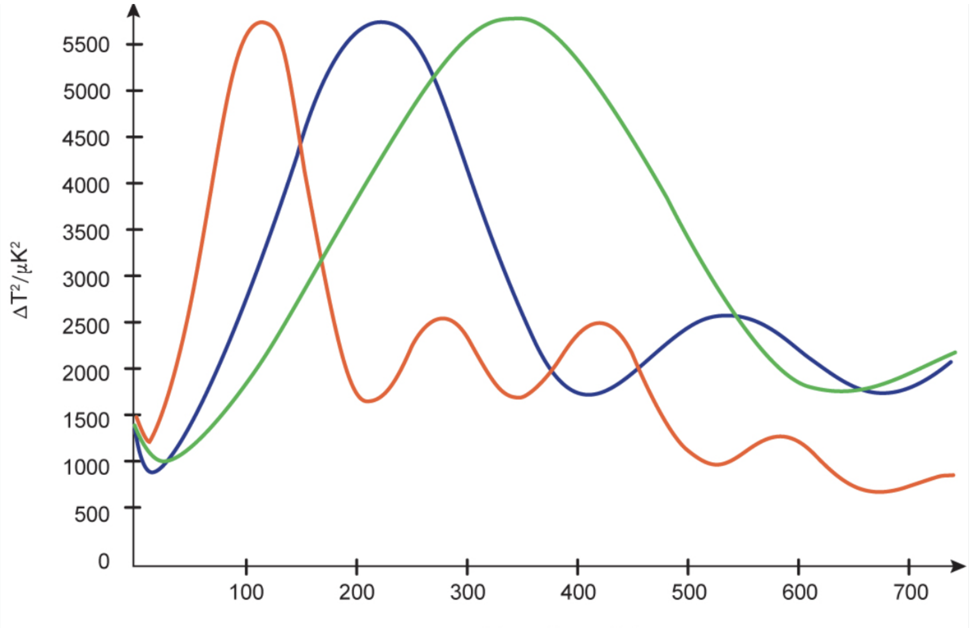


(The above image depicts the three different ways the universe could expand. Libretexts. (2023). 15.5: Comparing Models and Data – The CMB and the Curvature of Space. *Physics LibreTexts*. https://phys.libretexts.org/Bookshelves/Astronomy__Cosmology/Big_Ideas_in_Cosmology_(Coble_et_al.)/15%3A_The_Cosmic_Microwave_Background/15.05%3A_Comparing_Models_and_Data_-_The_CMB_and_the_Curvature_of_Space)

The image above shows three different ways space-time could curve: spherical, flat or hyperbolic, the red lines show how the universe is curving while the dotted lines show the geodesic path light is following. The spherical path is a positive curve and here the light is passing beyond the red line while in the second diagram where the space is expanding without any curves, there is no external geodesic path, and hence light moves with the universe, while the third diagram showing the universe expanding in a hyperbolic shape shows in an inward geodesic. This also explains how CMB anisotropies with larger angles have bigger dark red and blue spots, while smaller angles show smaller dark red and blue spots, as the regions are either stretched out due to space-time expanding spherically or getting compressed due to expanding in a hyperbolic manner. (Libretexts, 2023).

The CMB power spectrum is shaped differently for these three possibilities of curvature of space-time.

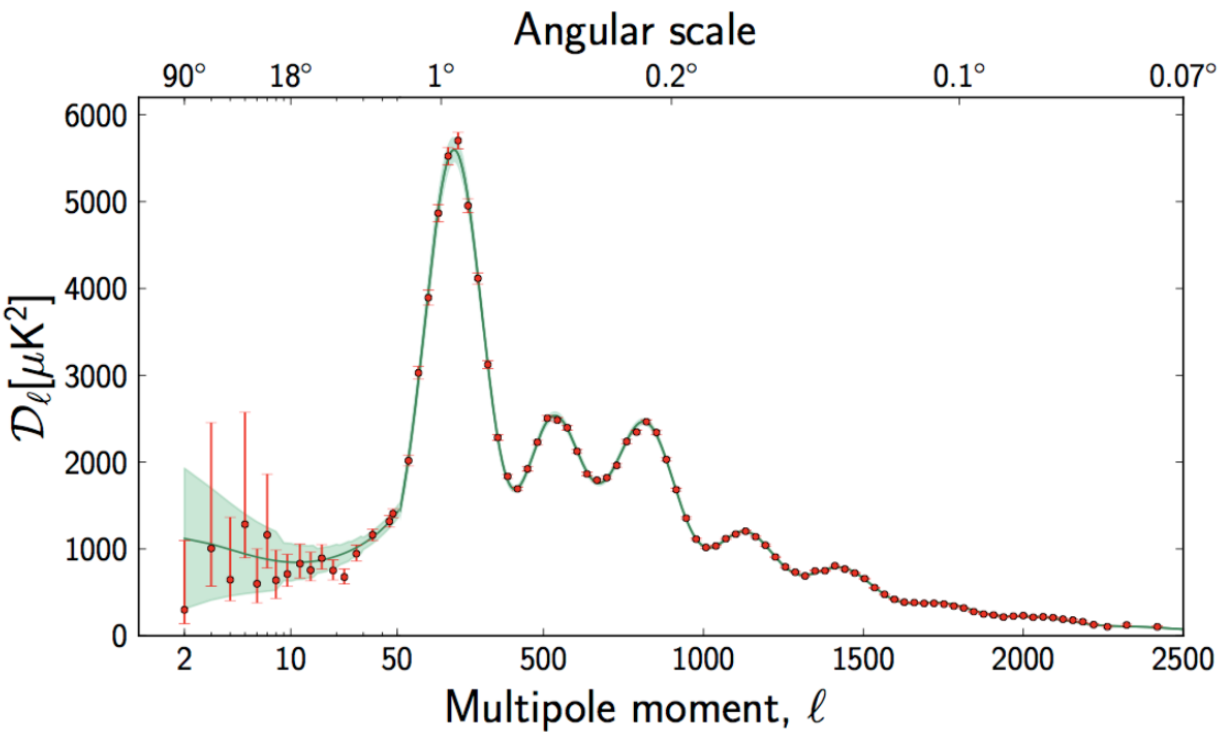
(Image 9)



(These models were run with CAMB software through NASA's Lambda interface. Libretexts. (2023). 15.5: Comparing Models and Data - The CMB and the Curvature of Space. *Physics LibreTexts*. https://phys.libretexts.org/Bookshelves/Astronomy__Cosmology/Big_Ideas_in_Cosmology_(Coble_et_al.)/15%3A_The_Cosmic_Microwave_Background/15.05%3A_Comparing_Models_and_Data_-_The_CMB_and_the_Curvature_of_Space)

This is the power spectrum depicting three different curves, each depicting a different configuration the universe could have expanded in. The orange curve is where the Universe is spherical, while the blue curve depicts a universe which is flat and the green where the universe is a hyperbola. Now, the most notable difference is the shift of the first maxima to the right. We can see that the orange curve's first maxima is around l≅100 or around 1.8 degrees, Similarly the blue curve's first maxima is around a multipole moment of 200-220 which is almost 1 degree and the green's curve's maxima is around 350-370 which in the angular scale is close to 0 (Libretexts, 2023).

(**Image 10)**



(*NivGK.png (1094×652)*. (n.d.). https://i.stack.imgur.com/NivGK.png)

This image is the CMB power spectrum created using data collected by the *Planck* satellite. Now the red lines and dots are the error bars, showing us how the data has been averaged out from multiple readings. If we look at the graph, the first maximum is around 1° in the angular scale, or around a multipole moment of 200-220. This shows us that the universe is expanding almost as a flat surface.

This data has been recorded without taking into consideration dark matter's influence. Dark Matter has an important impact on the deviation of the CMB photon's deviation of path. The dark matter, which we believe is invisible, reduces the amplitude of all the maxima in the CMB power spectrum, which is caused by introducing the ratio of dark matter to radiation (Biello, 2006).

How CMB helps us determine the rate of expansion

After the Big Bang, the Universe has been expanding at an exponential rate. Now to determine the rate at which the universe is expanding, there are many ways to determine it, such as, through direct observations using precise measurements or use something called CMB Monopole cooling. Now the constant we use to determine the rate at which the Universe is expanding is called the Hubble's Constant and the current value calculated by the *Planck* team is 67.4 ± 0.50 kms^{-1} Mpc^{-1}. The Hubble's Constant is an ever-changing constant influenced by the presence of dark energy, an invisible energy which we still do not have a complete grasp on. CMB Monopole cooling/ Hubble cooling of the temperature of CMB can be used to calculate the Hubble's Constant. The CMB monopole temperature and the cosmological scale factor(a) has an inverse relationship (Abitbol, Hill & Chluba, 2020)

$T_{CMB} \propto a^{-1}$

The following relationship is possible under some assumptions

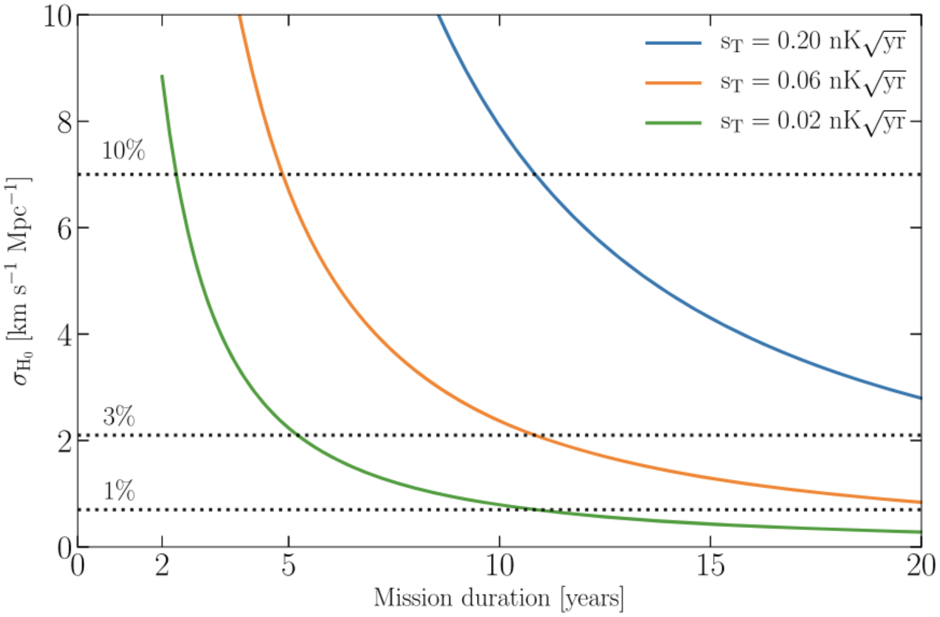
1- Photons are massless.

2- The CMB is thermal radiation.

3- The first law of thermodynamics is applicable.

4- The universe expands equally in all directions(Abitbol et al., 2020).

(Image 11)



(The graph shows the relationship between Hubble Constant's uncertainty(σ_{H0}) and Mission duration of the Fisher forecast in years using different effective sensitivities to T_{CMB}. 7. Abitbol MH, Hill JC, Chluba J. Measuring the Hubble Constant from the Cooling of the CMB Monopole. The Astrophysical Journal. 2020;893(1):18. https://doi.org/10.3847/1538-4357/ab7b70. doi:10.3847/1538-4357/ab7b70)

The three graphs here are exponentially decreasing over time. As we can see, the smaller the value of monopole temperature sensitivity, the closer the graph is to the centre. Now to calculate this data collected and calculate the rate of expansion we would need something called the cosmological scale factor. The cosmological scale factor is a parameter used to calculate the relative expansion of the universe using the Friedman equations.

Now let's imagine two galaxy clusters moving apart at Hubble's rate at a certain time t until time t_0. The equation would be equal to-

$$d(t) = a(t)d_0$$

Where

d(t) is the distance between two galaxy clusters during the time of recombination(t), a(t) is here the cosmological scale factor and d_0 is the distance between those same two galaxy clusters at time t_0 (Abitbol, Hill & Chluba, 2020).

Now, how does CMB monopole cooling help us determine the rate at which the universe is expanding, also known as the Hubble's Constant.

Now the function of Temperature(T_{CMB}≅T) with respect to time could be written as

$T(t) = \frac{T_0}{a(t)}$ where T_0 is the present temperature of the universe (2.725K).

Now the derivative of T(t) would be -

$T(t)' = - H(t)T(t)$ (Abitbol, Hill & Chluba, 2020).

Where H(t) is the Hubble's Constant.

Now let's take present Hubble's Constant (H_0) as 70 kms^{-1} Mpc^{-1} $= 7.2 \times 10^{-11}$ yr^{-1} and T_0 as 2.725K. Then the rate of change in temperature would be equivalent to

$T_0 = H_0T_0 = -0.20$ $nKyr^{-1}$

This means that over a span of 10 years, the CMB decreases by 2 nK(Abitbol, Hill & Chluba, 2020).

This shows us the relationship between Hubble's Constant and CMB Monopole cooling.

Conclusion

The discovery of the Cosmic Microwave Background (CMB) signalled a fundamental shift in cosmology and astrophysics. I tackled three key issues in my research, using the CMB to shed light on the intricate workings of the universe. This included mapping the CMB power spectrum and anisotropy, estimating expansion rates by CMB monopole cooling, and identifying patterns in the matter distribution. I had to tackle difficulties outside the scope of my formal education while exploring the world of mathematics and

Friedman's equations. The CMB has the possibility of revealing deeper mysteries and enticing us to explore the boundaries of the cosmos in ever-greater-detail as it continues to captivate the study of astrophysics.

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