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Planck Visualization Project: Seeing and Hearing the CMB

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Abstract. The Planck Mission, launched May 14, 2009, will measure the sky over nine frequency channels, with temperature sensitivity of a few microKelvin, and angular resolution of up to 5 arc minutes. Planck is expected to provide the data needed to set tight constraints on cosmological parameters, study the ionization history of the Universe, probe the dynamics of the inflationary era, and test fundamental physics. The Planck Education and Public Outreach collaborators at NASA's Jet Propulsion Laboratory, the University of California, Santa Barbara and Purdue University are preparing a variety of materials to present the science goals of the Planck Mission to the public. Two products currently under development are an interactive simulation of the mission which can be run in a virtual reality environment, and an interactive presentation on interpreting the power spectrum of the Cosmic Microwave Background with music. In this paper we present a brief overview of CMB research and the Planck Mission, and discuss how to explain, to non-technical audiences, the theory of how we derive information about the early universe from the power spectrum of the CMB by using the physics of music.

1. Introduction: About the Planck Mission and CMB Research

Planck is a mission led by the European Space Agency (ESA), with significant participation by NASA. Planck's purpose is to map the Cosmic Microwave Background radiation of the universe (CMB) – the oldest light we can detect. The CMB comes to us from the time when the universe became cool enough so as to be transparent, and protons could combine with electrons to form neutral hydrogen, approximately 380,000 years after the Big Bang. Planck's instruments will measure the minute fluctuations in the CMB with a sensitivity of a few millionths of a degree Kelvin, and an angular resolution as fine as five arc minutes on the sky. This task has been compared to being able to detect the heat of a rabbit which is sitting on the Moon, from the distance of the Earth (www.esa.int/SPECIALS/Planck/SEM0Y5S7NWF_0.html), and resolve a bacterium on the surface of a bowling ball![1] The next few years should

[1] If a bacterium has a diameter of, say, 50 microns, or 5×10^{-5} meter, then the cross sectional area of a spherical bacterium is around 2×10^{-9} m^2. The average radius of a typical bowling ball is around 11 cm, or .11 m, according to Wikipedia (http://en.wikipedia.org/wiki./Bowling_ball). Thus, a bacterium sitting on the surface of a bowling ball subtends a solid angle of approximately 1.6×10^{-7} steradians, or roughly 1.3×10^{-8} of the surface area of a bowling ball. The surface area of a sphere is 4π steradians = approximately 1.48×10^8 arc minutes^2. If we take an approximately square patch of sky, 5 arc minutes on a side, or 25 arc minutes^2, this is equal to $25 \times (1/1.48 \times 10^8)$ or approximately 1.68×10^{-8} of the total area of the sky – roughly comparable to the fraction of the surface of a bowling ball that would be occupied by a large bacterium.

prove to be quite exciting, as the data from Planck are expected provide answers to many of the fundamental questions about the early history and evolution of the Universe, and test fundamental physics beyond the Standard Model.
In this paper we first give a brief overview of the CMB and its discovery, and a short description of the two previous satellites which have mapped the entire sky. We then give a brief description of a few of the technical aspects of the Planck satellite and then discuss how we derive information about the early universe from the power spectrum of the CMB, using the analogy of the physics of music. We end with a short description of the products for public distribution that are currently under development.

2. A Brief Discussion of the Cosmic Microwave Background (CMB)

2.1. Imagining the Universe Before the CMB

The CMB is all around us, bathing the Earth and the Galaxy, and filling all the visible Universe with microwave radiation. It is the oldest light we can detect, coming from a time, around 380,000 years after the "Big Bang," when the Universe first became cool enough so as to be transparent to electromagnetic radiation. This time is also referred to as *recombination*, because when the universe cooled down sufficiently for matter and radiation to decouple (approximately 3000 Kelvin), protons and electrons could combine to form neutral hydrogen
Trying to see past the CMB to earlier times is like trying to see into the Sun; you cannot. The Sun is a useful analogy, in that it takes photons one million years from the time that they are released in the core of the Sun, bouncing off charged particles on their way to the surface, before they stream freely out into space, traveling at the speed of light, arriving at the Earth 8 minutes after escaping from the surface of the Sun. Photons in the early universe had only 380,000 years to bounce off charged particles in the early universe as it was expanding, and are arriving at the Earth 13.7 billion years after they escaped.
Visualizing an expanding universe from the inside out can be rather tricky, so now imagine that you are standing inside the Sun. Plasma is churning all around you, a deafening roar of pressure waves in your ears, and blinding light and heat in every direction, around 15,000 Kelvin, with nowhere to hide. Such was the environment that an observer in the infant universe might have experienced in the last few centuries before recombination. Now imagine that the Sun is expanding away from you on all sides. The temperature is falling, and the light growing redder. At a certain moment the temperature around you cools down to 3,000 Kelvin, and you begin to see shadows as the bright fog clears. After a while the space around you grows dark, as no stars have yet formed, but you see this glowing spherical wall of bright fog, now a beautiful red color, receding from you in all directions, growing cooler and darker as it speeds away from you on all sides. You can distinguish darker and brighter patches in the fog, the last vision of the churning plasma waves that once surrounded you.
Imagine now it is almost 14 billion years later; stars and galaxies have formed, and you can see them at varying distances. Now the temperature around you is a mere 3 degrees above Absolute Zero. Because space itself has stretched by a factor of 1,000 or so since the time that the universe first became transparent, the wavelengths of the

light from this fog are also stretched by the same amount, so that they are visible now as microwaves. The churning plasma and deafening sounds of the pressure waves are barely detectable now, as minute variations in these cosmic microwaves. This is the CMB!

2.2. The Expanding Universe

The first evidence for an expanding universe was Edwin Hubble's discovery of the red shifts of galaxies, which he announced to the world in 1929. Using the 100-inch telescope at Mt. Wilson in California, Hubble found that the absorption lines in the spectra of galaxies are shifted towards the longer wavelengths of the electromagnetic spectrum, relative to their wavelengths in a rest frame on Earth. This discovery led Hubble to derive the "law" which bears his name, that the apparent velocity with which a galaxy is receding from us is directly proportional to its distance:

$$v(r) = H_0 r \tag{1}$$

Hubble's discovery also prompted a decades-long search for the "after glow" of the Big Bang, predicted to be observable as microwave radiation.

In the early 1960s, Arno Penzias and Robert Wilson, then at Bell Labs in Holmdel, New Jersey, noticed a small discrepancy in their microwave instruments that indicated an excess of radiation coming from space. At first, they thought it was due to droppings of pigeons roosting in their microwave horn but, even after thoroughly cleaning it, the background noise remained. After confirming their observation with the predictions of Robert Dicke, James Peebles, David Wilkinson and Peter Roll of Princeton University, Penzias and Wilson announced their discovery to the world in 1965: They had discovered the CMB - the afterglow of the enormous heat left over from the Big Bang, for which they received a Nobel Prize in 1978.

2.3. Looking for Small Temperature Fluctuations in the CMB.

The first measurements of the CMB were consistent with a perfect "black body" spectrum, meaning that its temperature is closely related to the wavelength at which it emits most of its light. The CMB spectrum peaks at a wavelength of around 2 mm, corresponding to a temperature of space of 2.725 Kelvin – just under 3 degrees above absolute zero, consistent with the prediction that space has stretched by a factor of 1,000 since the universe first became transparent.

Although it was very gratifying to confirm that the Universe has a temperature consistent with a hot Big Bang origin, the observed uniformity was puzzling. If the temperature of space is *completely* uniform in every direction, how did structures such as galaxies and clusters of galaxies originate? This reasoning prompted the search for *CMB anisotropies* – small deviations from uniformity in the temperature of space, which hold the clues as to how the universe grew to be the one we observe today. Thus the CMB is like the genetic code of the Universe – if we can unravel its secrets, we can understand how we came to be!

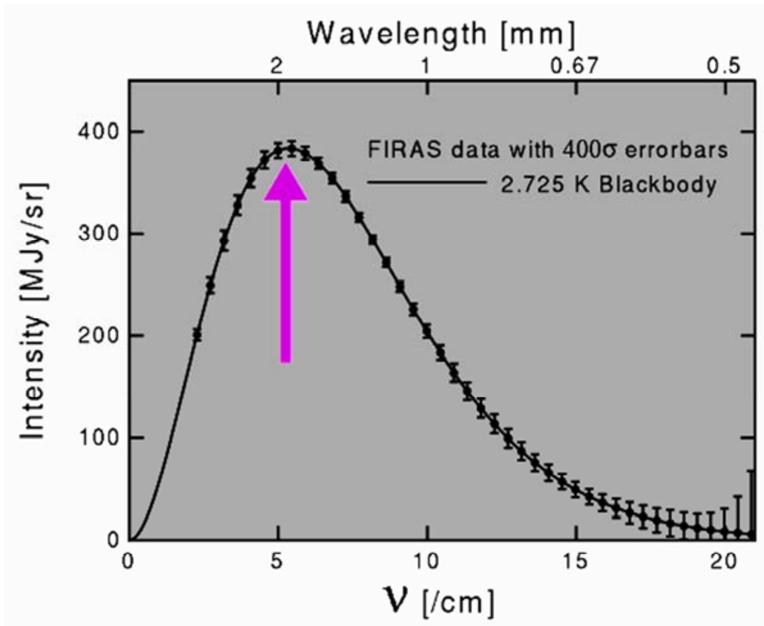

Figure 1. Data from the FIRAS instrument on the COBE satellite, plotted over a temperature spectrum of a blackbody with a temperature of 2.725 Kelvin. Image credit: Jet Propulsion Laboratory, NASA.

2.3.1. The Dipole Anisotropy. The first anisotropy that was experimentally detected during the decade following Penzias and Wilson's announcement was the dipole anisotropy, so-called because of its bipolar nature. [2] The dipole anisotropy is not of cosmological origin, but is an effect of our overall motion through the Universe, relative to the CMB. Thus the CMB appears a few milliKelvins warmer in the direction in which we are moving, and cooler in the opposite direction.

2.3.2. COBE sees the "echoes of the Big Bang." Throughout the 1980s several groups around the world used balloon-borne and ground-based instruments to search for the elusive anisotropies. Instruments called differential microwave radiometers were developed to measure the differences in temperature across regions of the sky separated by a few degrees of arc. In 1989 the NASA launched the Cosmic Microwave Background Explorer (COBE) from Vandenberg Air Force Base in Lompoc, California. COBE was the first satellite to map the entire sky at frequencies of 31, 53, and 90 GHz, spanning wavelengths from approximately 1 cm to 3 mm. Orbiting the Earth in a near-polar orbit, staying just out of the Sun's harsh glare, COBE surveyed the sky

[2] The history of the discovery of the dipole anisotropy, and claims of who found it first, is an example of a juicy controversy in the history of science! For a fascinating discussion of the discovery of the CMB dipole anisotropy, we refer you to the web page of Professor Edward Wright at the University of California, Los Angeles: www.astro.ucla.edu/~wright/CMB-dipole-history.html.

for two years. In 1992 COBE scientists announced they had indeed found the "echoes of the Big Bang," confirming that there really are anisotropies in the CMB across the entire sky. COBE's differential microwave radiometers measured these anisotropies with a sensitivity of a few parts in 100,000 in temperature, and an angular resolution of around 9^0 - 10^0 on the sky. (For reference, 10^0 of arc is the angle subtended on the sky your fist, held at arm's length, and observed by closing one eye – about 20 full Moons across.)

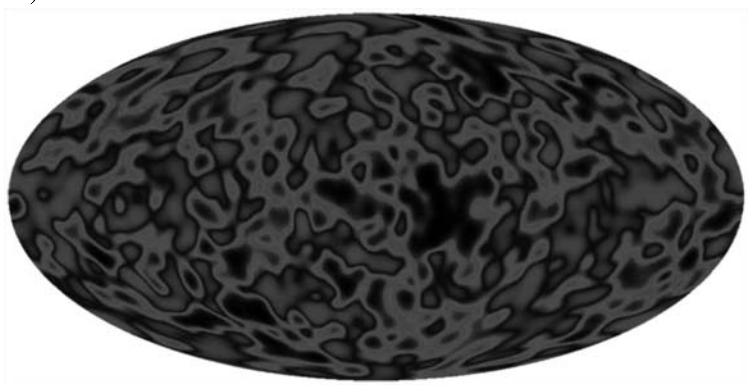

Figure 2. COBE all-sky map at 53 GHz, converted to grey scale from the usual magenta-cyan color scale. An all-sky map of CMB temperature data is plotted using the equal-area Mollweide projection. The data for this map have had the dipole anisotropy and Milky Way Galaxy removed. (Image Credit: NASA Legacy Archive for Microwave Background Data Analysis (LAMBDA), courtesy of John Arballo, NASA/JPL.

2.3.3. WMAP confirms degree-sized anisotropies. As exciting as the COBE results were, the resolution was not sensitive enough to measure anisotropies small enough to be associated with the actual seeds of structure in the Universe, as such anisotropies would be expected at scales of 1^0-2^0 or less. Many balloon-borne and ground-based experiments between 1990 and 2000 mapped portions of the sky, honing in on the predicted degree-sized anisotropies. In 2001, NASA launched the Wilkinson Microwave Anisotropy Probe (WMAP) which, as of 2009, is still operating, in orbit around the second Lagrange point in the Earth-Sun system (L2), 1.5 million kilometers from the Earth, beyond the orbit of the Moon.[3] WMAP has produced detailed maps of the CMB in five frequency bands (center frequencies of 22, 30, 40, 60, and 90 GHz) with a spatial resolution of 0.3^0 of arc and temperature sensitivity between 20 and 35 microKelvin.[4] WMAP confirmed the CMB anisotropies at the 1^0-2^0 scale, but unanswered questions such as the nature of the mysterious "dark energy," and the

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[3] The Lagrange Points are named for Joseph-Luis Lagrange who, in 1772, first predicted the existence of five points in the Sun-Earth system where the gravitational and Coriolis forces on an object would be balanced.
[4] See http:// map.gsfc.nasa.gov/mission/observatory_sens.html.

mechanisms that could have broken a supposed primordial symmetry and initiated inflation, remain.

2.3.4. Planck – the third generation of CMB-mapping satellite. In 1996 the European Space Agency (ESA) approved a mission to map the CMB with unprecedented sensitivity in temperature and angular resolution. Originally a merger of two proposed satellites (COBRAS and SAMBA), the mission was renamed Planck, after the German scientist Max Planck (1858 – 1947). NASA joined the international Planck Mission in 1996, contributing technical expertise that was critical to the development of Planck's sensitive detectors. Planck was launched on May 14, 2009, and also placed into an L2 orbit. From this vantage point, looking out into space, away from the blinding glare of the Sun, Planck is now (in the fall of 2009) mapping the sky with unprecedented detail down to 5 arc minutes (0.08^0) in angular resolution, and temperature sensitivity of a few microKelvin.[5]

3. The Planck Mission

3.1. A Brief Description of Planck's Instruments

The Planck spacecraft is the most comprehensive, international CMB-mapping mission to date, with contributions from industry, academic institutions, and government agencies in three continents: Europe (France, Austria, Germany, Denmark, Finland, Belgium, Italy, Ireland, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom), North America (United States and Canada) and South America (Brazil).

3.1.1. The detectors. There are two types of sensitive detectors on board Planck: the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI). The LFI detectors utilize high electron mobility transistor (HEMT) technology, and are designed to measure the microwave sky in the frequency range of 22 to 77 GHz (wavelength range of 11.1 to 3.9 mm). These detectors are cooled to a temperature of 20 Kelvin using hydrogen sorption coolers. The HFI detectors utilize "spider web" bolometers – small thermistors that are less than half a centimeter in diameter, made of a circular grid of special material which has impedance matched with that of the vacuum of space. These tiny thermistors are cooled in stages down to 100 microKelvin - within a tenth of a degree above Absolute Zero. This cryogenic feat is accomplished in the final stages of the cooling process by the mixing of liquid Helium-3 and Helium-4, an endothermic reaction which takes the detectors down to their final temperature. The HFI detectors are designed to measure the microwave sky in the frequency range of 84 GHz to 1 THz (wavelength range of 3.6 to 0.3 mm). The measurements made by the LFI and HFI detectors will be combined to produce full

[5] Mission updates are can be found on the official Planck websites at http://planck.caltech.edu/news.html, at www.nasa.gov/mission_pages/planck/index.html and even on "twitter."

sky maps in nine frequency bands, extending to frequencies beyond the actual CMB emissions into the infrared (Efstathiou, Lawrence, and Tauber, 2005; Lawrence and Arballo, 2009).

3.2. Science Goals of the Planck Mission

From the very accurate temperature maps, the Planck science team will be able to calculate the *angular power spectrum* of the CMB – that is, the spectrum of the spatial distribution of temperature anisotropies across the whole sky. From a careful analysis of the CMB power spectrum, we expect to derive important characteristic properties of the universe, such as the total density, density of baryonic (normal) matter, dark matter, and dark energy, and resolve questions in fundamental physics.

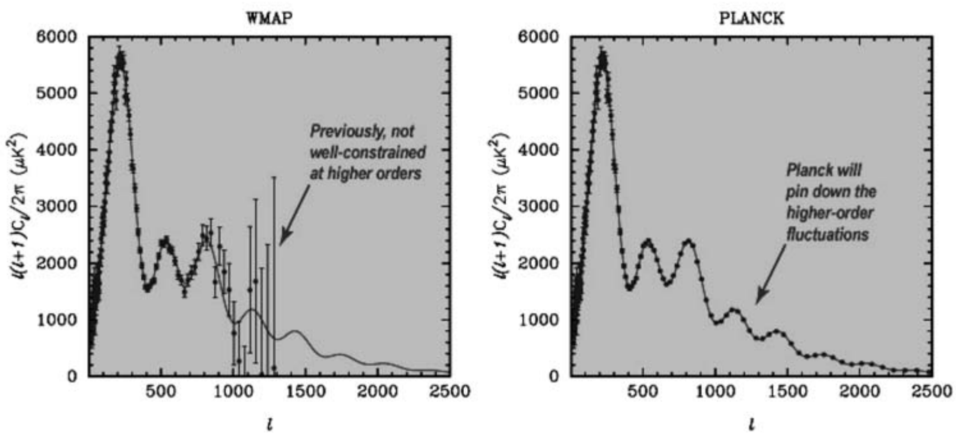

Figure 3. Simulated power spectra expected from Planck, compared to that of WMAP. Adapted from Planck Bluebook, ESA.

In addition, Planck will measure the polarization of the CMB – that is, measure the way light was scattered for the last time off the charged particles in the universe at the moment that it first became transparent. Mapping the direction and intensity of the polarization of the CMB will provide a closer look at the actual distribution of matter and radiation in the early universe, similar to the way in which sunlight scattering off the surface of a lake reflects the undulations in the surface of the water. Mapping the CMB polarization will also allow us to probe for the existence of gravity waves that are expected to have been produced by the Big Bang itself!

4. Interpreting the Data: From Temperature Measurements to the Sounds of the CMB

How do we translate from measuring microwave fluctuations, to calculating temperature differences, to the power spectrum of pressure waves in the early universe? The relationship between temperature and wavelength (or frequency) of radiation was discovered by Max Planck (the namesake of this satellite), Wilhelm Wien, and others in the late nineteenth to early twentieth centuries, which is why we can use microwave detectors to measure temperature differences across the sky. Anisotropies in the CMB *temperature* that we observe give us information about anisotropies in the *density* of the universe before recombination.

As far as we understand, these anisotropies in density developed from two different mechanisms. The very largest anisotropies represent initial distortions in the actual shape of the universe which originated in the first moments of its existence. As the universe expanded, initial density differences provided a mechanism to initiate gravity-driven pressure waves in the matter-radiation fluid which filled the universe during the first 380,000 years of its existence. It is these gravity-driven pressure waves, observable today as variations in the CMB at angular scales of $1\text{-}2^0$ and smaller, which are believed to be responsible for the large-scale structure we observe in the form of great walls of galaxies, and which determine the shape of the CMB power spectra shown in Figure 3.

These gravity-driven pressure waves which propagated in the early universe have some of the characteristics of acoustic waves generated in the air inside the resonating cavity of a musical instrument in that they have a fundamental frequency and higher harmonics. As we shall see, however, the comparison between the universe and a musical instrument is only approximate; never the less we can use our understanding of the physics of music to begin to interpret the power spectrum of the CMB.

To begin with, since the finite speed of light means that looking out in space is equivalent to looking back in time, it is useful to think of the sounds of the early universe as being produced 13.7 billion light years away, broadcast across spacetime as electromagnetic radiation. We "see" this radiation with microwave detectors, and can translate it back into sound with a bit of computer processing. The principle is the same as sitting in your living room in Chicago, and listening to a live broadcast over the internet of an orchestra which is playing a concert in Sydney, Australia – except the time delay is 13.7 billion years as opposed to only a few seconds!

4.1. A Comparison of the Sounds of the CMB with Music

4.1.1. Some preliminary definitions. In order to understand how we can interpret the sounds of the early universe, we first define a few terms from the physics of music on Earth. Sound is the name we give to pressure waves that we humans can hear, which have frequencies of vibration between 10 or 20 vibrations per second (Hertz) and 15,000-20,000 Hertz (Hz). We characterize sounds by their pitch, volume, and *timbre* (pronounced "tamber"). Pitch is determined by the frequency of vibration of the sound, while volume is controlled by the amplitude of the pressure variations. Lower frequencies have longer wavelengths and higher frequencies have shorter wavelengths, thus organ pipes produce lower tones than flutes, and louder sounds have higher amplitudes of vibration than quieter sounds.

The fundamental frequency, f_0, is the lowest pitch (longest wavelength) that can be produced by an instrument of a given size and shape. The fundamental period, T_0 , is the time it takes for the that lowest pitch wave to cross the resonating cavity once, and is found by calculating $1/f_0$. Higher harmonics are integer multiples of the fundamental, and doubling the frequency of a note produces a pitch which is one octave higher. Wavelength (λ) and frequency (f) are inversely proportional, related by the speed of sound (v_s) in the medium in which the waves are propagating:

$$v_s = \lambda f \qquad (2)$$

Timbre is the sound quality that allows us to distinguish a flute from a clarinet from a bagpipe from an organ pipe, even if they are all playing the same pitch at the same volume. It is the audible manifestation of the power spectrum of an instrument. The power spectrum of an instrument is a like a finger print which distinguishes it from other instruments, and depends on the characteristic properties of the instrument: the material it is made of, its size and shape, whether it is a wind or string, among others.

4.1.2. Musical Resonators vs. Natural Systems. Musical instruments are good resonators and sound pleasing to our ears because they have well-defined peaks in their power spectra. Natural systems, such as the Sun, stars, and the Earth, also vibrate with a characteristic fundamental and higher harmonics, except they are not very good resonators, in that they have broad peaks in their power spectra, and sound very noisy to our ears. Never the less, we can use a technique called Fourier Analysis to mathematically "clean up" their power spectra so that we can pick out the fundamental and higher harmonics from the noise. A selection of notes produced by synthesizers and musical instruments, with their corresponding wave forms and power spectra can be found on our web site, http://planck.caltech.edu/epo.html, along with the sound of the Sun compressed to audible frequencies and the "chord" of the Sun mathematically extracted from the noisy power spectrum.

4.1.3. Investigating the Fundamental Frequency of the CMB. The broad peaks of power spectrum of the CMB indicate that the early universe was a noisy resonator, never the less from the fundamental and higher harmonics we can infer the characteristic properties of the universe which distinguish *our* universe from other possible universes. This is a very exciting prospect indeed!

The power spectrum of the CMB is based on the two-dimensional distribution of pressure waves on the surface of a sphere of radius 380,000 light years. Recall that these pressure waves were propagating through a 3-dimensional volume until recombination, when their image was frozen onto the last scattering surface, which we now see from the inside out.

Sound waves are alternating compressions and rarefactions of a medium – in this case, the matter-radiation fluid of the early universe. Compressions occur where matter is compressing due to gravitational attraction, initiated by an excess concentration of dark matter. Rarefaction occurs where radiation pressure is causing the gas to expand. The first peak in the CMB power spectrum is called the fundamental, and represents the wavelength with the lowest pitch that existed in the universe before its image was frozen onto the last scattering surface. Just how long was this fundamental wavelength? We can calculate it if we know the speed of sound at that time, and the age of the universe. The speed of sound in the early universe at the time of recombination was approximately 58% of the speed of light, or:

$$v_{sound} = \frac{c}{\sqrt{3}} \cong 1.7 \times 10^8 \, m/s \tag{3}$$

In the first 380,000 years until recombination, a sound wave traveling at that speed could have a wavelength of roughly $\lambda = vt = 2 \times 10^{21}$ meters, or 220,000 light years. A fundamental wavelength of 220,000 light years means that one wave would pass by the ears of a hypothetical listener in 220,000 years, or 6.94×10^{12} seconds. Inverting this number to get the fundamental frequency, we find the fundamental frequency of the CMB:

$$\frac{1}{6.94 \times 10^{12} \sec} = 1.44 \times 10^{-13} \, Hz \tag{4}$$

This is approximately 3×10^{15} times *lower* than the concert A of 440 Hz, or about 50 octaves too low for humans to hear! [6]

The units in which we represent the CMB power spectrum are a kind of angular wavelength on the sky, "*l*" numbers, derived from the *spherical harmonics* which are calculated by dividing a sphere into 2-dimensional waves by latitude and longitude. Each *l*-number is approximately equal to 180 degrees divided by the angular separation of features observed on the sky. Thus features separated by 1^0 of arc on the sky have an angular wavelength, or *l*-number of $180^0/1^0 = 180$, very close to the fundamental in the CMB power spectrum! That is why the degree-sized anisotropies in the CMB have been so important to cosmologists.

Looking at the power spectra in Figure 3, we see that the fundamental is actually closer to an *l*- number of 200, which gives an angular separation on the sky of $180/200 \cong 0.9^0$. Planck's expected angular resolution of 5 arc minutes (0.083^0) will be able to resolve features in the sky more than 10 times smaller than the fundamental, out to an *l*- number greater than 2000 – in other words, essentially *all* the small-scale anisotropies in the CMB!

4.2. The Music of the CMB

Finally, if we want to hear the sounds of the universe we have to scale the frequencies up to the range of human hearing, and then do some power spectrum clean up. Since the fundamental is approximately 50 octaves too low for us to hear, we scale

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[6] Going down in pitch by one octave means reducing the frequency by half, thus every time you go down in pitch by one octave, you reduce the frequency by another power of 2. Thus, the log in base 2 of 3×10^{15} gives 51.4, or approximately 50 octaves.

the cosmic frequencies up by 50 octaves, or 15 orders of magnitude, to match our ears.

4.2.1. Comparing the CMB Power Spectrum to a Keyboard. The lower limit of human hearing is around 20 Hz. If we map 20 Hz to $l = 20$, this is roughly the limiting angular scale at which COBE mapped the CMB, which is approximately an order of magnitude larger than the fundamental at the time of recombination. The lowest note on a piano keyboard is A0 at 27.5 Hz.

If we go up an order of magnitude in l-number, we get to the fundamental at $l \cong 200$, which we map to the audible frequency of 200 Hz, slightly lower in tone than A3 at 220 Hz, below C4 (Middle C) at 261 Hz. The fundamental tone of the CMB poetically maps approximately to 1 octave below the "sound of an orchestra tuning up" at A4 of 440 Hz.

Going up an octave above the fundamental should be a doubling of frequency, but we see that the second peak in the CMB power spectrum is not simply twice the fundamental, or $l = 400$, but around 2½ times the fundamental, at $l \cong 500$. The universe is not as simple as a musical instrument! Unlike a musical instrument in which the compressions and rarefactions are due to the bouncing and rebounding of air molecules, the odd harmonics in the CMB come from gravitational attraction of matter, while the even harmonics come from radiation pressure. Add to this the expansion of the universe, so that the distance crossed by the second harmonic is more than twice the distance crossed by the first harmonic.

Our analogy with music is useful for developing a conceptual understanding of how to interpret the CMB power spectrum, but the model deteriorates if we take it too literally beyond the first peak. Never the less, we can map the peaks of the CMB power spectra from Figure 3 to audible frequencies of 200, 500, 800, 1100, and 1300 Hz and hear what this primordial chord sounds like. If you try to play it on a piano, you will come close by playing keys G3# (207 Hz), B4 (493 Hz), G5# (830 Hz), C6# (1108 Hz), and E6 (1318 Hz). If you do not have a piano, you can try synthesizing these notes with any number of freeware packages, such as *Virtual MIDI Piano Keyboard* from http://vmpk.soundforge.net, or other software package.

Planck is expected to map small scale anisotropies in the CMB out to $l > 2000$, so according to our piano mapping scheme, this maps close to C7 (2093 Hz), one octave below the highest note that a piano can play.

Summarizing what we have done so far, we understand that acoustic waves in the early universe left their imprint on the light as it scattered off matter for the last time, at recombination – around 380,000 years after the Big Bang. We map the light echoes of these acoustic waves as small scale anisotropies in the CMB. Temperature variations of $1\text{-}2^0$ on the sky correspond to the fundamental wavelength at the time of recombination. From detailed maps of the small scale anisotropies in the CMB, we can plot the angular power spectrum, and we can pick out a fundamental and higher harmonics. We can scale the CMB harmonics to the range of human hearing and "listen" to the chord of the cosmos, but we find that the universe is not quite like a musical instrument, in that the higher harmonics are not integer multiples of the fundamental, but depend on a range of physical properties beyond simple cavity resonators, thus the analogy of the CMB with music can take us only part way to a complete explanation.

5. From Power Spectra to Physical Properties

It is conceptually straight forward to map the *l*-numbers of the observed CMB power spectrum to a scale that humans can hear, but trying to synthesize the CMB power spectrum from the physical characteristics which could have produced the observed power spectrum is extremely complicated! There are close to 30 parameters that go into the model (Hinshaw, et al., 2009). Some of them, such as the Hubble constant (H_0) have been independently measured, while others are best estimates, based on a combination of observations and assumptions. Some of the cosmological parameters that go into any model which produces a CMB power spectrum are: the present expansion rate of the universe, H_0; the age of the universe at recombination; the fraction of the universe which is made of baryonic, matter (made of protons, neutrons, and electrons); the fraction which is dark matter (gravitates but does not shine); the fraction which is the so-called dark energy, and whether the source of the dark energy is a cosmological constant or comes from some as-yet-undiscovered particle or field; the fraction of the Helium produced in the first few minutes of the universe; and the age after recombination when the first stars had sufficiently re-ionized the universe so that it became somewhat foggy again. All these parameters interact to determine the location and amplitude of the peaks in the CMB power spectrum.

5.1. Exploring the Sounds of the Universe with Students

Fortunately, the cosmology community has devised a number of modeling routines which take the cosmological parameters as input, and produce a hypothetical CMB power spectrum that would be derived from a universe with precisely those cosmological parameters. The original such modeling routine is CMBFAST (Seljak and Zaldarriaga, 1996) which can now be run interactively on line at NASA's Legacy Archive for Microwave Background Data Analysis (LAMBDA) website http://lambda.gsfc.nasa.gov/toolbox (Hinshaw, 2009). Thus, you can explore the effects of changing the fractions of baryons, dark matter and dark energy, total density, expansion rate, or other cosmological parameters on the CMB power spectrum. By scaling the angular frequencies to audible frequencies, you can generate the primordial chords and hear the sound of a universe with different properties.

5.2. Planck Visualization Products

The U.S. Planck Team's Education and Public Outreach (E/PO) group at NASA's Jet Propulsion Laboratory, with collaborators at the University of California, Santa Barbara and Purdue University, are (as of fall, 2009) preparing several products for use in museums, classrooms, and the Internet to educate the public about Planck, the science goals of the mission, and about how we can visualize the processes that began our universe. These include: an interactive simulation of the Planck Mission in Virtual Reality, from launch to orbital insertion, to data gathering operations; an interactive presentation on understanding the CMB through music; cosmology curricula for high school and college; and a multi-modal simulation of the universe before recombination in Virtual Reality. These products will be distributed initially via the Planck Mission website at http://planck.caltech.edu as they become available, as well as mirror sites at partner institutions.

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