Modeling the CMB Power Spectrum with CMBFAST

Jatila van der Veen and Carlos Alexandre Wuensche

The purpose of making these models is to see the effects of changing the various cosmological parameters on the shape, location of peaks, and height of peaks, in the power spectrum of the CMB, as explained in class. Your mission (whether or not you choose to accept it!) is to make a collection of models, varying one or two parameters at a time, using the program CMBFAST (because it is purported to be the "fastest code in the west"). This is the same code that is used by the "pros". You will graph the Power Spectrum of the CMB for each model universe that you create, and compare your models to see the effects of varying each cosmological parameter on the power spectrum.

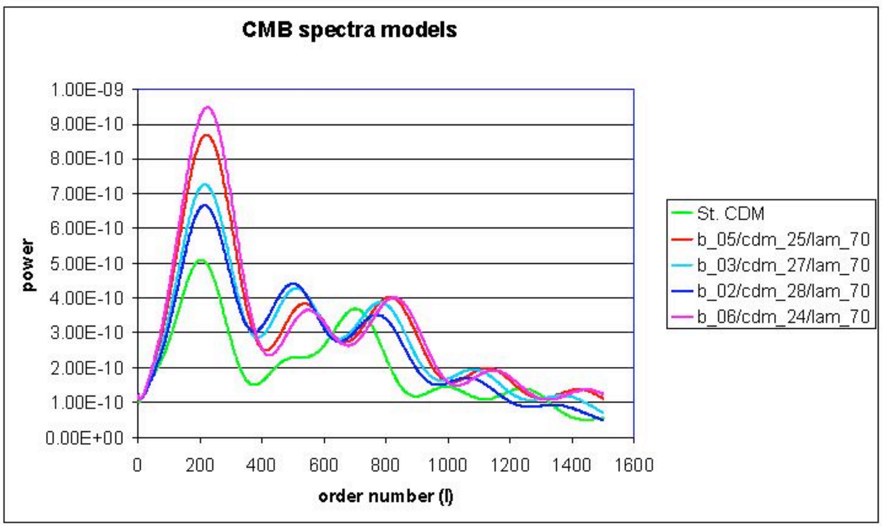
This is your chance to play Major Deity, and create your own model universe. At the end of the quarter, however, you will have to make a prediction and select one of your models that is most favored - and turn in a few page paper explaining why, and backing up your prediction with data!

As you read the introductory information, you will come to questions flagged with an icon. These are the questions that we want to answer in order to understand the real questions of how to extract information about the cosmological parameters from the power spectrum of the CMB.

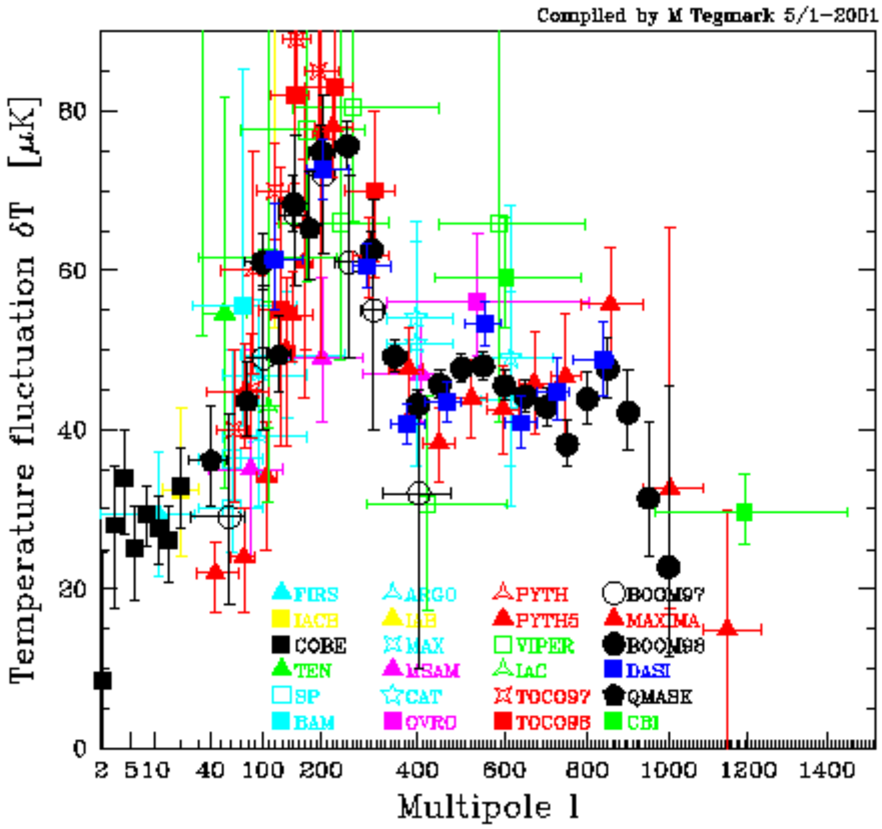
To give you an idea of what we are looking for, here is an example in which we use the current (spring, 2002) "best estimates" for H_0 = 70 km/sec/Mpc, and the total matter density parameter = 0.3, with "lambda" density parameter = 0.7, but we vary the ratio of baryons and cold dark matter.

The effect of increasing Ω_b and decreasing Ω_{cdm} with $\Omega_{Lambda} = .7$

H-0 = 70 for all



You can see the effect on the height of the first peak, and also on the positions of the second and third peaks. The green curve is the "standard model" from the mid-1990's, with H_0 = 50, baryon density = .5, cold dark matter density = .95, and no lambda at all. The graph below shows a compilation of CMB experiments that have been performed, as of 2001. The BOOMERANG data are the black dots. When taken altogether, the power spectrum differs from the "standard model" (green curve in graph above). As more data are collected, the less likely models will "drop out" of the running...



For the purposes of this class, you may start the modeling using the following assumptions in generating your models:

- Flat Universe
- Non-zero Omega lambda
- Precisely 3 flavors of massless neutrinos
- Compute spectrum only, don't worry about the "transfer function"
- Don't compute polarization or tensor modes
- Use l and k-eta-max as 1500 and 3000, respectively when you run jlgen, ujlgen to compute the files of spherical Bessel functions and ultra-spherical Bessel functions.
- When you run CMBFAST, be sure to specify 1500 and 3000 for l and k-eta-max, to be consistent with your Bessel function files.

After you get used to the programs, you can play with the values and intervals. For their meaning, refer to page 7 and after.

Creating your power spectra with CMBFAST

For this project you are going to create a set of your own CMB power spectra using CMBFAST, representing different model universes.

In order to run the CMBFAST code, you need to have files of Spherical Bessel functions, and for open models, Ultraspherical Bessel functions. Before you can run your models, you need to create a directory on whatever computer you are using, and then download the following files to that directory:

1. Download the file of spherical Bessel functions called JBES.DAT from the site http://www.physics.ucsb.edu/~jatila/astro/astro2/cmbfast/JBES.DAT
2. Download the file of ultraspherical Bessel functions called UBES.DAT which you will only use for open models from the site http://www.physics.ucsb.edu/~jatila/astro/astro2/cmbfast/UBES.DAT
3. Download the program itself, CMBFAST from the original site http://www.cmbfast.org

This program runs under Linux,. To install and run the program, open a Linux terminal and go to the directory where you downloaded cmbfast.tar.gz. Type tar –zxvf cmbfast.tar.gz. To create the executable files, type ./configure and, thereafter, make. If you want to check different possibilities during the instalalation, type ./configure –help.

VERY IMPORTANT: When you run CMBFAST, it is necessary to have the spherical Bessel functions pre-computed. You must type ./jlgen and input the maximum values the program asks for (1500, 3000). The output file can be named as you wish but, for the sake of memory, it is easier to call it something like jl.dat or jbes.dat. The same thing should be done to create the ultraspherical Bessel functions. You must type ./ujlgen and input the maximum values the program asks for (1500, 3000). The output files can be called, for instance, ujl.dat or ubes.dat.

Investigating the effects of baryon density on the CMB power spectrum : 5 graphs

Keep H_0 constant at 70 km/sec/Mpc. Keep Omega-lambda = .7. Keep the sum (Omega-baryon + Omega-cdm) = .3, but vary their proportions. (for example: .05 + .25; .03 + .27) Do 5 runs of CMBFAST with 5 different combinations of Omega-baryon and Omega-cdm, keeping all the other parameters constant, and set the re-ionization = 0. Import your data (it will be created as a text file) into gnuplot or grace. CMBFAST will generate an ASCII file of 4 columns; the first column is the "l-number" and the second column contains the normalized power spectrum values. The third and fourth are the E-mode polarization and cross correlated temperature and E-mode, respectively. You should graph them all on one graph, using different colors. Be sure to label your graph, and label which color refers to which parameter. When you have all the 5 curves on one graph, import it into OpenOffice and save it as a .JPG file.

NAMING YOUR IMAGE OF THE GRAPH: Be sure to give it a name like "cmbmodel#1.jpg".

➲	*How does changing the ratio of baryons to cold dark matter affect the CMB power spectrum?*

Investigating the effects of changing H_0 on the CMB power spectrum : 6 graphs

The old "standard model" had H_0 = 50 km/sec/Mpc. In the mid-1990's careful measurements of Cepheid variables in the Virgo Cluster of galaxies by Wendy Freedman and colleagues, using data taken with the Hubble Telescope instruments, measured a distance to the Virgo Cluster that was consistent with a value of H_0 between 65 and 78 km/sec/Mpc. This created quite an uproar in the cosmological community, because in a "Lambda = 0" universe, such a value for H_0 implies a universe that is only about 9 billion years old - younger than the ages of the globular clusters. Since people BELIEVE in the theories of stellar evolution, all sorts of folks tried to prove her wrong. She published and re-published with increasing care her very precise measurements and impeccable statistics - and kept coming up with an embarrassingly fast value of H_0.

As long as we accept a non-zero value for Omega-lambda, then all is well. H_0 is as fast as Dr. Freedman calculates, and the age of the universe is consistent with its oldest structures!

In this next set of graphs, keep Omega-baryon = 0.05, Omega-cold-dark-matter = 0.25, and Omega-lambda = 0.70, but vary H_0. Start with H_0 = 50 km/sec/Mpc, and work up to H_0 = 75 km/sec/Mpc, in increments of 5 km/sec/Mpc. Follow the same procedures as in part 1 to make your graphs and save all 6 plots on one graph. Again, set the re-ionization = 0. Label accordingly, and email your final jpeg file to your instructor, and one copy to yourself.

➲	*How does changing the value of H_0, while keeping everything else constant, affect the CMB power spectrum?*

Investigating the effects of re-ionization of the neutral hydrogen in the early Universe on the CMB power spectrum: 6 graphs

We can see by mapping the distribution of neutral hydrogen in the early universe, by looking back through the Lyman alpha forest that even at redshifts of 5, which represent a look-back time of around 90% of the age of the universe, that there was not as much neutral hydrogen as would be expected. Something re-ionized the neutral hydrogen (that was formed at "recombination"). Because photons are actually traveling disturbances in the electric fields in space, they interact with charged particles (protons and electrons, which is what hydrogen becomes when it is ionized) more readily than they do with neutral gas. So early re-ionization of the universe should have an effect on the CMB photons on their way to us.

1. Scroll up to the link to the on-line documentation, and then follow the instructions under #5 about how to include the effects of re-ionization.
2. Keep H_0 = 70, $Omega_b$ = .05, $Omega_{cdm}$ = .25, and $Omega_{lambda}$ = .7; keep everything else the same as before. Start with a reference graph of 0 ionization, so you have a baseline for comparison.

3. Since the last scattering surface is specified at z = 1000, and we know that by red shifts of around 5 the universe was almost completely re-ionized. Select 5 different combinations of red shift and percent re-ionization, and plot them all on the same graph.
4. Compare your graph with no re-ionization to the 5 graphs with varying amounts of re-ionization.

➲	*How do the amplitude and locations of the peaks in the CMB power spectrum change as you vary the time and amount of re-ionization in the universe?*
➲	*What could have caused early re-ionization of the neutral hydrogen that formed at the recombination time (t ~ 300,000 years)? (You may need to do some searching in your text or on line to find this one!*

Predict the Spectrum you Expect after WMAP and Planck return the maps of the whole sky : One graph

Now, based on what you have learned in class, from your readings, and by running these models, select ONE set of parameters that you consider MOST LIKELY for our Universe, and run CMBFAST with these parameters. In other words, predict what you think is the "correct" value for H_0, $Omega_{baryon}$, etc, and a redshift at which you think the re-ionization should have been complete. Be sure you understand what you are doing and why, because you may be asked to write a report about it!

Play Major Deity and Create an Alternate Universe : One graph

Now you go for it! Experiment with the parameters and create an alternative universe - maybe one in which there is no lambda, or one in which there are massive neutrinos, or one in which there was never any re-ionization. Input that set of cosmological parameters into CMBFAST and make one final graph. Be sure that you understand what kind of universe you have created, because you are going to have to explain its evolution!

SIMPLE DOCUMENTATION FOR USING CMBFAST

INTRODUCTION

There are about 8 - 10 crucial parameters that play a role in determining what the CMB power spectrum should look like for inflationary models. With data from BOOMERANG and other experiments, it is possible to constrain many of these parameters so as to eliminate models which are incompatible with the data. These parameters are not independent of each other, thus we look for the most likely region in "parameter space" that satisfies observations.

This software will allow you to create a suite of models with different parameters (such as Hubble constant, baryon fraction, etc.) to study how changing your parameter space effects the CMB spectrum. As more data continue to arrive from increasingly sensitive instruments (the WMAP satellite has already released the highest-quality CMB data up to now and better data are expected to come from the Planck satellite) we will be able to eliminate models whose spectra do not fit the observations, and thus hopefully get a handle on what the actual values of these cosmological parameters really are.

CMBFAST has become the "industry standard" for computing CMB power spectra, polarization, and transfer functions. It uses a method based on integration over the sources along the photon past light cone, in which the temperature anisotropy is written as a time integral over the product of a geometrical term and a source term. This method allows for significantly faster computation time than previous methods. We have compiled it in a user-friendly package, and distribute it with permission of the authors, Uros Seljak and Matias Zaldarriaga. If you use it in any educational research, please be sure to reference the authors.

The program is run interactively in a DOS window. The user is prompted for each input parameter, and the output is an ASCII file consisting of four columns of real numbers. The first column is the "l" value; the second is the normalized "C_l" value. The third and fourth columns are transfer functions, and can be deleted if you only want the temperature anisotropy power spectrum. (See our on-line article, "Small Scale Anisotropies: The Final Frontier".)

For more extensive documentation, or to contact the authors, we refer you to the CMBFAST webpage, http://www.cmbfast.org.

This document is written specifically for physics students and educators. For an extensive treatment of the implications of all the cosmological parameters on the CMB power spectrum, see Wayne Hu's PhD thesis at

http://www.sns.ias.edu/~whu/thesis/thesispage.html.

The original codes - main program and all the subroutines in Fortran - can be downloaded from the CMBFAST web site, at http://www.cmbfast.org.

INSTALLATION

Download the file CMBFAST.ZIP from the UCSB CMB curriculum website, http://www.physics.ucsb.edu/~jatila/raap/cmb_edu.html and extract all the files to one directory.

You should now have the following files in your directory:

- cmbfast.doc : a WORD document which contains the original documentation from the authors - included in case you want to read all about what the program is really doing, so you can explain it to your students without resorting to black-boxing or arm-waving;
- distribution.doc : THIS FILE.
- cmbfast.exe : the program that will generate your power spectrum
- jlens.exe: This program will compute the spherical Bessel functions for you. We have included it in case you want to extend the spectrum, or calculate your own Bessel functions.
- jlgen.exe : This program will compute the spherical Bessel functions for you. We have included it in case you want to extend the spectrum, or calculate your own Bessel functions.
- ujlgen.exe : This is the program that will compute the ultraspherical Bessel functions.

RUNNING THE PROGRAM

Open a Linux terminal, change to the directory where you have installed CMBFAST (suppose you name the directory CMBFAST also) and its subroutines and supporting .dat files.

First: Run jlgen.exe by typing "./jlgen" and create the file of Spherical Bessel functions for the scalar modes. The program will ask you the maximum l and keta values to calculate, and to tell the name of the output file you want.

Second: Run ujlgen.exe by typing "./ujlgen" to create the file of Ultra-Spherical Bessel functions for the open codes and tensor mode calculations.

Third: Run CMBFAST itself by typing "./cmb".

It is interactive, and will prompt you to enter the parameters to compute the CMB power spectrum for your model universe. In the rest of this document we present all of the prompts that the software will give you, in the order in which they are presented, what each variable means, and how to interpret what the program is asking for.

1) CMB (0), transfer functions (1) or both (2) :

Enter 0 if you only wish to compute the CMB power spectrum (this is the most common usage of this software, by far!); enter 1 to compute the transfer function only; enter 2 to compute both the power spectrum and the transfer function. (If you just want to compute the power spectrum, you can skip the next explanation and go directly to prompt 2).

The basis for the matter transfer function is that, after multiplying by some factors of k and normalization constants, it gives the power spectrum of the matter in the universe. This matter power spectrum is the 3-dimensional analogy of the 2-dimensional CMB spectrum. In practice, the distribution of matter in the universe is found by mapping the position and redshift of galaxies (see any reference to the major redshift surveys that have been done in the last decade) and computing the power spectrum from that map.

2) Value of lmax, ketamax (e.g., 1500 3000)

Remember to be consistent with the file in the flat case.

What this means is that you must input here the same values that you used to compute the spherical Bessel functions. l is the order number and k_{eta} is the wavenumber. If you entered 1 or 2 at the first step, then after you input your values of lmax and ketamax, the program will prompt you to:

2a) Enter tf kmax (h/Mpc), # of k per log. int. (5,5).

You enter two numbers:

The first, k_{max} is the maximum wavenumber that the code will calculate. The transfer function output file will consist of the computed transfer function for each wavenumber, up to the value of kmax you requested.

a note about k...

> The units of k may seem a bit odd: h/Mpc, but here's how these units arise:
>
> H_o itself is expressed in units of km/sec/Mpc, which reduces to the dimension of Time^{-1}. Because of the inherent uncertainty in measuring H_o in the first place, we usually express it as 100h km/sec/Mpc. So, h is itself dimensionless, thus k has the dimension of Distance^{-1}.
>
> In the CMB we are looking at acoustic waves that were frozen in time on the surface of last scattering. The expansion rate of the universe has the effect of stretching these features at all scales. Whether a particular feature of a given size is within the "horizon" depends on the expansion rate of the universe and the local speed of sound, because that is the limiting speed with which a pressure oscillation could travel.

The second number is the number of k's (wavenumbers) that will be calculated per logarithmic interval of k - kind of like a "k-sampling rate". The greater you make this second number, the greater will be the sampling rate of the output transfer function. The more wiggles one expects in the transfer function, the finer sampling one must do so as to accurately graph the function.

3) Enter Omega_b, Omega_c, Omega_v , Omega_nu (e.g. .05, .95, 0, 0,)

The "critical density" of the Universe which would precisely balance the energy of expansion and the gravitational energy of all the matter is found to be

$$\rho_c = \frac{3H_o^2}{8\pi G}$$

Present day densities of various species are expressed in terms of the critical density:

$\rho_x = \Omega_x \rho_c$ or $\Omega_x = \frac{\rho_x}{\rho_c}$

Thus we look for the relative abundances of each species - baryons, dark matter, neutrinos, photons, and even "lambda", and hope that all the fractions add up to unity for a flat universe. (See article: if $\Omega < 1$ then the universe is open, and if $\Omega > 1$, then the universe is closed, and will eventually recollagse. CMBFAST requests you to input the following relative densities in terms of each "Omega" (Ω).

- Omega_b (Ω_b) is the contribution from baryons ("normal" matter);
- Omega_c (Ω_c) is the contribution from cold dark matter;
- Omega_v ($\Omega\Lambda$) is the contribution of the cosmological constant, Λ , also called the vacuum energy density, to the total energy density of the universe;
- Omega_nu (Ωv) is the contribution from massive neutrinos.
- Omega_K is for curvature.

4) Enter H0, T_cmb, Y_He, N_nu (massive), N_nu (massless)

H_o is the Hubble constant, in units of km/sec/Mpc. Standard lore puts H_o at 50 km/sec/Mpc, but recent data from high redshift supernovae and Cepheid measurements put it closer to 65 - 75 km/sec/Mpc. You can see how changing this parameter effects the acoustic peaks. What do you predict?

- T_{CMB} is the current temperature of the microwave background, around 2.726 Kelvin.
- Y_{He} is the fraction of helium that existed at the time of last scattering, generally believed to be .23 - .24
- N_nu (massive) is the number of massive neutrinos.
- N_nu(massless) is the number of massless neutrinos.
- If you enter 0 for Omega_nu above, then N_nu must also be zero. If you entered a non-zero value, then you will have to also input nnur and nnunr.
- nnur = number of relativistic neutrinos
- nnunr = number of non-relativistic neutrinos

5) Enter 0 for no reionization

Enter 1 for specified optical depth to lss (xe = 1)

Enter 2 for specified redshift and xe

If you wish to see a spectrum in the case that the universe never re-ionized after recombination, enter 0 here.

Re-ionization of the neutral hydrogen should have the effect of damping out the higher order fluctuations in the power spectrum. The most intuitive way to express the re-ionization of the universe is in terms of the redshift at which you believe it became apparent, and the fraction of neutral hydrogen that should be ionized - this is option 2.

The concept of "optical depth" has to do with the density of matter ("n", the number of absorbers and scatterers) for the cross section of a given process ("σ ") and a given path length "l". It is a rather messy concept, to which we refer you to the explanation in any good cosmology text.

Recommendation: To model re-ionization, select choice 2, to specify redshift and percent ionization.

6) Enter 0 for scalar modes alone, 1 for tensor + scalar, or 2 for tensors alone.

You only need tensor modes if you are going to play with polarization, not if you are only modeling temperature spectra, so choose option 0.

7) Enter number and values of scalar spectral index n(1,1)

The most widely held belief is that the CMB spectrum most closely follows a "flat" power law, n = 1. That was the "Harrison-Zeldovich" spectrum of about a decade ago. Putting n other than 1 gives a "tilt" to the spectrum. More recent experiments constrain n so that 0.86 < n < 1.16, while the best-fit to the BOOMERANG results has n = .95. Try various values of this spectral tilt and see how power spectrum changes!

8) Enter outpout filename for SCALAR cl

Type in any valid file name that your system can handle to accept the output of CMBFAST.

9) Enter initial conditions

1 = Isentropic (adiabatic)

2 = Isocurvature CDM

3 = Isocurvature baryon

4 = Isocurvature seed conditions

The best bet here is to enter 1 for adiabatic initial conditions. See the literature for detailed explanations!

10) Enter input filename for jl

Enter the name of the data file that contains the spherical Bessel functions - suchas jbes.dat. If you are computing an open universe model, you will also need to enter the name of the file that contains your ultra spherical Bessel functions. You should have created these using jlgen and or ulgen. Now you just sit back and wait a minute or two while the software crunches away! When it is finished, it will tell you so, and give you an estimate of the best likelihood fit to the COBE normalized curve. You are ready to graph your output using Gnuplot, Grace, or your favorite graphing program! A plot in Windows Excel would look something like this: