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Estimating Baryon Density through the CAMB and Assessing its Reliability

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Abstract: The Cosmic Microwave Background Radiation and its anisotropies allow us to analyze many properties and phenomena of the early universe. One such important property is the Baryon Density(Ω_b), a cosmological constant for the density of Baryons in the universe in comparison to its critical density. Baryon Density affects the interactions of matter in the early universe and therefore the analysis of CMB Anisotropies to study how matter interacts allows for the estimation of the Baryon Density in the Early Universe. Understanding Ω_b, is crucial as it reveals information about the composition of the universe, such as the amount of dark matter and dark energy, the early formation of celestial bodies and matter-antimatter asymmetry. This paper aimed to test the reliability of CAMB, a simulation algorithm for CMB anisotropies, by estimating $\Omega_b h^2$. The CAMB mainly utilizes a combination of field equations, the Friedmann-Lemaître-Robertson-Walker metric, Fluid Equations, the Boltzmann Equation and Linear Perturbation theory in order to compute the CMB power spectra. We estimated the value of $\Omega_b h^2$, maintaining other cosmological parameters constant and changing $\Omega_b h^2$ from 0.01 to 0.03 in increments of 0.000625. The peaks, troughs, positions, damping scale and amplitudes of the resultant TT and TE power spectra were compared with data from the Planck Satellite. We use chi-square minimization and find the best fit value and uncertainty for$\Omega_b h^2$ to be 0.02325 ± 0.00015. The estimated value of the baryon density from our study was compared to existing estimates to evaluate the reliability of CAMB as a simulation and source of information for further CMB Anisotropy related research, where it was confirmed to be accurate. However, further developments using wider sets of data was acknowledged with deep learning being a potential step forward.

Keywords: Cosmic Microwave Background; Baryon Density; CAMB; Anisotropy; Estimation; Likelihood Analysis

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1. Introduction

Ever since its accidental discovery, physicists have refined the detection and analysis of the Cosmic Microwave Background. It is one of the strongest proofs for the Big Bang Theory and holds information which reveals much about the early universe as well as information which can give insight into many of the phenomena which led to the universe now. Originating from light that was emitted as baryons began to fuse, the Cosmic Microwave Background serves as a photograph of the state of the Universe in its earliest moments (Shu, F.H., 2023). Hence different basic parameters found from the beginning of the universe can be found through the analysis of the Cosmic Microwave Background. One such parameter is Ω_b or Baryonic Density, a cosmological constant for the density of Baryons in the universe in comparison to its critical density, the density at which the universe's gravitational pull would be equal to that of its expansion, resulting in a flat universe (Kamionkowski et al., n.d).

The derivation of Ω_b is significant in understanding the universe for a myriad of reasons. Mainly, understanding of the material composition of the universe and its resultant shape is made possible. Part of this is the connection between gravitational force from density and the expansion of the universe. The cosmic microwave background is the radiation first released approximately 400,000 years after the big bang. In those 400,000 years, the collision of baryons formed nuclei. Where before, the intense heat and free electrons scattered light, recombination fused free electrons with the nuclei to form neutral atoms. This allowed light to finally travel and with the expansion of the universe, the wavelength of the radiation stretched to a microwave. Being the oldest and farthest into the past that is possible to be observed through light, the CMB has been an important area of research and analysis (Chow, Denise, and Scott Dutfield, 2022). The method of viewing and analyzing the CMB is through anisotropy, the mapping of temperature differences as measured in the sky from Earth. The temperature differences within the anisotropy reveal the denser regions of space at the time of the first radiation. Understanding this gives insight into the composition of the universe, such as the amount of dark matter and dark energy, the early formation of celestial bodies and matter-antimatter asymmetry (Gawiser, 2001) (Kaplinghat & Turner, 2001). The analysis of the anisotropies is done through the power spectra created, the graphing of temperature and/or polarization against angular scale. Common types of power spectra that are analyzed are Temperature (TT), Polarization (EE) and Temperature Polarization Cross (TE) (Balkenhol et al., 2023). These spectra are where the aforementioned gravitational force from density and the expansion of the universe come into play.

The baryon density of the universe affects the power spectra of the CMB and thus the CMB itself. In theory, the density of baryons in the early universe would heavily affect the manner in which matter dense regions were formed, as a greater density would result in greater mass in smaller areas and therefore stronger regions of gravity (Scott et al., 2016). These areas would then be greater in heat as traveling photons are more affected by the stronger gravitational pull, losing energy to escaping the field in an effect called the Sachs-Wolfe effect (Sachs, R.K. & Wolfe, A.M. 1967). Through the use of simulations, specific areas of the TT, TE, and EE power spectra are affected by the changes in Baryon Density as a parameter. The significance of this correlation between the cosmological parameter and resulting power spectra means that the estimation of the empirical cosmological parameter is possible using those simulations.

In this study, we estimate $\Omega_b h^2$, which is baryon density multiplied by the square of the reduced hubble constant. This parameter takes into account the expanding universe and is what is commonly used in papers. In order to estimate the cosmological parameter $\Omega_b h^2$ however, two key components of a customizable simulation and recorded data are required. The Code for Anisotropies in the microwave background (CAMB) is a code that simulates the cosmic microwave background based on the input parameters and is widely used in cosmological research of the Cosmic Microwave Background. The CAMB mainly utilizes a combination of field equations, the Friedmann-Lemaître-Robertson-Walker metric, Fluid Equations, the Boltzmann Equation and Linear Perturbation theory in order to compute the simulated data of the resulting CMB (Lewis A, 2014).The CAMB code outputs power spectra graphs which can be used to compare with the power spectra from recorded data and estimate the empirical value of any cosmological parameter. The recorded data was taken from the Planck Satellite, specifically from the Planck Legacy Archive's 2018 cosmology products. Explanations for the data and simulation chosen are elaborated in the methods section.

To estimate $\Omega_b h^2$a custom code was written which runs and records the results of a range of CAMB simulations, plots and records key features of the data recorded and uses the chi-squared likelihood test in order to find the simulation with the closest power spectra to that of the Planck data. By finding the closest power spectra, the estimate of $\Omega_b h^2$ was found and the reliability of CAMB was considered.

2. Research Design, Data collection and analysis Methods

2.1. CAMB data

2.1.1. Understanding the Code

Simulations utilize established theories and equations in physics in order to come closest to the expected situations. In the case of CAMB, the Friedmann-Lemaître-Robertson-Walker metric, Fluid Equations, the Boltzmann Equation and Linear Perturbation theory are used (Lewis A, 2014). The key component lies with the fluid equations, which models the behavior of various aspects of the expansion of the universe. In the case of this research, the simulation finds the solutions to the fluid equations with baryons and its interactions with other components. To use CAMB, a package containing its code was downloaded from github (Lewis A. & Challinor A., 2023) and code that ran multiple simulations while recording data from each one was written. Each simulation was run with $\Omega_b h^2$ increased at an increment of 0.00015, from a range of 0.015 to 0.03. The range was selected in accordance to the currently accepted value of $\Omega_b h^2$ which is at 0.02237 ± 0.00015 (Aghanim et al., 2020) and the increments were taken from the error.

2.1.2. Choosing Data Sets

Among the four different power spectra that are generally produced from CMB simulation, TT and TE power spectra were selected for further studies as they show the most variance from the change in baryon density. CAMB also outputs several data types, of which lensed total was chosen as it is the same data type that the Planck Satellite data is recorded in. Of the TT and TE spectra, specific features of each graph were greatly affected, making them perfect markers for statistical analysis. For the TT graph they are the amplitude, position and width of the first and second peak as well as the ratio between the amplitude of the first and second peaks. For the TE graph they are the amplitude, position and width of the first, second, third peaks and first anti-peak as well as the ratio between the amplitude of the second peak and first anti-peak (Larson et al., 2015) (Page et al., 2003a, 2003b). In order to extract these features for analysis, the scipy package was used in the code and the data points were saved as a csv file.

2.2. Planck Data

The data from the Planck satellite was taken from the Planck Legacy Archive under the Cosmology CMB angular power spectra bookmark. From there, the unbinned 2018 legacy data for the TT and TE power spectra were used. As the data sets were noisy and had several outliers which made the analysis unreliable, the savgol_filter on scipy was used in order to smooth the data and exclude the outliers. The window size of the TT data was set as 65 with a polynomial degree of 3 and the TE data's window size as 51 at the same polynomial degree. The down sampling for TT was set to 500 while TE was set to 399 based on each of their data set sizes. This was based on its data sets similarities to the best-fit curve found on the same legacy archive (Rosenberg et al., 2022). The smoothed data sets from the Planck satellite were then run through the same program as the simulated data in order to find the values of the aforementioned features of the TT and TE graphs.

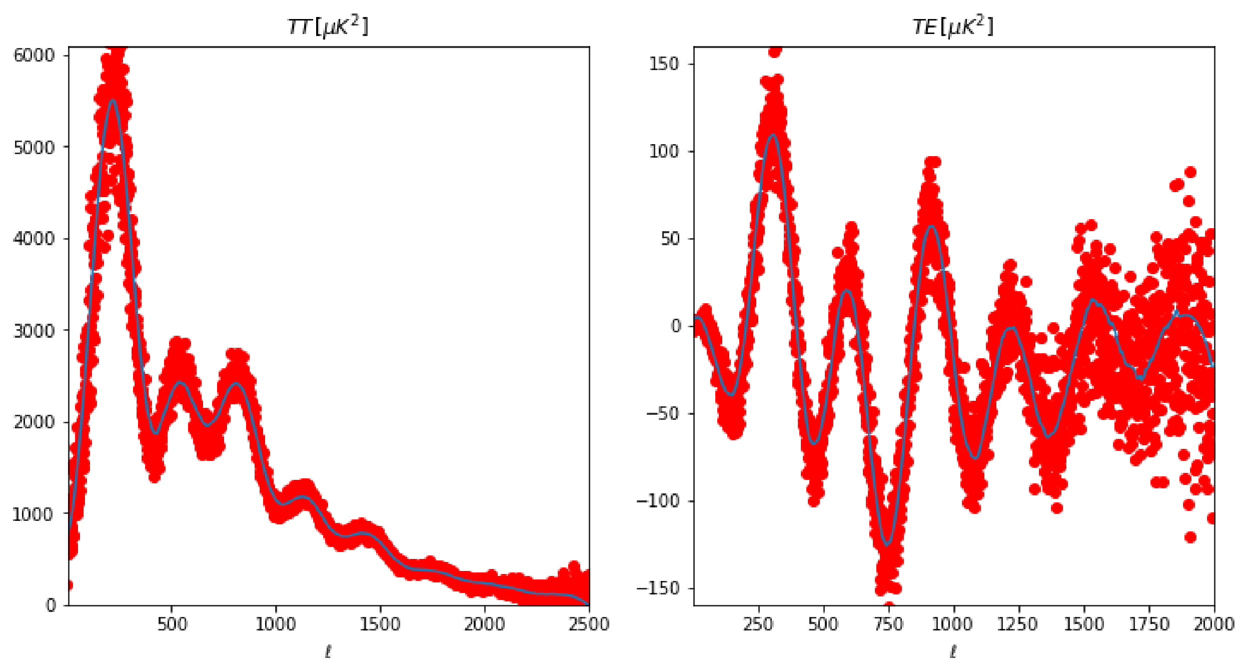
2.3. Statistical Analysis Method

For statistical analysis, the chi-squared likelihood test was used in order to find the closest power spectra from the simulations to the recorded power spectra from the Planck satellite. For this, the previously extracted data points of the features of each power spectra were run through to find the chi-squared values between each simulation and data from Planck. Then, with a degree of freedom of 19 as there are 20 features, the value of 1 minus the p-value was found in order to determine which simulation had a result closest to the expected value from Planck. This was done through the chi2 contingency package from scipy's statistics package. The simulation with the smallest p-value would be the one that deviates the least from the expected value and hence the closest to the empirical value for $\Omega_b h^2$.

3. Results

3.1. Raw Data

Figure 1. Overlap of the best-fit graphs with scatter plots of the raw Planck data. .The x axis is the angular scale (ell) and the y axis is the power (μK^2). With certain exceptions like a few of the anti-peaks, the graphs successfully remove the outliers and maintain the general shape of the data.



3.1.1. Power Spectra

Figure 2. Overlay of Planck data with CAMB data at $\Omega_b h^2$ of 0.015.The x axis is the angular scale (ell) and the y axis is the power (μK^2).

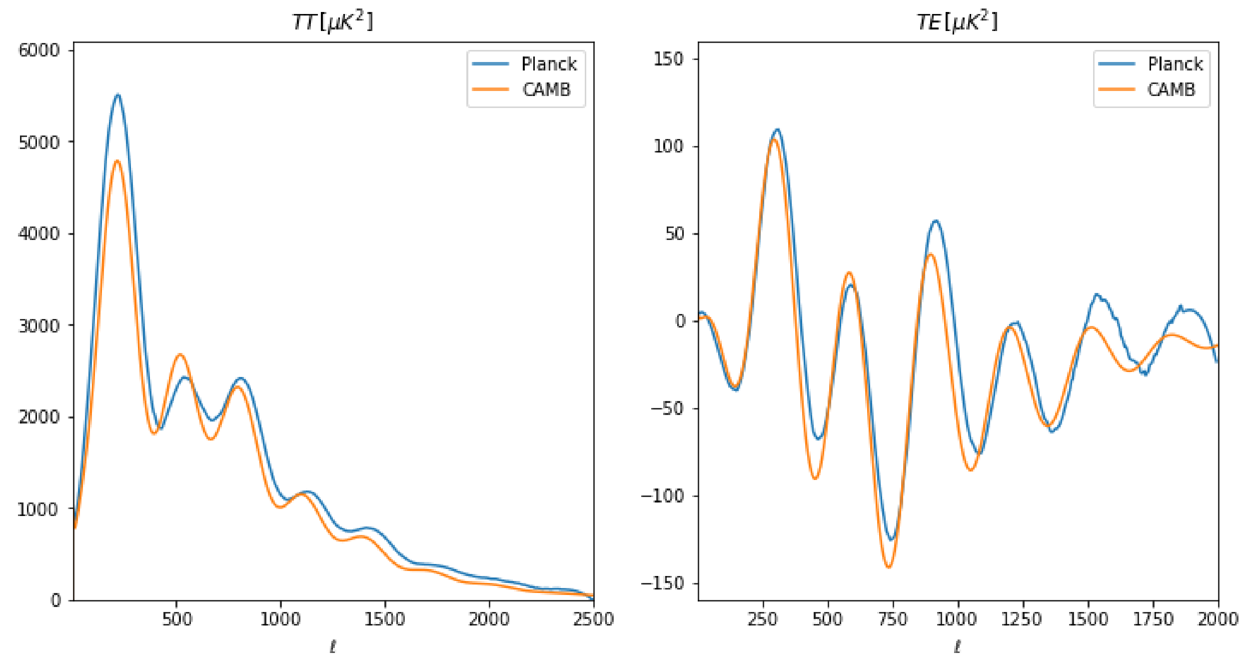


Figure 3. Overlay of Planck data with CAMB data at $\Omega_b h^2$ of 0.0255. The x axis is the angular scale (ell) and the y axis is the power (μK^2).

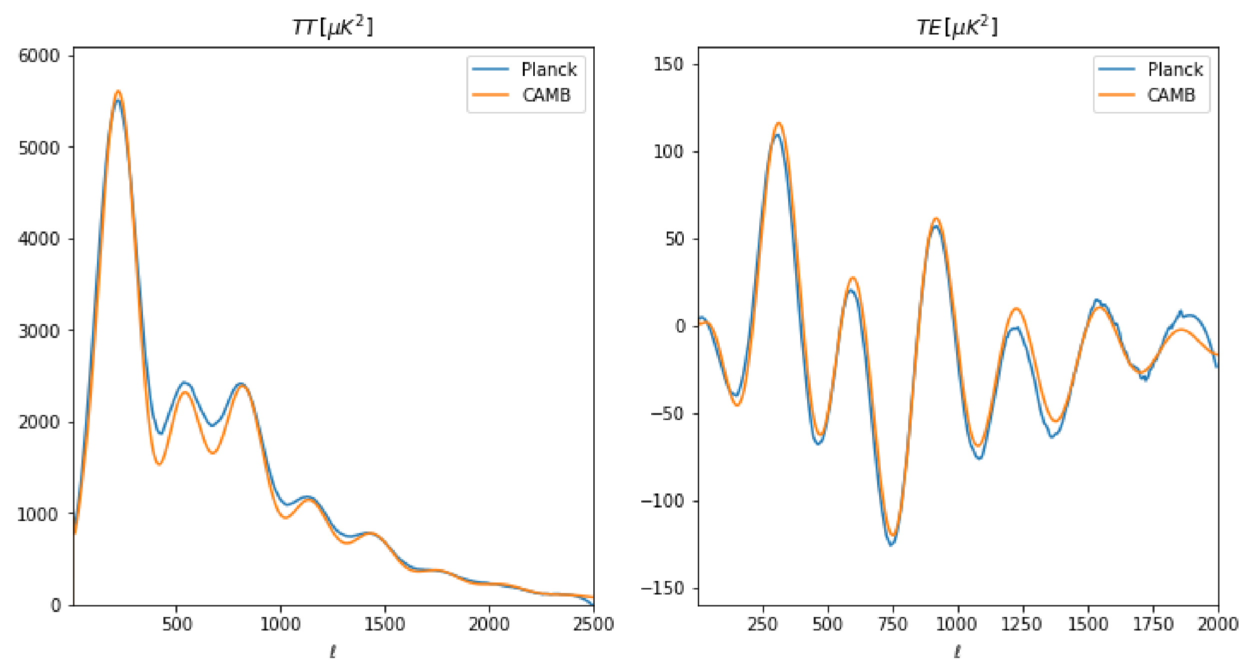
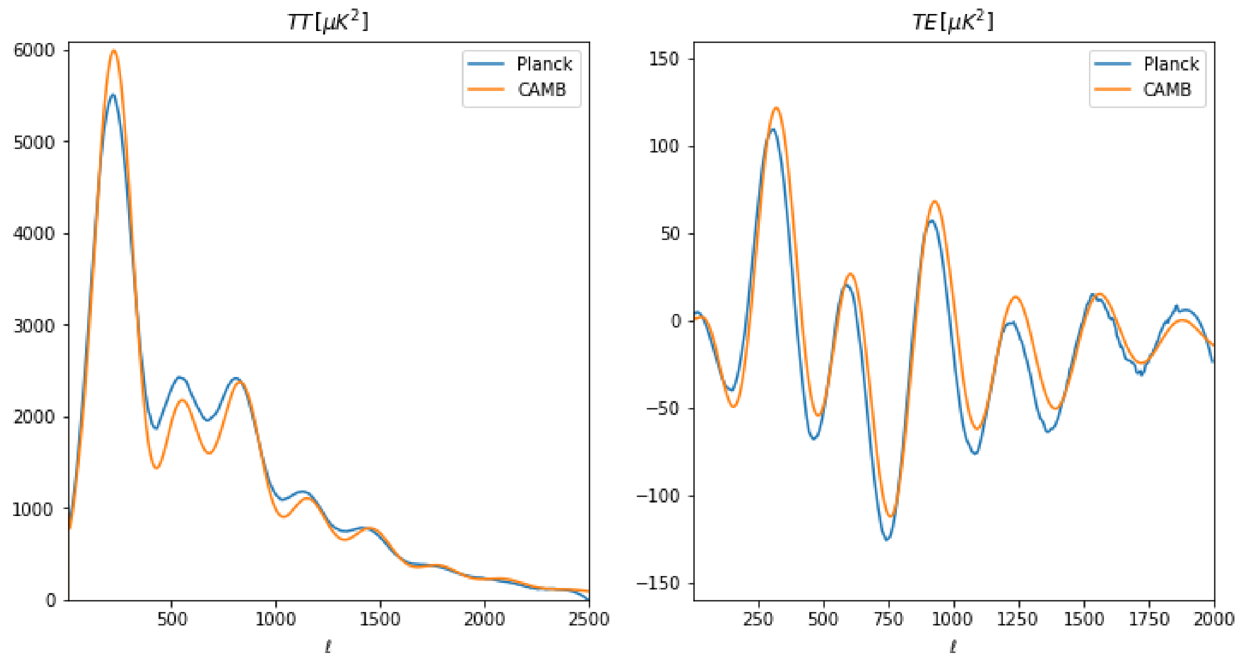


Figure 4. Overlay of Planck data with CAMB data at $\Omega_b h^2$ of 0.03.The x axis is the angular scale (ell) and the y axis is the power (μK^2).



The figures above are taken from the ends of the range of $\Omega_b h^2$ and one random value. As 0.015 seems to mostly be below the graph and 0.03 is mostly above, it is reasonable to assume that the likely answer is to be found in-between the two end numbers. This is to be expected as the range was chosen with the empirical value of $\Omega_b h^2$ in mind.

3.2. Key Features Processed

Table 1. Key features from the TT graph for selected baryon density.

Type	TT First Peak Position(ell)	TT Second Peak Position(ell)	TT First Peak Amplitude (μK^2)	TT Second Peak Amplitude (μK^2)	TT First Peak Width(ell)	TT Second Peak Width(ell)	TT 1,2 Amp Ratio
Planck	220	535	5509	2426	229.7	140.4	2.271
CAMB: 0.015	217	519	4789	2673	233.2	133.5	1.792
CAMB: 0.02295	220	536	5400	2405	228.9	138.0	2.245
CAMB: 0.0231	220	537	5413	2400	228.9	138.0	2.255
CAMB: 0.02325	220	537	5425	2395	228.9	138.1	2.265
CAMB: 0.0234	220	537	5437	2390	228.9	127.3	2.275
CAMB: 0.02355	220	538	5449	2385	228.9	127.1	2.285

CAMB: 0.03	224	552	5994	2178	229.3	120.3	2.752

Table 2. Additional Key features from the TE graph for selected baryon density.

Type	TE First Peak Position (ell)	TE Second Peak Position(ell)	TE Third Peak Position(ell)	TE First Antipeak Position(ell)	TE First Peak Amp(μK^2)	TE Second Peak Amp(μK^2)	TE Third Peak Amp(μK^2)	TE First Antipeak Amp(μK^2)
Planck	310	590	915	150	109.2	20.17	56.93	- 40.30
CAMB: 0.015	297	584	897	146	103.4	27.27	37.71	- 37.98
CAMB: 0.02295	310	594	912	152	112.8	27.61	56.91	- 43.78
CAMB: 0.0231	310	595	913	152	113.0	27.60	57.19	- 43.90
CAMB: 0.02325	310	595	913	152	113.2	27.58	57.47	- 44.02
CAMB: 0.0234	310	595	913	152	113.4	27.56	57.74	- 44.14
CAMB: 0.02355	311	595	914	153	113.6	27.54	58.01	- 44.26
CAMB: 0.03	321	606	929	157	121.6	26.43	67.98	- 49.58

Table 3. Key features from the TE graph for selected baryon density.

Type	TE First Peak Width(ell)	TE Second Peak Width(ell)	TE Third Peak Width(ell)	TE First Antipeak Width(ell)	TE -1,2 Amp Ratio
Planck	148.4	119.9	149.6	106.2	- 1.998
CAMB: 0.015	136.1	126.8	139.9	92.52	- 1.393
CAMB: 0.02295	146.9	122.0	145.0	97.77	- 1.586
CAMB: 0.0231	147.1	121.9	145.1	97.87	- 1.591
CAMB: 0.02325	147.3	121.8	145.2	97.97	- 1.596
CAMB: 0.0234	147.5	121.8	145.2	98.07	- 1.601
CAMB: 0.02355	147.7	121.7	145.3	98.17	- 1.607
CAMB: 0.03	156.1	119.0	148.9	102.2	- 1.876

From the tables above, we notice that as we near the center, most features from the Planck data matches up with a couple exceptions. An evident outlier is the TE second peak amplitude and as a result the TE amplitude ratio between the first anti-peak and second peak are also outliers.

Table 4. The Baryon Densities and the results of their chi-squared likelihood tests.

Baryon Density	chi-square results	p-value
CAMB: 0.015	55.74	0.9999
CAMB: 0.02295	2.401	1.70E-06
CAMB: 0.0231	2.339	1.36E-06
CAMB: 0.02325	2.270	1.06E-06
CAMB: 0.0234	2.764	5.50E-06
CAMB: 0.02355	2.845	6.98E-06
CAMB: 0.03	35.59	0.9882

Figure 5. Overlay graph of the estimated $\Omega_b h^2$ of 0.02235 with the Planck data. The x axis is the angular scale (ell) and the y axis is the power (μK^2).

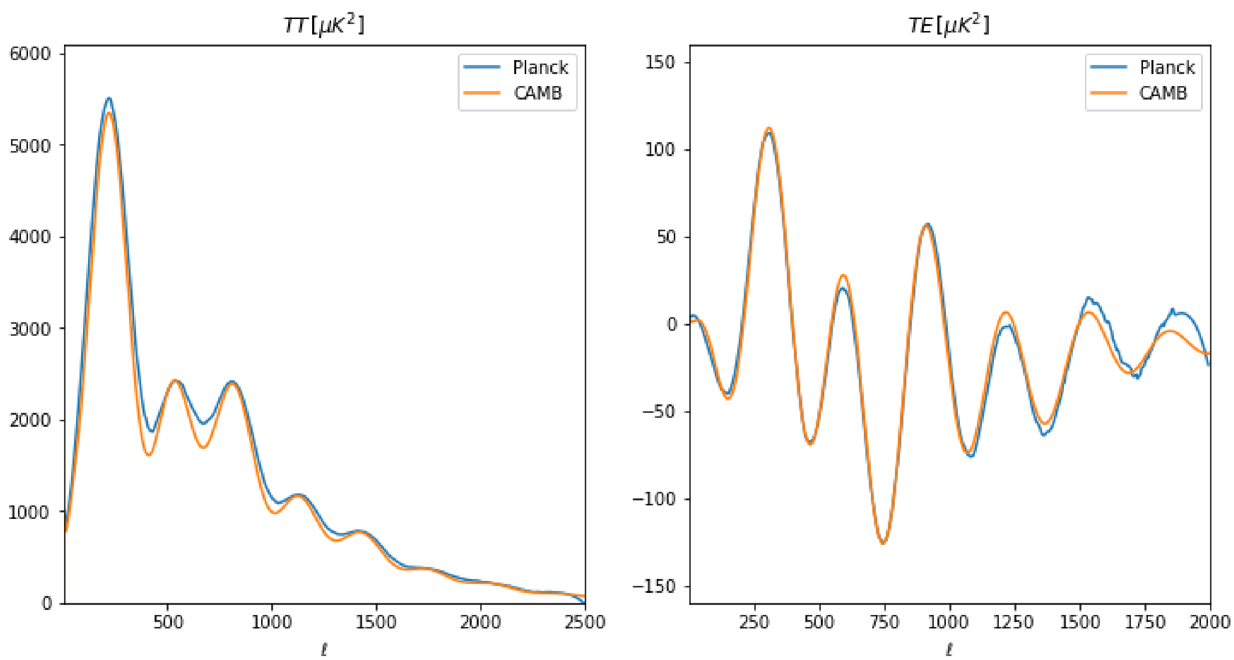
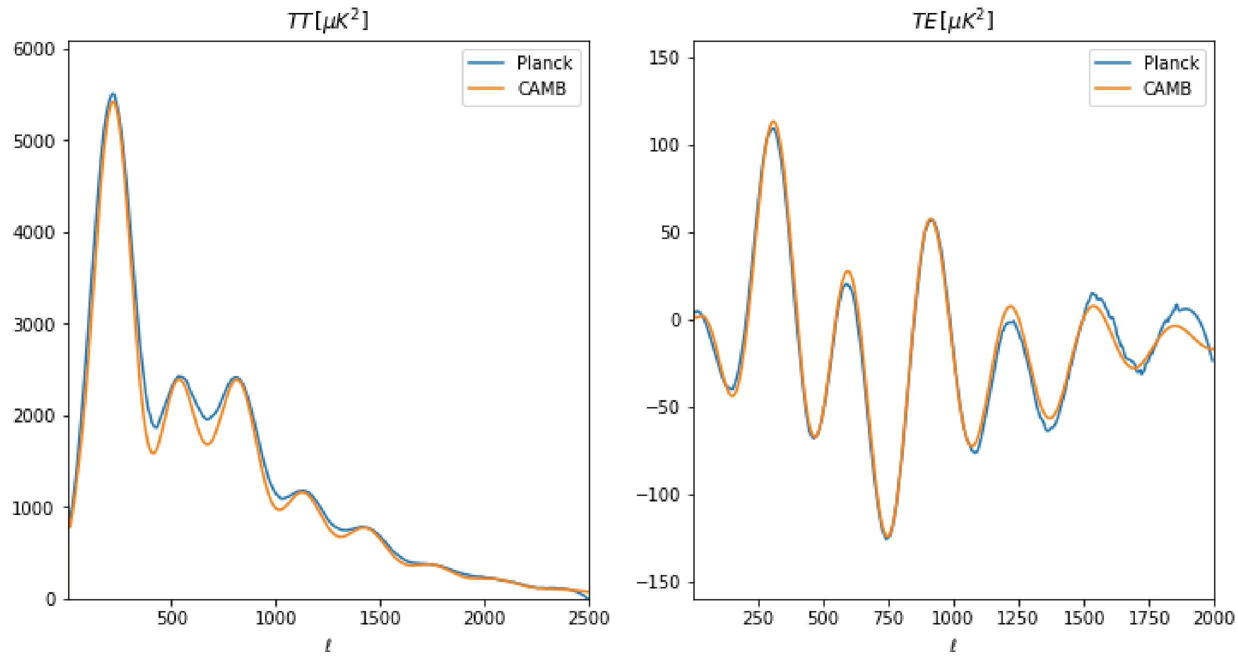


Figure 6. Overlay graph of the estimated $\Omega_b h^2$ of 0.02325 with the Planck data.The x axis is the angular scale (ell) and the y axis is the power (μK^2).



As can be seen with the graphs above, the key features are nearly if not entirely overlapping with deviations in certain areas. The deviations are likely a result of the approximation for the best-fit data.

4. Discussion and Synthesis

With the data collected, the estimation of $\Omega_b h^2$ is possible. First taking a look at **Figure 2** and **Figure 4**, the resulting power spectra are not overlapping with the Planck data. Notably, **Figure 2** which is for $\Omega_b h^2$ set at 0.015 shows the CAMB graph's key features generally below the Planck graph while **Figure 4** which is for $\Omega_b h^2$ set at 0.03 shows the CAMB graph's key features generally above the Planck graph. This suggests that the closest estimate is between the two values. Taking a look at a random simulated graph like **Figure 3** which has $\Omega_b h^2$ set at 0.0255 shows its CAMB graph's key features being much closer to the Planck data than 0.015 and 0.03. However, there are still discrepancies in certain features like the second peak in the TT graph and the peaks of the TE graph.

The next step in the process is to extract the 20 key features from the data sets in preparation for the chi-square likelihood analysis. **Table 1**, **Table 2**, and **Table 3** are the compiled results from the ends of the simulated range and near the center. Something to note is that there are certain values from the Planck data that match near perfectly with certain data sets while some are completely out of the acceptable range as notable by the second peak amplitude for the TE power spectra visible in **Table 2**.

Finally, the chi-square likelihood analysis is performed with the resulting p-values stored to find the simulated data set with the least variance to the Planck data. As highlighted in **Table 4**, this simulated data set is one where was set to 0.02325. Compared to other studies with the Cosmic Microwave Background as the basis for estimation, conclusions are drawn from or similar to results from the 2018 Planck results which found to be equal to 0.02237 ± 0.00015 (Aghanim et al., 2020). In comparison with the results of this paper, there is a difference of 0.00088 or a percent difference of 3.93%. **Figure 5** is an overlay of Planck data to CAMB data with set to 0.02238 while **Figure 6** is an overlay of Planck data to CAMB data with set to 0.02325, and it can be noted that there is a definite difference in how much the first peak of the TT power spectra overlap with the Planck data. Taken as an error, there are multiple areas in which this error could have risen compared to the approaches taken by other papers.

The most prominent error is likely from the approximation of values for the best-fit graph of the Planck data. Although the Savitzky-Golay filter was used for the purposes of maintaining the shape of the graph while removing the noise from the Planck data, in comparison with the best-fit data approximated from Planck shows varying levels of discrepancies in the heights and depths of peaks and troughs. More specifically, the best-fit data from Planck is sharper compared to the best-fit data approximated in this paper. Variations in methods for verifying the smoothing done to the data likely is where the error comes from as Planck utilized data from prior releases.

Another area for error is in the limited number of features taken into account for the likelihood analysis. While this paper mainly focused on the Cosmic Microwave background, current research for estimating cosmological parameters also utilize calculations from Big Bang Nucleosynthesis and Baryon Acoustic Oscillations (Möckel, C., Pd, D., & Bemmerer, 2019). Both are significant areas to consider as they have direct ties in explaining the beginnings of the universe. Even within the constraints of the CMB, this paper touches on 20 features from the TT and TE graphs combined while most papers refer to EE and low multipole graphs as well. This limitation mainly comes from the calculation and fine-tuning of the multitude of variables to be considered when estimating from all of the aforementioned areas is difficult without sufficient time and resources (Smoot, 2000).

This limitation suggests that although simulations are capable of simplifying the process of estimating for different cosmological parameters, further precision may require a different method. Instead of physically having to run through countless ranges of possible values, deep learning could be utilized to train and pin point possible values for multiple parameters while considering multiple areas for estimation (Mishra et al., 2019).

5. Conclusions

This paper aimed to estimate the value of $\Omega_b h^2$ through the use of CAMB and data from the Planck Satellite. By running multiple simulations with $\Omega_b h^2$ increasing in constant increments and using the chi-squared likelihood test the estimate of 0.02325 was found. With an error of 3.93%, the estimation of cosmological parameters through the use of CAMB was shown to be acceptably accurate with limitations in methodology being a major reason for the deviation from the expected value of 0.02237 ± 0.00015. With the need of considering different models for the expansion of the universe however, it will be necessary to develop further efficient methods to estimate precise cosmological parameters to be used in further research. In order to overcome issues with fine tuning and calibrating simulations by hand, the integration of deep learning into the methodology may be required.

Supplementary Materials: The code used in this study can be found online athttps://github.com/JYSamuel/Code-for-Estimating-Baryon-Density-through-the-CAMB-and-Assessing-its-Reliability.git

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