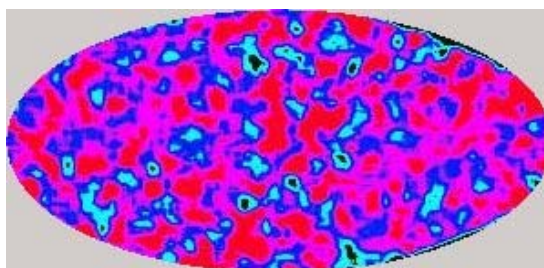
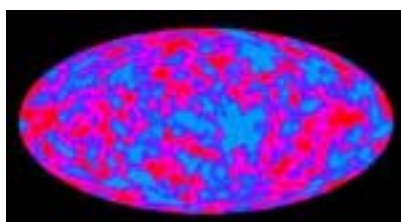
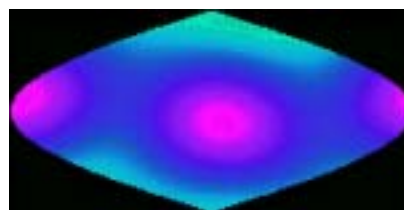
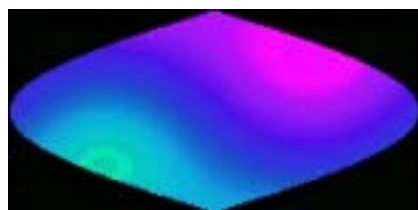


COBE for (BIG) KIDS:

Discovering how the results of the
COSMIC **B**ACKGROUND **E**XPLORER SATELLITE
help us understand the early
UNIVERSE



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Discovering how the results of the

COSMIC BACKGROUND EXPLORER SATELLITE (COBE)

constrain models of structure formation in the EARLY UNIVERSE

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August, 1993; revised: August, 2003 by JvdV.

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The following series of image processing activities utilizes the program UCSB Image, by Russell Woods. This software is available by request from the Remote Access Astronomy Project at UCSB, and was funded by a grant from the UCSB Office of Instructional Development.

BACKGROUND READING: *(included as pdf files on the workshop CDROM)*

Small Scale Anisotropies: The Final Frontier, *van der Veen, Lubin, et al., from The Physics Teacher, Dec. 1998* and The History and Fate of the Universe, *Lawrence Krauss, from The Physics Teacher, March, 2003*

The quest for anisotropies in the CMB that would give clues about the origin of the universe prompted the launch of the COSMIC BACKGROUND EXPLORER satellite (COBE) in 1989. When the results of the first year of data analysis were announced in April, 1992, there was a great deal of excitement in the scientific community. It was apparent, for the first time, that an experiment had actually found extremely small but real anisotropies in the Cosmic Microwave Background radiation (CMB), which were consistent with models of structure formation in the early universe, based on other clues, such as cosmic elemental abundances and the growing evidence for dark matter.

In this exercise you will:

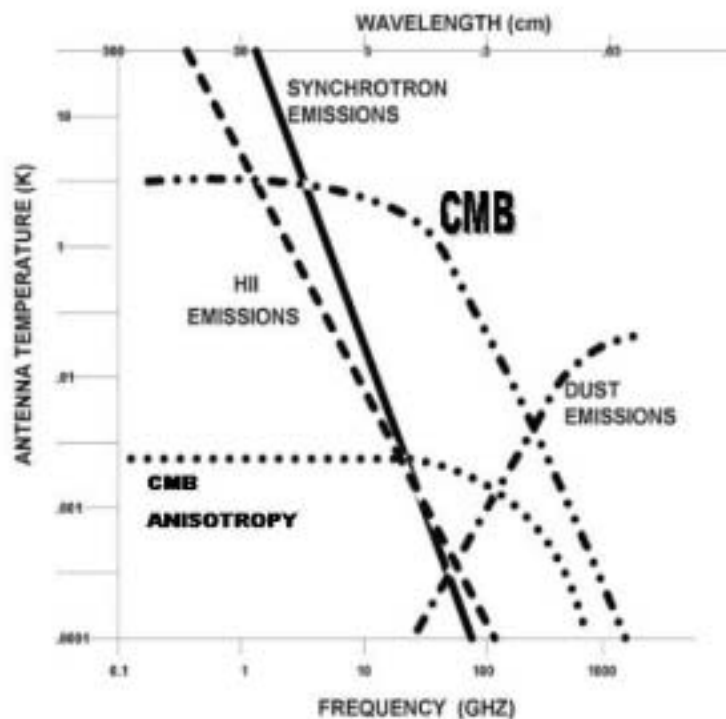
1. *Learn how the COBE team selected the optimal frequency bands in which to observe the CMB;*
2. *Calculate our velocity relative to the CMB as a reference frame, from the Dipole Anisotropy;*
3. *Learn how we can model the temperature variations on the last scattering surface with a Spherical Harmonic Series;*
4. *Learn how the data were analyzed to bring out the small variations in temperature that were found by COBE.*

All of the images you will use in this lab are maps of our galaxy, as seen from our point of view, at microwave frequencies. The maps are in *galactic coordinates*: the plane of the galaxy is the "equator", and 0° of "longitude" is looking toward the galactic center. (To find the galactic center: if you live in the northern hemisphere, look outside in the evening of a summer night (or, the wee hours of the morning in the wintertime) toward the constellations Scorpius and Sagittarius. The galactic center is somewhere in between those two constellations...and, in case you did not already know this: there is a HUGE SUPERMASSIVE BLACK HOLE lurking at the galactic center!)

Part I. Looking for the optimal frequency window

Since the CMB is not visible, but is in the microwave part of the electromagnetic spectrum, in order to measure it we need microwave detectors. In order to design an instrument to measure very small-amplitude microwave signals, where the variation in temperature above background is a few parts in 10^5 , it is important to find the right frequency window at which signals from all other possible sources are at their absolute minimum, and the expected CMB signal is at a maximum.

There are a number of galactic and extragalactic sources that emit considerable radiation at microwave frequencies: interstellar dust, interplanetary dust, infrared galaxies, huge clouds of neutral hydrogen, and interstellar electrons that get caught in large magnetic fields and spiral around the magnetic field lines, emitting electromagnetic radiation at a variety of wavelengths. These are some of the kinds of *foreground sources* that come from our own galaxy and others, and which get in the way of our ability to measure the CMB. Before we can look for very small microwave signals in the *background* radiation, we need to fully understand the spectrum of microwave emissions from *foreground* sources, so that we can subtract out the unwanted foreground signals from our observations. Another option, which the COBE team found, was to see if there was any window of frequencies where the foreground emissions happened to be at a minimum, but the CMB signal was still substantial.



(figure 1)

That is exactly what the COBE scientists did before they designed their microwave detectors that flew aboard the satellite. This graph, (Smoot, et al., 1992), shows the relative intensity of foreground emissions at various wavelengths in the microwave region compared with the CMB blackbody emission at 2.7 Kelvin and the expected strength of CMB anisotropies.

1. In order to observe small anisotropies in the CMB, what range of frequencies would you design your instruments to measure in, where the CMB signal is maximum but the signal from dust, HII, and synchrotron emissions are minimum?

If your answers came out somewhere between 30 and 90 gigahertz (GHz), you are correct. (A gigahertz is 10^9 Hertz.) The COBE team of scientists designed three differential microwave radiometers (DMRs) which measured the CMB signal at 31, 53, and 90 gigahertz, corresponding to wavelengths of 9.6, 5.7, and 3.3 millimeters. These instruments could resolve extremely small temperature differences down to about 50 microKelvin (50×10^{-6} Kelvin) per pixel, and to a few microKelvin where averaged over the sky.

Now open the image processing program UCSBImage, and load the following maps: SKY31.FTS, SKY53.FTS, and SKY90.FTS. These are Hammer-Aitoff projections of the emission from our galaxy, in galactic coordinates, at different microwave frequencies. Each map was compiled from a variety of sources, including data from the Infrared Astronomical Satellite (IRAS) sky survey, and the Haslam, et al., 1982 sky survey.

Now, as you load each map, click and drag on the title bar and move them so that they do not overlap, and you can compare them to each other.

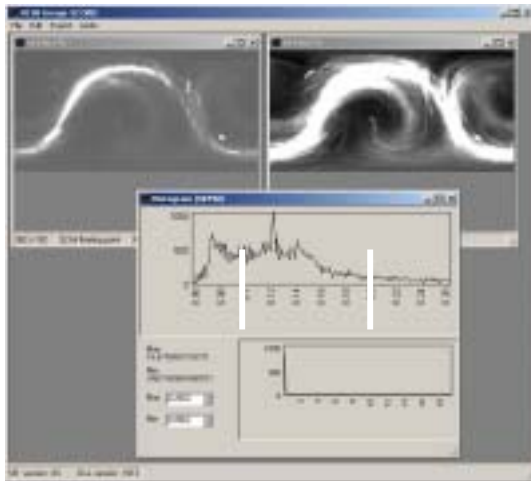
Choose one of the maps...it does not matter which one you choose first. Move the cursor around inside the map. As you do so, the coordinates are displayed at the bottom right of the window. Digital images in this software are always displayed with (0,0) in the upper left corner; the z-values are relative pixel intensity.

A note about these images:

These maps are similar to Mercator projections that you might make of the Earth. They are intended to represent Celestial Coordinates, in which the Plane of the Ecliptic is the "equator". Due to the tilt of the Earth's rotation axis relative to the plane of the galaxy (the Milky Way), the galactic plane appears as a snaky line across the map. Like a Mercator projection of the Earth, there is a lot of distortion the closer you get to the North and South Celestial Poles.

The coordinates of the image run from (0,0) in the upper left corner, to (360, 180) in the lower right corner. Translating these pixel coordinates into Celestial Coordinates, the y-coordinates should be (top to bottom) +90 to -90 Declination, and the x-coordinates should be (left to right) 0 to 24 hours Right Ascension.

The microwave antennas are sensitive to the power output of the galaxy for a particular frequency; this is then calibrated to the corresponding black-body temperature for each wavelength. For each map individually, click on View, and then **HISTOGRAM**. (See the tutorial Introduction to Digital Image Processing on your CDROM for a detailed explanation of what the Histogram function does.)



(figure 2)

Once you get all three maps on screen, set the "black" (RGB=0,0,0) and "white" (RGB=255, 255, 255) limits for each image to include only the portion of each histogram that contains the greatest number of pixels. Do this by clicking on the upper plot in the histogram window. This click will cause a white line to appear; drag the mouse over the range with the greatest number of values, and you'll see that portion of the histogram become white. Now see how the display window changes! You are able to bring out the details in that intensity range in this way.

Here is an example using the map "SKY90.FTS". The image on the left is plotted using the standard deviation as the limits of the histogram (the default); the image on the right is plotted using only the range of values where the greatest number of pixels lies.

In the histogram window, the bottom plot shows the full range of intensity values contained in this image; the upper plot shows the range that I have chosen to plot. This image is a map of the microwave emissions from the plane of the galaxy at 90 GigaHertz.

RAAP Image Processing Curricula for High School and College Physics and Astronomy

Now display each map in this way – by "histogram-limiting" each one. Write down the minimum and maximum values for each image that are displayed. (These is not the *absolute* minimum and maximum values: they are the minimum and maximum only for the range that you have chosen to display.)

31 GHz: min. = _____	max = _____
53 GHz: min. = _____	max = _____
90 GHz: min. = _____	max = _____

1. Which map has the lowest maximum for the galactic emission?

Now, to compare the intensity of the galactic emission at each frequency visually, we need to display them all at the same intensity range. This should be the intensity range you found for the map with the lowest maximum intensity. (...which should be the 53 GHz map!)

Open the histogram for each map and this time manually type into the number boxes the minimum and maximum values that you used for the 53 GHz map; in this way you can compare the emissions from the galactic plane at each frequency.

Now compare the way all three maps look, now that the 256 available colors are limited to the same range. The brightest regions represent the most intense microwave emissions from galactic sources for each frequency.

1. If you were to design an experiment to look for microwave signals from beyond the galaxy, but you are stuck observing from within the galaxy, which frequency band would you choose?

If you chose 53 GHz, your answer matches that of the COBE team. Actually, they did measure the microwave emissions of the whole sky at all three of these frequencies. Two more experiments on board the COBE satellite measured the infrared spectrum of the CMB: the Diffuse Infrared Background Explorer (DIRBE) and the Far Infrared Absolute Spectrophotometer (FIRAS).

Just for comparison, keeping these three maps on your screen, open one more file: **SKY408.FTS**. This is a map of the sky at 408 megahertz (MHz). (Recall: GigaHertz = 10^9 Hz, and MegaHertz = 10^6 Hz.)

1. What wavelength does 408 MHz correspond to? (Hint: $c = \lambda f$, where $c = 3 \times 10^8 \text{ m/sec}$ = speed of light)

Now try to normalize the maximum and minimum to the same values you used for the GHz maps.

1. Can you do this??? Plot - and describe what the image looks like when you attempt to normalize it to the same range of pixel intensities you used for the other three maps.

1. What can you conclude about the intensity of galactic emissions at 408 MHz as opposed to the emissions at 31, 53, and 90 GHz?

Locate where 408 MHz would plot on the x-axis of the graph of galactic emissions on page 3.

1. From the graph, what do you think the source(s) of the 408 MHz emissions is (are)?

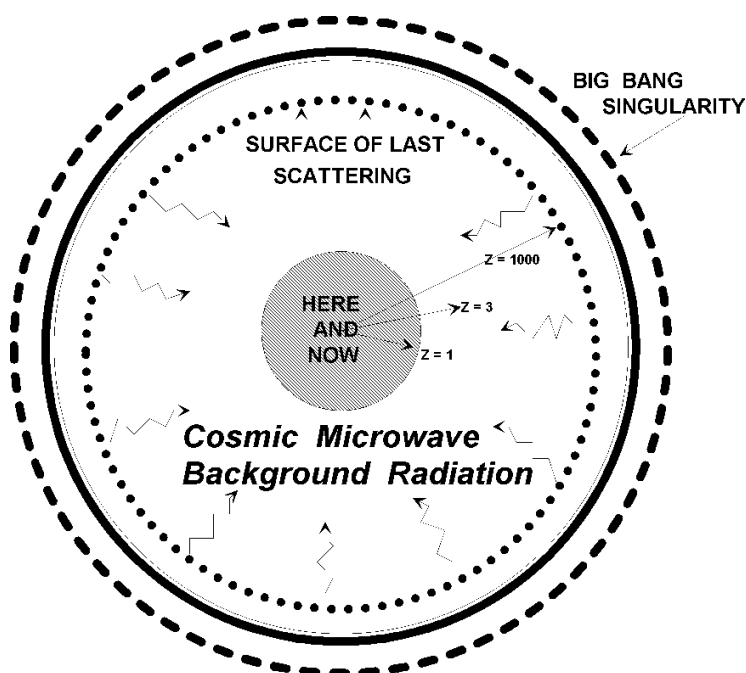
The 408-MHz radiation is due to synchrotron emission by relativistic electrons, which are accelerated by magnetic fields in the galactic plane. The HII line on the graph shows the spectrum of Bremsstrahlung radiation from clouds of ionized hydrogen in the galactic plane.

Now close these images, and begin the next part of this lab...

Part 2. Analyzing the variations in the Cosmic Microwave Background Radiation

But first: some background information to help you understand what you are looking at:

Since the CMB comes to us from all parts of the sky, from our point of view it appears to form an imaginary sphere, at a redshift of ~ 1100 . This imaginary sphere is called the surface of last scattering, and represents a short period of time in the history of the universe when the temperature cooled sufficiently for neutral



hydrogen to form, and for matter and radiation to *decouple*. Before that time the young Universe was so hot that it was opaque to all forms of electromagnetic radiation – like the interior of the Sun. The origin of the CMB comes from the time when the Universe cooled enough to become transparent to electromagnetic radiation. Before this time, the entire Universe was filled with a plasma of photons (light particles), baryons (protons and neutrons in the form of single hydrogen and helium nuclei and a little bit of Lithium mixed in), and electrons, tightly coupled in a "fluid". Also present (we have reason to believe!!) were large pockets of dark matter particles that interact gravitationally but not electromagnetically.

For about 300,000 years after the Big Bang, acoustic waves just kept sloshing around this "photon-baryon fluid" as the Universe expanded.

During this time, the temperature was so high that you could not see through it – that's why we can't actually see anything that went on before the CMB – the Universe was opaque. It would have been like trying to see through the Sun – you can't do it. But, all the sloshing around of these pressure waves made some regions denser and hotter, and some regions less dense and cooler than others. In addition, dark matter would have

decoupled from the radiation at an earlier time, and would be collecting in pockets, creating denser regions that would be "gravity wells" in which the baryons and photons would have tended to collect. These variations in density in the early Universe translate into temperature variations in the CMB that we observe now.

Then suddenly, within a short time interval (no one knows how long, but it was very short compared to the history of the Universe, like a very, very thin sedimentary layer in a geologic column) the Universe cooled and became transparent, and neutral hydrogen could form. The photons were free to travel outward, but the imprints of the hotter and cooler regions were left in the photons forever, as they propagated outward, through space and time, getting stretched more and more as the Universe expanded, finally reaching our detectors, around 13 billion years later. We observe them not as the hot, bright photons that they were when they left that plasma inferno 300,000 years after the Big Bang, but as very cold microwave photons that permeate the whole Universe today, at temperature of around 3 K above absolute zero.

In order to understand something about the conditions in that photon-baryon fluid, we observe the distribution of small variations (*anisotropies*) in the background temperature of the CMB, and try to figure out their *Angular Power Spectrum*, meaning that we look for the most popular sizes of temperature anisotropies that are superimposed on the background 2.716-K temperature. We model the distribution of the temperature variations on the surface of last scattering with a *spherical harmonic series*, in a manner similar to the way in which we model the gravitational "shape" of the Earth.

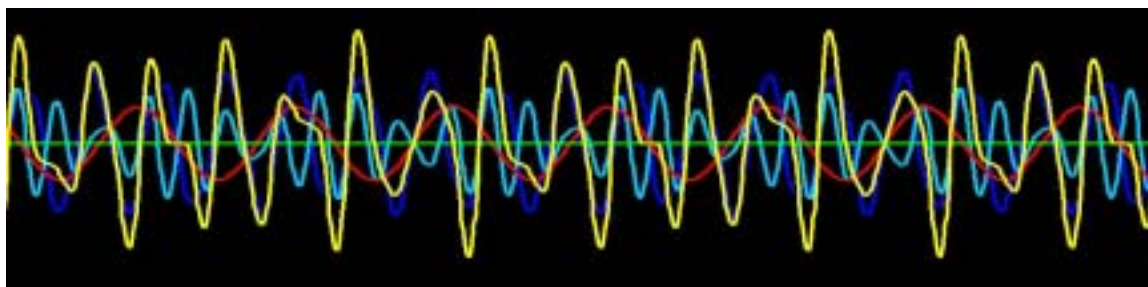
But first, let's digress for a moment to a one-dimensional analogy of a vibrating string...

You know that when you pluck a guitar string, for example, you hear a certain tone. If you pluck the string over the neck, or over the body, or over the hole in the sounding box, you hear a slightly different tone. This is because, depending on where you pluck the string, you excite different **normal modes** of vibration (also called *overtones*). The tone you actually hear depends on the number of overtones you excite and the amount of power in each overtone (power is proportional to the amplitude²), as well as the physical properties of the string (length, thickness, tension, density), the medium through which the sound waves travel (air, for example), and the response of the detector (your ear, for example).

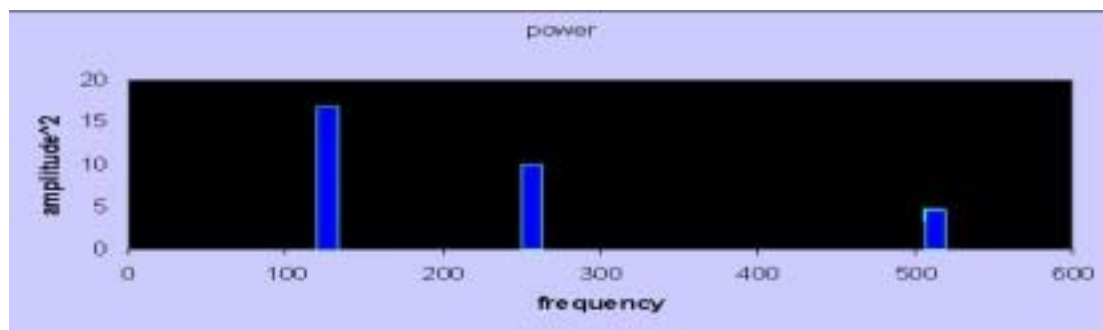
When you pluck a guitar string the dominant note you hear is the fundamental (lowest frequency, longest wavelength), but there are many *higher order harmonics*, or *normal modes* that are also excited. Although your ear cannot distinguish all of them, if you had a microphone and hooked up the signal from the plucked guitar string to a spectrum analyzer, you could see **power spectrum** displayed on the screen. Then you would know just what frequencies you have in that sound, and the relative strengths of each one.

Let's see what this might look like for a very simple case...

Here is a plot of three waves, each one with double the frequency of the previous one, added together. The resultant sound that you might hear (if these were audible frequencies) would be three octaves played all together – like Middle C, the C above Middle C, and the C below Middle C (on the piano, for example). The yellow wave is the sum of all three.



The POWER SPECTRUM of this complicated-looking signal would look something like this:



If ALL you saw was the power spectrum, you could immediately know exactly which frequencies were present, and their relative strengths. This power spectrum would tell you that you have three sine waves, one at 128 Hz, the next at 256 Hz, and the third at 512 Hz, and that the 256-Hz signal has twice the power as the 128-Hz signal, and the 512-Hz signal has twice the power of the 256-Hz signal.

Now back to the universe...

We simply extend the one-dimensional analogy of a string to the 2-dimensional analogy of the surface of a sphere – the shape of the Earth or the Surface of Last Scattering.

To a "first order" (*monopole term*), the Earth is a sphere, however if we look a bit more carefully, we find that the equatorial radius is somewhat larger than the polar radius, giving the Earth a flattened appearance (*dipole term*). This is because the Earth is not perfectly rigid, and as it spins, the material around the equator tends to pull outward. This is like what happens if you tie a rock to a string, let the string hang down, and then start spinning around. The rock will no longer hang straight down, but will pull outward a bit, depending on how fast you spin! So this "second order term" is due to the rotation of the Earth on its axis.

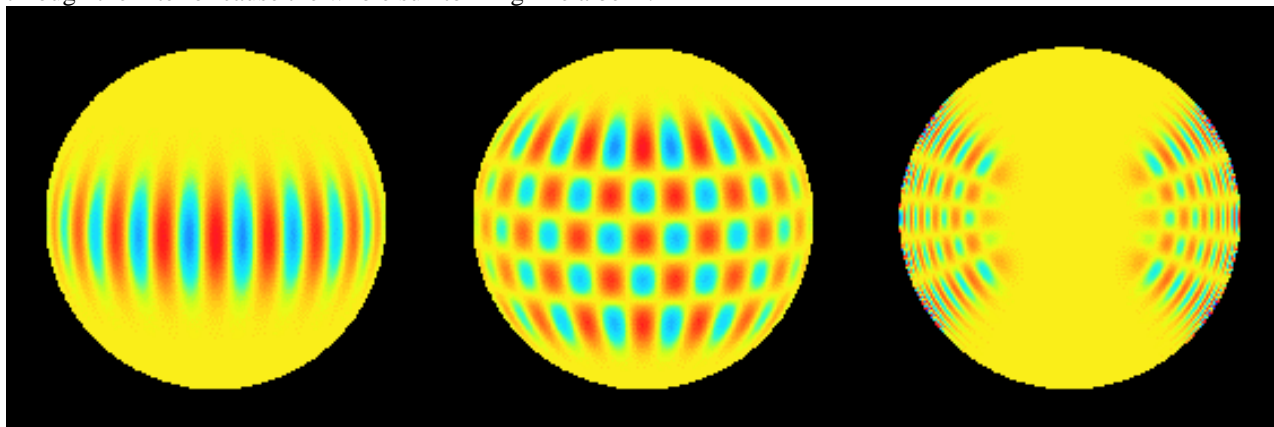
If we look in still more detail, we see that the north pole actually sticks out a bit, and the south pole is a bit indented, giving the Earth somewhat of a flattened pear shape. If we look in increasing detail, at smaller and smaller scales, we find more and more small scale bumps and lumps (*higher order harmonics*). Because a gravitational field results from a given distribution of matter, if we can model the gravitational field of the Earth with great detail, we can understand something about the way mass is distributed in the Earth.

We can think of the temperature of the CMB in much the same way, and model the temperature distribution with a spherical harmonic series. The *monopole term* is the overall black-body radiation, at a temperature of around 2.726 K above absolute zero. There is a *dipole term*: superimposed on the overall 2.726 K black-body temperature, there is subtle variation in temperature, that in one direction that reaches a maximum of a few *thousandths* of a Kelvin warmer than the background, and a few thousandths of a Kelvin cooler in the opposite direction. This is not due to the temperature of the early Universe, but simply due to our motion through the CMB itself. There is also a *quadrupole term* superimposed upon the background: an even subtler variation in temperature that is on the order of a few hundred-thousandths of a Kelvin warmer and cooler than background.

It is the small scale variations in temperature – on the scale of one degree of angle on the sky or less, which are the higher order terms in the spherical harmonic series description of the CMB, that contain the important information relating to the density variations in the early Universe. These temperature variations are even subtler: a few *millionths* of a Kelvin warmer or colder than background.

We see a similar effect in the light emitted from the surface of the Sun. There are subtle shifts in the frequency of the light – Doppler shifts, toward warmer or cooler – superimposed on the average temperature of the Sun's surface, which are due to shock waves passing through the interior of the sun. The small scale waves that travel just beneath the surface of the Sun cause small ripples, while the very largest disturbances that travel

through the interior cause the whole sun to "ring like a bell".



Vibrational modes of the Sun

from <http://www-solar.mcs.st-andrews.ac.uk/~eric/TALKS/Haleweb/6/page2.html>

In this lab you are going to look at the very fuzzy maps that were made of the CMB by the COBE satellite in order to understand how we measure the temperature variations in the CMB (the signal).

In another lab, you will investigate the CMB Power Spectrum, and see just how sensitive it is to the physical properties of the Universe, and why it is that we can learn so much about the Universe from the CMB Power Spectrum (the physical properties of the source and the medium).

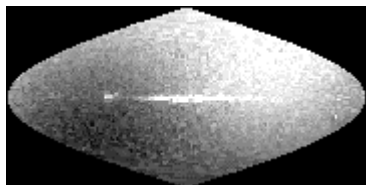
Now, open the image ALLSKY.FTS. This is a map of the galaxy that contains the galactic foreground signal, the actual CMB dipole, quadrupole, and anisotropy, as well as some simulated random instrument noise.

A note about these images:

These images were designed to look like maps of our galaxy, with the plane of the galaxy as the "equator". This type of projection is called a Hammer-Aitoff projection, and the x-coordinate would be galactic longitude, with 0° in the center, -180° at the extreme left and 180° at the extreme right, however due to an artifact of the way the image files are displayed by the software, the x-coordinate of the image runs from 0 on the left to 360 on the right. The y-coordinate is designed to look like galactic latitude, with 0° in the middle, $+90^\circ$ at the top, and -90° at the bottom. Again, due to the way the image files are displayed, the actual y-coordinates run from 0 at the top to 180 at the bottom. Keep this in mind when you want to translate from pixel coordinates to actual galactic coordinates.

The z coordinate represents antenna temperature in milliKelvin (.001 Kelvin), with respect to a baseline of 2.726K, the average background temperature. The way to read the z values is as temperatures above or below the 2.726K background radiation.

A. Subtracting the galactic signal from the background.



The streak that runs across the middle of the map is due to the galactic emissions at 53 GHz. Even though the galactic signal at this frequency is a minimum, it is still present and must be subtracted out as an unwanted foreground signal.

Open the image GAL53.FTS onto your screen. This map represents only the galactic signal at 53 GHz.

You will need to histogram-limit each map to see the details, as you did for the galaxy foreground maps.

First: subtract the galaxy signal from the sky.

1. Click on the ALLSKY map to make it the active window.
2. Click on Create on the upper menu bar, and Math on the pull-down menu.
3. Click on Dual.
4. Click on Select, and then select GAL53.FTS.
5. Click on the Subtract button, and be sure that the output type is 32 bit floating point. *Voila!* you have subtracted the galactic foreground from the microwave map of the sky.
6. Now "histogram limit" the new image so you can see the details.
7. Click on File on the upper menu bar, and save this image as a .FTS file. I suggest you call it something like "nogal.fts" so you will remember that this is the map with the galaxy removed.

Note: *If you don't like the image after you have histogram-limited it, you can go back to the original display by clicking on Limits on the top menu bar, and go back to Standard Deviation, and then try again.*

Another note: *at any time you can create a colored palette to enhance your viewing pleasure!* Just click on the word palette on the upper menu bar. Try it – you'll like it!

1. What is the appearance of the CMB map after you have removed the galaxy?

After subtracting out the galactic foreground signal, you can see that the CMB signal is dominated by the DIPOLE TERM.

B. Interpreting the dipole map of the CMB.



This warm/cool temperature distribution which is superimposed on the background radiation field was first discovered in the 1970's with detectors flown in high-altitude balloons or aircraft. The results of the COBE satellite confirmed the existence of the dipole anisotropy, and measured its amplitude with greater accuracy than had been done in previous experiments.

Among the various causes of anisotropies in the CMB, the simplest is due to the motion of the observer with respect to the general expansion of the universe. If the observer is moving relative to the reference frame of the universe, then photons reaching the observer from different parts of the sky will be red or blue shifted, and this will lead to a dependence of temperature on $\cos \theta$, where θ is the angle between the direction of motion and the direction of observation. The dipole anisotropy is actually a Lorentz contraction of the radiation field (CMB) that we observe due to our motion through it, in the same way that Special Relativity explains why, if you are moving very fast, lengths of objects out in front of you appear shortened relative to the lengths of objects at rest next to you.

When the dipole anisotropy was first discovered, it revealed a surprise: our galaxy is not "at rest" in the expanding universe reference frame. Rather, the whole galaxy is moving *through* the universe, superimposed on the over all expansion rate, towards some unseen concentration of mass with a huge gravitational field, somewhere in the vicinity of Virgo and Leo!

C. Calculating our velocity with respect to the CMB from the dipole map.

A measurement of the maximum temperature of the dipole anisotropy gives an estimate of our velocity with respect to the CMB, superimposed on the general expansion of the universe. In the last several years scientists have been measuring the streaming motions of galaxies, independent of the Hubble expansion, which has lead to inferences about the distribution of matter in our region of the universe.

An observer moving relative to an isotropic radiation field will observe a Doppler-shift in the radiation

that is expressed as: $T(\theta) = T_{\text{CMB}} [\gamma(1 - \beta \cos \theta)]^{-1}$ (1)

where $\beta = \frac{v}{c}$ in the usual definitions from Special Relativity,
 $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$

v is the observer's velocity, and c is the velocity of light, 3×10^8 meters/second. T_{CMB} is the cosmic background radiation temperature of 2.726K, θ is the angle between the direction of observation and the direction of motion of the observer, with 0° = the direction directly in front of you, and 180° = the direction directly behind you. $T(\theta)$ is the temperature as a function of the angle at which you observe, as you move with velocity v through the CMB.

This expression can be expanded as a series of higher order terms in $\cos(\theta)$:

$$T(\theta) = T_{\text{CMB}} (1 + \beta \cos(\theta) + \beta^2 \cos^2 \theta + \dots) \quad (2)$$

The first term gives the black body temperature of the CMB, and the second term gives the dipole anisotropy, which is in milliKelvins (10^{-3} K). The higher order terms get very small, and we will neglect them here.

The pixel values within the map on your screen are actually given in the units of microKelvins above and below the background temperature of 2.726K. (The black region "outside" the map is meaningless, and just an artifact of the simulation. DO NOT CONFUSE IT WITH THE NIGHT SKY!!!)

1. Locate the "warmest" region of the sky. What is the maximum average pixel value in that region?

1. The pixel values represent milliKelvins above and below 2.726 background. What, then, is the "actual" temperature measured in that direction? ($\theta = 0$)

1. From equation (2), neglecting the higher order terms, derive an expression for our velocity with respect to the CMB, and then calculate it in km/second:

If you obtained a value somewhere around 350 to 375 km/sec, you are in the right "ballpark". The published value given by the COBE team is 365 +/- 18 km/sec.

Now, it would be really useful to be able to go out at night and point to a certain direction in the sky and amaze your friends with the information that we are moving in THAT direction at about 370 km/sec! The location of the dipole axis (warmest point) in galactic coordinates published by the COBE team is $265^\circ, 48^\circ$, with an uncertainty of +/- 2° for both. In celestial coordinates of RA and DEC, the location is given as 11.2 h +/- .2 h, - 7° +/- 2° . This is in the direction of the Virgo Supercluster of galaxies. To locate the constellation Virgo in the sky, you follow the arc of the handle of the Big Dipper until you come to the nearest bright star. This star is Arcturus ("arc to Arcturus"); you then follow a direct line approximately south to the nearest isolated bright star, which is Spica ("drive a spike to Spica"). Spica is in the constellation Virgo, which is in the approximate direction of our motion.

The dipole anisotropy, then, is not due to any intrinsic anisotropy in the CMB itself, so we shall subtract it out.

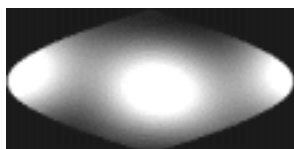
D. Subtracting the dipole from the microwave signal.

Now subtract the dipole, DIP53.FTS from your NOGAL map, using the same steps outlined in section A above. Save the file as something like "Nodipole.fts", so you'll remember what you did to it. (Of course, you could give your maps uninteresting names like map1, map2; or Joe and Bill; or unusual names like Henriette or Poindexter, but it will be more difficult later to recall what you did to each image...)

Anisotropy map:

The map you have left contains small temperature fluctuations in the CMB that contain information about the distribution of matter and energy in the early universe, BUT *we also have instrument noise*.

ASIDE: A LOOK AT THE QUADRUPOLE MAP



Now click on the floppy disk icon again, and bring up the image entitled QUAD53.FTS. This is a map at 53 GHz of the quadrupole term in the spherical harmonic expansion of the temperature field of the CMB.

Notice that you can hardly see any detail at all! Move the mouse around inside the image, and notice the z-values. They are around 3 orders of magnitude smaller than those of the dipole map. View the histogram... and find the optimal limits with which to see the slightly warm and slightly cool spots.

The quadrupole term represents two slightly warmer regions around the equator, and two slightly cooler regions at the poles. (The reason you see three warm spots is just an artifact of the projection. Think of this map in 3-D, and mentally wrap the left and right sides around into a sphere - you get two warm spots: one at 0° and the other at 180° .)

The quadrupole anisotropy in the CMB has been measured for the first time by COBE, and is about 2 orders of magnitude smaller than the dipole anisotropy, as expected.

For comparison: the baseline background temperature is roughly 2.726 Kelvin;
the dipole anisotropy is roughly 3.4×10^{-3} Kelvin;
the quadrupole contribution is roughly $1.5 - 2.0 \times 10^{-5}$ Kelvin.

For some really cool graphic representations, try making a COBE palette in cyan and magenta, and viewing this image with the 3-D Zoom feature!

E. Filtering the data.

You know that every measurement that you ever make has some level of error, and you have to account for this in your data analysis. The way in which you handle noise in your data depends on what you believe about the nature of the expected signal and what you know about the instrument noise.

We will assume that the instrument errors are random Gaussian fluctuations about some mean and that they average out to zero amplitude. We will use a technique in which we average the data by moving a 2-dimensional Gaussian window across the map, one pixel at a time. We sum the values of all the pixels in our window, giving a weight of 1 to the center pixel, and decreasing the weight of each pixel from the center. We then divide by the sum of all the weights in the window. In this way we "smooth out" random fluctuations which are due to instrument noise. We choose the window to be slightly larger than the size of the beam width of the COBE DMR instruments (7°) to account for the way in which the instruments sampled the sky. (For a discussion on filtering techniques, see the section Filters and Masks in the Introduction to Digital Image Processing.)

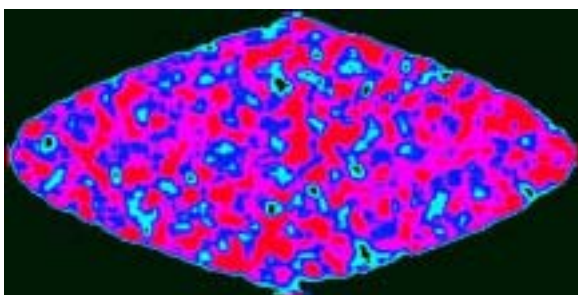
1. Click on Create from the top menu bar.
2. Click on Filter Masks – the mask window will appear.

3. Set the dimension to 9 x 9.
4. Click on Load – load the file GAUSS.MSK from the Images directory on your CDRom.
5. Change the font to something readable, like 10 points so that you can see the actual numbers (which are not zeros).
6. Click on OK – and what you have left is the smoothed map of temperature anisotropies in the CMB that were first mapped by the COBE satellite! (Well, more or less... these are simulated data, but based on real numbers.)

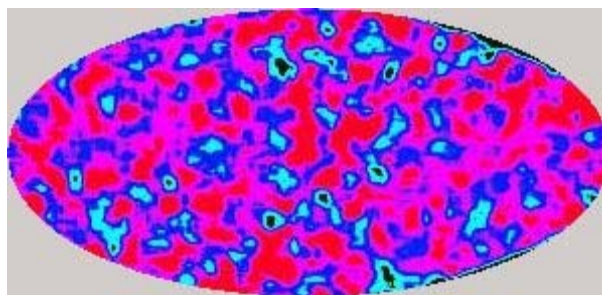
Now you can limit the histogram to bring out the details, and play with the palette function to further enhance the details.

Play with the graph palette and see if you can make your map look like the magenta-and-cyan COBE map that is now so famous...

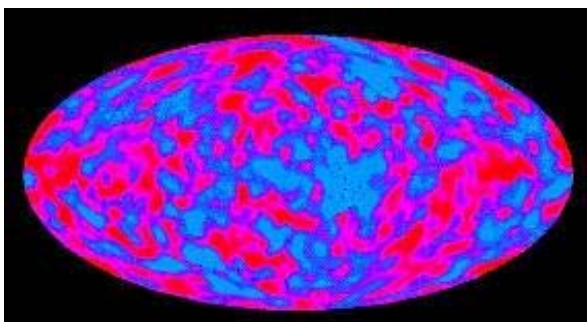
Here's my best attempt: see if you can do better!



...filtered and colored in UCSB Image32 ...



...and cropped using Adobe Photoshop™ ...



...compare to the COBE map...well, statistically not bad!