INTRODUCTION TO THE COSMIC MICROWAVE BACKGROUND (CMB)

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Abstract. The goal of this short paper is to provide a working reference and brief introduction to the history, foundation and formulation of the Cosmic Microwave Background. This will be a working draft that shall be updated after all the weekly meetings so that all involved have a condensed reference to the subject at hand.

1. The Big Bang and Standard Model of Cosmology

After the Advent of General Relativity, the Einstein equations were used to talk of the evolution of the universe as a whole, most notably under the Robertson Walker Metric solution to the field equations. These equations laid the framework for a universe consisting of a perfect fluid which can be used as a matter or radiation fluid that evolved from a time $t = 0$, in which the universe would later spread uniformly and isotropically. This metric allowed for a model of cosmology in which a time based equation of both the age and size of the universe can be formulated, beginning from the original time where all the energy was concentrated at some singular or finite point, and evolves as stated. This model is known as the Big Bang. After the success of the Robertson Walker metric as a working model of cosmology, specific times or era's were input into the model based on Nuclear Physical principles, to try and determine a more specific view of the particular expansion epochs of the universe. This model allows us to form a cohesive theory accounting back to fractions of seconds after the big bang (since the initial time is implicitly singular, talk of before the big bang is left to a philosophical question rather than a scientific one), and compare data from todays universe (such as counts of photons in the universe, Baryon mass, etc) to put bounds on the initial conditions to be input into the model. Hence we shall state some important aspects of the first crucial moments after the big bang, to shed some light on how and why we are in the current state of being.

By the current model, we assume that at some infinitesimally small time after the big bang, the universe was very hot, dense and radiation dominated. All known particles were in a thermal equilibrium, and quantum processes such as particle pair creation were all the norm. The initial state is thus a quantum sea, or quark soup as some of the literature states. Soon after (not discussing the quark interactions or decoupling of the strong interactions), when the universe was only fractions of a second young, at around a temperature of 10^11K, the thermal equilibream of the radiation was scattered with very little matter, roughly 1 proton per 10^10 photons. All particles including neutrino's were in constant contact and constant interactions, while the universe was expanding and slowly cooling, but

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the small size (relatively speaking)and temperature was such that even neutrino's interacted across very small mean free paths. The estimated density of the universe at this phase is roughly $4 * 10^10$ times the density of water. After some cooling, at around 10^10K, the temperature was cooled enough so that neutrino's now would cease to interact, and would essentially become decoupled from the universe soup, and begin to free stream across the expanding universe. At around $3 * 10^8$K, as the universe was roughly 14 seconds old, pair productions of positron and electrons began to slow due to cooling and expansion. This is a crucial time because shortly after, deuterium and helium nuclei begin to become stable due to the expansion and reduction of prominent reactions. As expansion continues, primordial helium values are established, and the rest of the baryon mass is mostly contained in free protons. Small trace amounts of heavier elements are created, but are relatively unstable due to neutron decays into protons. These processes are considedered the Big Bang Nucleosynthesis, or BBN. As the primordial helium settles and BBN slows, we are left with a bathe of remnant photons that are now released and free stream across the universe, forming the basis for our study of the CMB. Later at around 380,000 years later, the universe enters a phase of recombination occurs as the universe is now cool enough for the helium and hydrogen nucei to capture free electrons and form stable atoms.

This summary although breif, is an account that laid out the framework of the early universe in a very elegant form, combnining many fields of physics. Up to this point, current theories such as inflation have not been mentioned, but will be discussed later. But we are left with the following scenario: After BBN, when photons were decoupled from the cosmic soup, they are now set to roam the universe freely. Thus, they are in essence a radiation present in the universe, flowing in all directions, left over as a footprint of the big bang. It is these left over photons, the trace of the big bang, that has been come to be known as the cosmic microwave background, or CMB.

2. History of the CMB before 1980

Now that we have the relevant framework, a brief history of work on the CMB is in order. First notably, Gamov between the 1940's made some groundbreaking work in the theory of BBN, and hypothesized about this footprint left by the big bang, which would occupy a current temperature between $10and7$K. Although this is different from the current observed value, the initial calculation was quite a good estimate. In 1964 A. G. Doroshkevich and Igor Novikov publish a brief paper, where they name the CMB radiation phenomenon as a detectable quantity. It was then by accident, in 1965 that Penzias and Wilson, working out of Bell labs, discover a bizzare "‘interference"’ signal on a radio telescope they built in order to observe radiation from outside the galactic plane of the Milky Way. This signal was independent of direction and was discovered while trying to remove baseline RFI from the signal to be sure that ONLY radiation outside the Milky Way disk was to be found. After several painstaking months of fine tuning, this background noise could not be removed. It was even believed that the pigeons who roosted near the apparatus could be blamed due to a "‘white di-electric material"’ present on the equipment. Even after removing all sources of known errors (including the pigeons), the signal was still present. The signal registered an Antenna temperature of 3.5K. It was then that via a phone conversation with fellow physicist Bernard Burke, that Penzias and Wilson decided to publish the results, as Burke informed the two of a paper written by Peebles in which he stated that Radiation was present in the early universe. Peebles calculated, using the BBN models (mostly due to the helium bounds and abundance) that the radiation required would today roughly correspond to a temperature of 10K. Thus, after collaboration, and due to the highly symmetric properties of the incoming signal, Penzias and Wilson discovered the first traces of the footprint of the Big Bang. The name CMB then soon emerged since at a temperature of 3.5K, the radiation wavelength corresponds to that within the microwave region of the electromagnetic spectrum. Penzias and Wilson's discovery was published in Astrophysical Journal, with cosmological interpretation provided by Dicke, Peebles, Roll and Wilkinson. Soon later, since the physics of quantum mechanics was well established, it was shown that since as stated above that universe was in thermal equilibrium before the streaming of the CMB, then as the universe expands and cools, it should be a perfect black body, and follow the black body spectrum identically. Due to technology limits at the exact time of the initial discovery, the experimental proof was slightly delayed, but later, using balloon experiments out of MIT and Berkely independently showed that the background radiation at a temperature of 3K was nearly a perfect black body. Also, since the radiation was completely isotropic, this was one of the most convincing arguments for the cosmological principal. It should be noted that Penzias and Wilson received the nobel prize in 1978 for their historical work.

3. Current History of The CMB

Due to technology boots in the late 1980's, and the successes of satellite and shuttle missions, it was decided that a satellite would be placed in orbit to look for (amongst other things) a pure signal of the CMB, without any interference from the Earth's atmosphere. In 1974, NASA issued an Announcement of Opportunity for astronomical missions that would use a small- or medium-sized Explorer spacecraft. Out of the 121 proposals received, three dealt with studying the cosmological background radiation. When NASA seen the desire to study and the relevance in which the CMB had to verify the big bang theory and standard model of cosmology, the announcement in 1977 was made that a satellite named COBE (cosmic background explorer) would be launched. After years of work, COBE was ready for launch in 1988, but due to the Challenger disaster, was slightly delayed and placed upon a delta rocket in 1989 with three primary instruments on board. The two most notable, was the FIRAS detector, which is a spectrophotometer used to measure the spectrum of the CMB and compare it to the black body spectrum at the current accepted value of 2.7K, and the DMR, which was a Differential Microwave Radiometer used to measure the precision of isotropy of the CMB. The first, headed by George Smoot, established to amazing precision (see diagram attached) that the CMB was indeed a prefect blackbody. This extreme agreement also spelled the end of the steady state theory of cosmology and further pushed the idea of the Big Bang theory. Smoot was later awarded the nobel prize for his contribution to the COBE Satellite, an honor to be shared by John Mather, who headed up the DMR portion of COBE, which shook the foundations of the current model to the core.

After four years of operation, the DMR device on the COBE satellite provided some very startling data. As the radiometer data was parsed over all possible modes of radiation emission spectra, maps were made of the incoming CMB data on a 3 dimensional sphere of the isotropic universe. When closely observed without the interference of the atmosphere, full maps of the CMB were made by subtracting out galactic emissions and dipole fluctuations at various frequencies. The corresponding maps (see below) showed that the CMB was not isotropic as previously believed. Instead, faint cosmic microwave background fluctuations, only one part in 100,000 compared to the 2.73 K average temperature of the radiation field were uncovered. For the first time, the cosmological principal seemed to be challenged, and space, began to take a different shape, since now it seemed to have some sort of implicit structure that was previously unexpected. These fluctuations would give water to some of the more far-fetched theories that must accompany the current big bang model of the universe. The fluctuations are known now to the scientific community as the anisotropies in the CMB.

4. Review of more recent BBT theory

As stated above, the original history section is somewhat incomplete due mostly to 2 problems. The first is known as the horizon problem. When taking the current cosmology model, and calculating quantities such as the age of the universe, expansion rates via the Hubble parameters, etc, and comparing it to the data and technology explosion in the mid eighties, we find that the universe is accelerating. By its very nature, an accelerating universe already contradicts the current model unless some other, new matter or energy is introduced, namely dark matter and dark energy. These aside for the moment, with the data from the eighties, it can be shown that using the current estimated age of the universe, the most distant objects from us, could not have been in causal contact without violating relativity. In essence, they could not have been from the same big bang as us. Now since we believe that the big bang is a singular occurance, some new physics had to be employed to make the current model work. It was the work of Alan Guth, called the Inflationary theory that states that in the very early stages of the development of the universe, the universe underwent exponential expansion for a brief time, but enough to resolve the horizon problem. We shall come back to more about inflation in a few moments. The second issue, is that in the initial assumption of the structure of the universe was isotropy, which we have now stated seems to be challenged.

5. Why the CMB?

As we can now see, the CMB is one of the most crucial discoveries in the entire history of cosmology, and there is still plenty of work which needs to be explored. The consequences of the anisotropies discovered by COBE, are believed to lead to large scale structure in the universe. This means that where these density fluctuations in the CMB are located, correspond to regions of galactic clumping in the universe. Prior to COBE it was believed that large scale structure should be uniform, but now this view must be rethought, thus giving fuel to the theories of

dark matter, which is said to be the cause of baryonic matter clumping and galaxy formation.
The inflationary theory of Guth (which was written before the results of COBE) requires there to be perturbations (both scalar and tensor perturbations) to the initial field equations which govern cosmology. These perturbations which cause inflation would also result in anisotropies in the CMB. Thus, upon Mather's discovery of such anisotropies, makes inflation a strong candidate for a valid theory.

Hence we see from this short introduction, that plenty of work still exists in the field of the CMB. Some other notables that are possibilities that were not mentioned, are perturbative order inflations, gravitational wave fluctuations/detection via the CMB, and the possible discovery of a Neutrino Background radiation.