# Measuring the Temperature Variations of the Early Universe


Research Mentor: Dr. Kevin Huffenberger; Presenter: Shaheed Perez

Florida State University, Tallahassee, Fl



## Abstract

Cosmology is a unique field of physics that asks questions such as, “How was the universe created?”, “Why does it have the cosmological structure it does?”, and “What is the evolution of our universe in the future?” Although these are tough questions to answer, the Cosmic Microwave Background (CMB) discovery in 1965 ushered in a new era for cosmologists (Penzias and Wilson). The CMB provides data on the light from the universe when it was 300,000 years old (Hu and Dodelson) and by mapping that light, we can get an accurate picture of the early universe that can be analyzed by computing a power spectrum over the map. Gathering CMB data also comes with unwanted information from sources such as ground obscuration or galactic contamination (Hivon et al.). As a result, we would only be able to compute a power spectrum over the uncontaminated part of the sky. Fortunately, Hivon et al. have already described a method to convert the pseudo-power spectra (the power spectrum of the partial sky) into a power spectrum for the whole sky using the MASTER (**M**onte Carlo **A**podised **S**pherical **T**ransform **E**stimato**R**) method.


## Introduction

Some common terms that you will see throughout this poster are detailed below:

- **CMB** - the Cosmic Microwave Background radiation from the early universe (around 300,000 years old), where t = 0 is defined to be at the Big Bang
- **Power Spectrum** - a statistical measure of the sky, computed by using spherical harmonics that will be discussed more in the methods section
- **Pseudo-Power Spectrum** - a statistical measure of only a part of the sky, due to unwanted emission or pick-up that can contaminate the data from the CMB
- **Temperature Anisotropies** - small variations in the temperature of the microwave background radiation, computing a power spectrum over this is the main objective of this project
- **Acoustic Peaks** - peaks seen in the power spectrum caused by oscillations of the early universe when it was opaque
- **Multipoles** - the $\ell$'s that arise from using spherical harmonics, also known as the angular wavenumber
- **Temperature Fluctuations** - a measure of the variance of the temperature anisotropies, usually denoted as $D_\ell$, which will be defined in the methods section

To begin, cosmologists have formulated a standard cosmological model to help explain the formation and structure of the universe. For this project, the important part of the model is that it assumes the universe is spatially flat, which implies that the universe has a critical density $\rho_c = 1.88h^2\times10^{-29}$ g cm$^{-3}$ (Hu and Dodelson), where $h \simeq 0.7$ (Freedman et al.). Observations have shown that the universe appears to be flat. For this reason, the model contains photons, neutrinos, baryons, cold dark matter, and dark energy (Hu and Dodelson). The photons and neutrinos contribute a small amount to the critical density and measurements of the density of the baryons show that they are not sufficient to sum to the total critical density (Hu and Dodelson). Therefore, the model incorporates cold dark matter, which along with ordinary matter (baryons) accounts for ⅓ of the critical density, and dark energy, which accounts for ⅔ of the critical density (Hu and Dodelson).

Although these are hypotheses, the CMB data allowed us to test this hypothesis by providing us with a snapshot of the early universe. By computing a power spectrum, we can obtain a statistical measure for the temperature anisotropies we observe in our map, which allows us to plot a graph (with multipoles vs temperature fluctuations) containing acoustic peaks. Moreover, the position of these peaks can allow us to determine whether the universe is flat.

## Methods

The main method used to create the multipoles vs. temperature fluctuations graph is called a power spectrum. The key idea is that we need to get the temperature fluctuations.

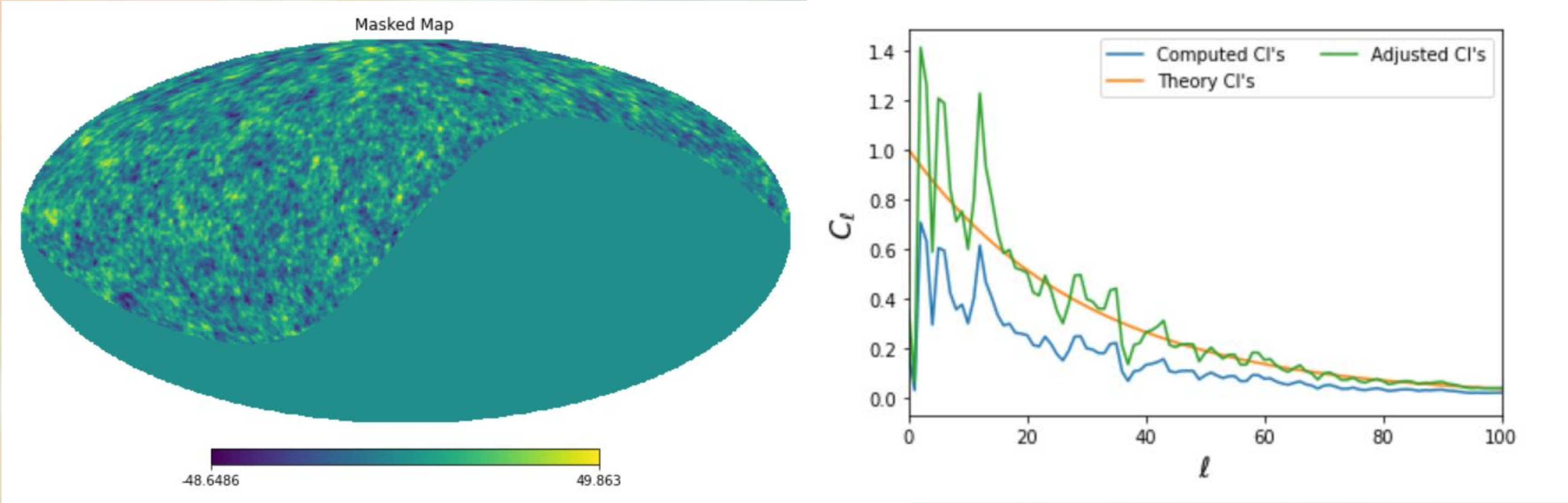
$$T(\Omega) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\Omega) \quad (1)$$

$$a_{\ell m} = \int d\Omega\, T(\Omega) Y^*_{\ell m}(\Omega) \quad (2)$$

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2 \quad (3)$$

$$D_\ell = \frac{(\ell)(\ell+1)}{2\pi} C_\ell \quad (4)$$

Although these are useful steps, they do not allow us to compute the power spectrum over a contaminated sky. For example, the illustration below shows that if we generate a random map from a general set of $C_\ell$'s and then mask the map, we will receive a set of observed $C_\ell$'s that do not align with our theory $C_\ell$'s.




The main reason is that the power spectrum over the partial sky only generates $C_\ell$'s for the part of the sky that was not masked and does not capture the $C_\ell$'s for the whole sky. Moreover, this creates a biased set of observed $C_\ell$'s. For this reason, Hivon et al. have described the MASTER (**M**onte Carlo **A**podised **S**pherical **T**ransform **E**stimato**R**) method, which can be used to compute the pseudo-power spectrum and convert that into an estimated power spectrum for the whole sky.

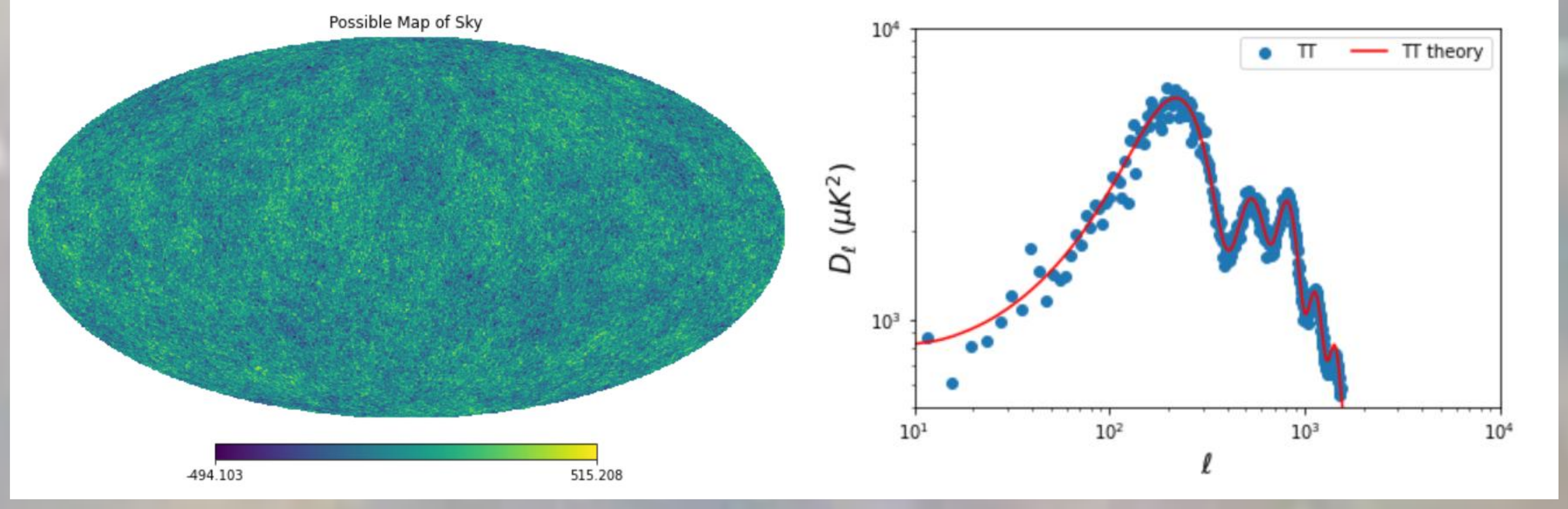
$$\tilde{a}_{\ell m} = \int d\Omega\, T(\Omega) Y^*_{\ell m}(\Omega) W(\Omega) \quad (5)$$

$$\tilde{C}_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |\tilde{a}_{\ell m}|^2 \quad (6)$$

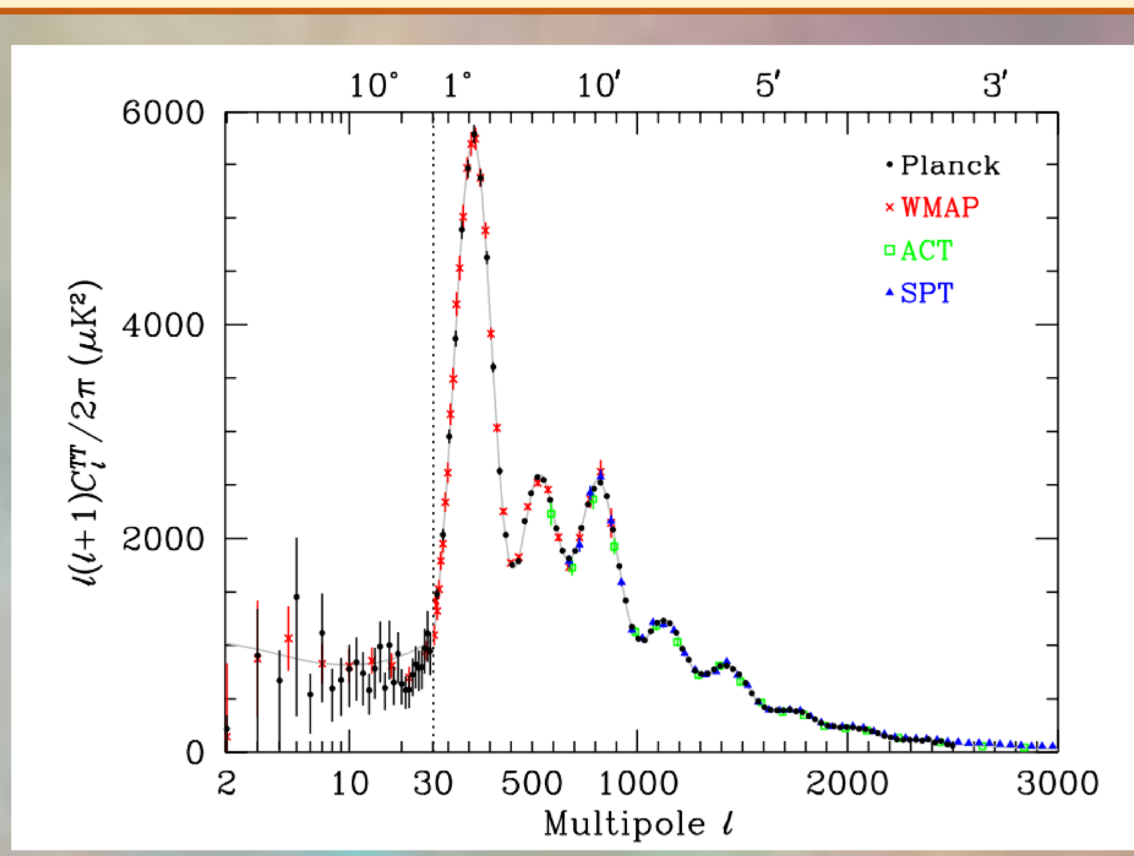
$$\langle \tilde{C}_\ell \rangle = \sum_{\ell'} M_{\ell\ell'} \langle C_{\ell'} \rangle \quad (7)$$

## Results

Typically, these methods would be applied after collecting our data from the CMB; however, for this project, I used the theory $C_\ell$'s to create a random map from which I could compute the power spectrum. Below is the multipoles vs temperature fluctuations graph for this power spectrum plotted against the theory temperature fluctuations, along with the random map.




Moreover, the results from the original experiment would prove more useful because the CMB data provides information independent of the standard cosmological model (ΛCDM model). Therefore, it can provide evidence that the current ΛCDM model is a somewhat accurate description of the universe. That graph is shown below (Scott and Smoot).




## Conclusion

Because the data gathered from the collection of missions and experiments have generally shown that the temperature fluctuations match those created by the ΛCDM model, it provides evidence that the universe is spatially flat. Moreover, there must be more constituents that make up the universe besides the matter that we can detect, which refers to the dark matter and dark energy that cosmologists accounted for in the model. Although cosmologists are not entirely sure what dark matter and dark energy are, nor can they detect them because they only interact with gravity, there is a consensus that something present in the universe is eluding our detection but can help to explain the phenomena we observe today. Many cosmologists have pointed out that the polarized light of the CMB may help in answering these questions (Komatsu). Nevertheless, the progress of CMB experiments within the past decades has increased exponentially with time (Komatsu). Our understanding of the universe may be a lot less murky in the coming decades, leading to the discovery of new physics and further contributions to the field of science.

## References


- Freedman, Wendy L., et al. “Final Results From the Hubble Space TelescopeKey Project to Measure the Hubble Constant.” The Astrophysical Journal, vol. 553, no. 1, American Astronomical Society, May 2001, pp. 47–72. https://doi.org/10.1086/320638.
- Hivon, Eric, et al. “MASTER of the Cosmic Microwave Background Anisotropy Power Spectrum: A Fast Method for Statistical Analysis of Large and Complex Cosmic Microwave Background Data Sets.” The Astrophysical Journal, vol. 567, no. 1, American Astronomical Society, Mar. 2002, pp. 2–17. https://doi.org/10.1086/338126.
- Hu, Wayne, and Scott Dodelson. “Cosmic Microwave Background Anisotropies.” Annual Review of Astronomy and Astrophysics, vol. 40, no. 1, Annual Reviews, Sept. 2002, pp. 171–216. https://doi.org/10.1146/annurev.astro.40.060401.093926.
- Komatsu, Eiichiro. “New Physics From the Polarized Light of the Cosmic Microwave Background.” Nature Reviews Physics, vol. 4, no. 7, Springer Science and Business Media LLC, May 2022, pp. 452–69. https://doi.org/10.1038/s42254-022-00452-4.
- Penzias, A. A., and R. W. Wilson. “A Measurement of Excess Antenna Temperature at 4080 Mc/S.” The Astrophysical Journal, vol. 142, American Astronomical Society, July 1965, p. 419. https://doi.org/10.1086/148307.
- Scott, and Smoot. Cosmic Microwave Background. Aug. 2019, pdg.lbl.gov/2020/reviews/rpp2020-rev-cosmic-microwave-background.pdf.