LULEÅ UNIVERSITY OF TECHNOLOGY

Dust in the Early Universe

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Dust

And dance as dust before the Sun,
And light of foot and unconfined,
Hurry from road to road, and run
About the errands of the wind.

And every mote, on earth or air,
Will speed and gleam, down later days,
And like a secret pilgrim fare
By eager and invisible ways,

Nor ever rest, nor ever lie,
Till, beyond thinking, out of view,
One mote of all the dust that’s I
Shall meet one atom that was you.

- *Rupert Brooke (1887-1915)*

Preface

The work presented in this Licentiate thesis is a result of a collaboration between Luleå University of Technology, Laboratoire d'Astrophysique de l'Observatoire de Grenoble, Institut d'Astrophysique de Paris and Centre de Recherche Astronomique de Lyon. My supervisor at Luleå University of Technology has been Sverker Fredriksson and my co-supervisor has been Johnny Ejemalm.

I would like to express my gratitude towards the world in general for being such a beautiful place, and towards my collaborators in particular for having helped me in my quest for knowledge and understanding of the workings of the universe. Of my collaborators I especially would like to thank François-Xavier Désert for his ideas, his concrete approach to problem solving and all the verifications he proposed to corroborate our results. Furthermore, I thank Bruno Guiderdoni for his invaluable support in the field of dark matter simulations. Of course, my supervisor Sverker Fredriksson has been of much help with his good general knowledge of astrophysics.

I am grateful to my office-mate, Fredrik Sandin, for our discussions and his help with practical as well as theoretical issues and to Tiia Grenman and Johan Hansson for the exchanges we have had. I would also like to thank Henrik Andrén for his help in the matter of geometry and to all my friends for our friendship.

Finally, a special thank goes to my wonderful, supporting wife, who is with me in my moments of defeat as well as of victory and to my parents, who have brought me up to who I am today.

Luleå in March 2005

Erik Elfgren

Abstract

This Licentiate thesis treats the impact of early dust on the Cosmic Microwave Background (CMB). The dust that is studied comes from the first generation of stars, which were hot and short-lived, ending their lives as giant supernovæ. In the supernova explosions, heavy elements, produced through the fusion in the stars, were ejected into the interstellar medium. These heavy elements condensed to form dust, which can absorb and thus perturb the Cosmic Microwave Background radiation. The dust contribution to this radiation is calculated and found negligible. However, as the dust will be produced within structures (like galaxy clusters), it will have a spatial correlation that could be used to detect it. This correlation is calculated using relevant assumptions. The planned Planck satellite is likely to be able to measure and thus confirm this correlation.

Keywords: *Dust – CMB – Reionization – Power spectrum*

Papers

The following papers are appended to this Licentiate thesis:

Paper I: **Dust from Reionization**
The production of dust in the early universe is estimated from the number of stars needed to achieve reionization. The spectral signature of the dust is calculated and compared to measurements. The contribution from the dust layer to the Cosmic Microwave Background is found to be small.
Published: Elfgren, Erik and Désert, Franęis-Xavier, 2004, Astronomy and Astrophysics, **425**, 9-14.

Paper II: **Dust Distribution During Reionization**
The spatial distribution of the dust is estimated using simulations of dark matter density evolution. Combining the calculated intensity from Paper I with this density and integrating along the line of sight, the spatial signature of the dust is obtained. The distribution of the dust gives a detectable signal.
Elfgren, Erik, Désert, Franęis-Xavier, Guiderdoni, Bruno, Submitted to Astronomy and Astrophysics.

Contents

Chapter 1

Introduction

The Universe is a wonderful place. Ranging from smaller than an atom to larger than a galaxy, with complex humans, beautiful flowers, powerful stars, and vast amounts of empty space. But where does it all come from? How did all this diversity come to be?

The universe is generally believed to have started out in the Big Bang – an immense concentration of energy, expanding and thus diluting. Different particles were created such as neutrons, protons and electrons, then ions and atoms. A long pause followed during which matter assembled through gravity to form large-scale structures such as stars and galaxies. And in the galaxies, around the stars, planetary systems assembled which can host life.

But how can we know all this? The truth is that we do not. However, we do have several pieces of indirect evidence. The single most important observation is the so called Cosmic Microwave Background radiation (CMB for short). This radiation was emitted when the universe was merely 300,000 years old and can be thought of as a kind of photograph taken of the universe at this time. Amazing! Furthermore, this radiation is present everywhere in the universe and has a very characteristic spectrum. The discovery of the CMB single-handedly convinced the scientific community of the validity of the Big Bang model.

In order to measure the CMB accurately, we must know what it has passed through; our solar system, our galaxy, other galaxies, further and further away until the first generation of stars. Very little is known about these first stars. One plausible hypothesis states that they had very intense and violent lives. This would mean that they finished as supernovae – giant explosions – thus spreading their contents in space. These left-overs are called star dust, and due to its abundant production and wide spread it will partly cloud the CMB. It is like looking at the Sun through a mist.

In this Licentiate thesis I try to assert the thickness, density and distribution of this dust layer, thus evaluating its impact on the measurements of the CMB. As a corollary, certain properties of the first generation of stars could also be obtained.

In the second chapter, the early history of the universe is outlined, from the Big Bang until the formation of the first galaxies. In the third chapter the Cosmic Microwave Background with its properties and its different foregrounds is described in some detail. In the fourth chapter, I present a brief introduction that is useful for the understanding of some of the particulars of the two appended papers. This includes a description of our general knowledge of dust and some concepts of dark matter.

In appendix A a short introduction to cosmology is provided along with some common formulæ. For further details on symbols, constants, and abbreviations, see Appendix B. Words which appear *slanted* are explained in the Glossary in the same appendix.

Chapter 2

History of the Universe

Our understanding of the evolution of the universe is far from complete, but the picture is getting clearer by the day with the advent of new detectors and new experimental and theoretical results. This section contains a description of the evolution of the universe as we understand it today, as illustrated by table 2.1. These results are fairly robust unless otherwise specified. This description of the evolution of the universe is called Λ-Cold Dark Matter (or ΛCDM for short) and has recently become predominant due to good experimental support.

2.1 The Big Bang

The universe started out some 14 billion years ago by being extremely dense and hot. Note however that we do not know what happened at the actual beginning, but we can extrapolate the current expansion of the universe back *towards* that time, which I call $t_0 = 0$. According to recent measurements, **?**, this was 13.7±0.2 billion years ago.

Contrary to common belief, there was no ”explosion”, but merely a rapid expansion of the fabric of the universe, like the rubber of a balloon stretches when you inflate it. The expansion of the universe still continues today and there is no indication that the expansion has a center. In an infinite universe, the Big Bang occurred everywhere at once. How we can conceive an infinite energy density at $t = 0$ or for that matter an infinite universe is a philosophical question. Physicists generally content themselves with starting the exploration a fraction of time after $t = 0$.

During this first (and extremely brief) period of the universe, all forces are believed to have been just one and the same. However, as the universe cooled off, the forces separated into the electric, magnetic, gravitational, and the weak and strong nuclear force. An analogy with this separation would be the melting of ice cubes in a glass, being separate objects below freezing but melting into one homogeneous water mass at higher temperatures.

Note that this unification of forces is a theory without direct experimental support. However, the subsequent evolution of the universe does not hinge on this unification.

2.2 Inflation

When the universe was roughly 10^{-34} seconds old, a period of intensive expansion occurred and the universe became $\sim 10^{50}$ times bigger in a fraction of a second. This expansion is called inflation.

This theory has some more experimental support than that of the unification of forces. In fact, it was introduced to alleviate three serious deficits of the Big Bang theory: the horizon, the flatness

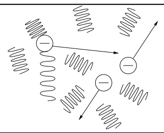
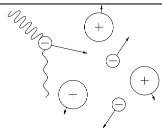
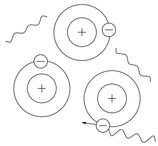
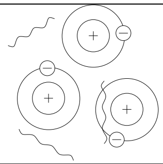
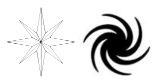
Time after BB	**Events**	**Illustration**
$\sim 10^{-43}$ s	Unification of forces?	
$\gtrsim 10^{-34}$ s	Inflation Exponential expansion	
$\gtrsim 10^{-10}$ s	Radiation domination Protons and neutrons are stable Antimatter disappears	
$\gtrsim 10^{2}$ s	Matter domination Hydrogen becomes stable Nucleosynthesis	
$\gtrsim 3 \times 10^{5}$ yrs	Decoupling of matter Transparent universe The Cosmic Microwave Background is released	
$\sim 10^{9}$ yrs	Structure formation The first stars and galaxies	

Table 2.1: History of the universe.

and the monopole problem. Here comes a brief explanation of them. For more detail, I suggest **?**. The horizon problem stems from the measured correlation between parts of the universe that never have been in contact (due to the finite speed of light). The flatness problem is that the universe can be measured to be nearly flat, as far as we can see, and this is unlikely from a theoretical point of view. The monopole problem is about the absence of so called magnetic monopoles, which are theoretically predicted as a consequence of the unification of forces.

Furthermore, inflation also provides natural seeds for star and galaxy formation, through the growth of tiny quantum fluctuations into macroscopic fluctuations.

Although inflation has many attractive features, it is not yet a proved theory because many of the details still do not work out right in realistic calculations without assumptions that are poorly justified. Probably most cosmologists today believe inflation to be correct at least in its outlines, but further investigation will be required to establish whether this is indeed so.

2.3 Radiation Dominated Era

After approximately 10^{-10} seconds the inflation period was at an end. The following epoch is called the radiation dominated era in which the principal component of the universe was radiation – photons.

During this era, the *antimatter* disappeared from the universe through contact with matter and subsequent annihilation. However, due to a slight excess of matter over antimatter, the antimatter was all consumed and only the excess of ordinary matter remained.

The universe had also become cool enough to allow protons and neutrons to form and become stable (before this time, the quarks and gluons possibly co-existed in some sort of plasma). The protons are nothing but ionized hydrogen, which was the first type of atoms to form.

This early formation of particles touches upon the subject of particle physics in which the author has a particular interest. For more information about other possible types of particles, see **?** and **?**.

2.4 Matter Dominated Era

Around one minute after the Big Bang, the radiation had lost enough energy density due to the expansion to allow matter to start dominating. This in turn, means that the expansion rate of the universe changed.

During the matter dominated era, the thermal energy became low enough to allow the ionized hydrogen atoms to capture and keep electrons, thus forming the first neutral atoms. Furthermore, protons and neutrons started to fuse to form helium and other heavier elements. This process is called the *Big Bang Nucleosynthesis* (BBN) but did last for only about three minutes, **?**. After that time, the density and the temperature of the universe dropped below what is required for nuclear fusion (neutron capture). The brevity of BBN is important because it prevented elements heavier than beryllium from forming, while allowing unburned light elements, such as deuterium, to exist. The result of the BBN is that the universe contains 75% hydrogen, 25 % helium, 1% deuterium and small amounts of lithium and beryllium. This predicted distribution corresponds very well with the measured abundances. For more detail on the BBN, see e. g. **?**.

The matter dominated era extended until the dark energy took over after roughly five billion years.

2.5 Decoupling of Matter

When the temperature of the universe dropped below $T \sim 0.25$ eV ~ 3000 K the photons no longer had enough energy to ionize or excite the atoms. This means that the photons could neither loose, nor gain energy. Thus, the universe became transparent and the photons kept their energy indefinitely (unless otherwise perturbed). These photons are called the Cosmic Microwave Background (CMB) and their properties will be described in more detail in chapter 3.

In order to estimate this transition temperature, we calculate the temperature at which there is one exciting photon per proton. For a photon to excite a hydrogen atom, it needs at least $E = 10.2$ eV, which corresponds to a transition from the ground state to the first excited state. This means that we require:

$$N_p = N_\gamma(E_\gamma > 10.2\,\text{eV}) = N_\gamma \cdot \frac{1}{e^{10.2\,\text{eV}/k_B T} - 1}, \tag{2.1}$$

where N_p and N_γ are the number densities of protons and photons respectively, k_B is Boltzmann's constant and T is the temperature of the photons. Using $N_\gamma \sim 10^9 N_p$, the temperature can be calculated to $T \approx 5700$ K. If a more detailed calculation is made, the temperature is found to be approximately 3000 K, which corresponds to $t \approx 300,000$ years after the Big Bang ($z \sim 1100$). As the universe expands, this temperature decreases as $1/R$ where R is the expansion factor ($= 1/(1+z)$). Since the universe has expanded by a factor of 1100 since decoupling, the temperature of the CMB has now dropped to 2.725 K.

Obviously, this transition is not something that happened at one single time, but rather took something like 50,000 years ($\Delta z \approx 100$).

2.6 Structure Formation

After the decoupling, the universe went through a period called the Dark Ages which lasted until the onset of star formation about a billion years later. During this epoch the only thing that happened is that the CMB propagated and the matter slowly contracted due to gravity. Regions in space with an initial over-density (created by the inflation) attracted more matter, and eventually the matter density became high enough to sustain fusion and thus the first generation of stars formed.

During the Dark Ages, dark matter played a key roll in shepherding matter into dense regions thus allowing star formation. The dark matter is described briefly in section 4.2.

2.7 The First Generation of Stars

The first stars are called population III stars due to properties that are rather different from those of the stars today. They are born in loosely bound gravitational structures defined by high baryon densities and a surrounding dark matter halo.

The source material of these stars is the matter that was created during the Big Bang nucleosynthesis, see section 2.4. This means that there is basically only hydrogen and helium in these stars. As time passed on, the source material for new stars had more and more heavy elements since the heavy elements were produced by the stars. The mass fraction of elements heavier than helium is called *metallicity*.

It is also believed that these first stars would have been rather heavy, see **?** and **?**. The mass of the stars is characterized by the Initial Mass Function (IMF). With a low metallicity and a high mass, the stars will be short-lived and hot, **?**. If the stars were not heavy, they would live longer and take more time to produce dust, thereby delaying the reionization to an improbable period.

2.8 Reionization

From decoupling until the reionization, the universe was made up of neutral atoms (along with photons, dark matter and dark energy).

At the onset of the first generation of stars, energetic photons were produced. This happened when $z \sim 10$ and thus the CMB temperature was only $T_{CMB} \sim 30$ K, while the star temperature could be over 80,000 K, see **?**. At this temperature, the maximum emitted energy was at $E_\gamma \sim 21$ eV, which was more than enough to ionize hydrogen ($E_{H,ion} = 13.61$ eV). At the end of the intensive star formation period some five billion years after the Big Bang the universe slowly neutralized again, leaving us with a layer of ionized gas from $t \sim 10^9$ years – 5×10^9 years ($z \sim 20$–5).

The universe was ionized in bulbs around the stars, and these bulbs expanded and eventually covered the entire universe. Due to this ionization the universe was no longer as transparent as it was before. The free electrons scattered the photons through the Compton process and thereby changed their energy and direction. The degree of change is characterized by the opacity, τ_e, which is defined through

$$e^{-\tau_e} = \text{probability of a photon to pass through the ionized layer without being scattered.} \quad (2.2)$$

The effect of the reionization on the properties of the CMB is important and will be discussed in more detail in section 3.3.

Chapter 3

The Cosmic Microwave Background

As described in section 2.5, the Cosmic Microwave Background (CMB) is simply radiation – light – with a blackbody spectrum of temperature $T_{CMB} = 2.725$ K (presently).

There are several aspects of the CMB that makes it a most important cosmological tool. In the words of Stephen Hawing "it is the discovery of the century, if not of all time". It is currently the only experimental tool that allows us to probe anything further away than distant quasars, which are ~ 12.7 billion light years away. The reionization was at its end by then and the first star generation had also passed, as well as the first structures in the universe. But the CMB has passed all this and been slightly affected by these events, which have left imprints in the spectral and spatial signature of the CMB.

Looking at the CMB, we see the universe largely as it has been in its infancy, when it was merely 300,000 years old (and we can even see some traces from beyond that time).

From the CMB we can determine the age of the universe and its expansion rate; how much of the total energy content that is made out of ordinary matter (*baryons*), dark matter and dark energy; what the matter distribution was 300,000 years after the Big Bang and also approximately the subsequent formation of structure, such as clusters of galaxies.

The CMB has an almost perfect blackbody spectrum. There are, however, small perturbations in the spectrum, called *anisotropies*. These have characteristic length scales,which correspond to angular scales for our measurements, and depend on what is causing the anisotropy.

The anisotropies can be divided into two categories; primary and secondary. The primary anisotropies occur at, or just before, decoupling, while the secondary anisotropies occur after this event. For a more exhaustive treatment of these anisotropies, the reader is referred to **?**.

The measured brightness can be divided into several components:

$$B(\hat{r}, \nu) = B_{CMB} + B_{SZ} + B_{dust} + B_{free-free} + ..., \tag{3.1}$$

where B_{CMB} is the intensity of the initial blackbody spectrum plus the primary anisotropies, B_{SZ} is the intensity due to the Sunyaev-Zel'dovich effect, B_{dust} is due to the dust contribution and $B_{free-free}$ is the intensity due to the thermal *bremsstrahlung* from within our galaxy. In section 3.2 and 3.3 we will return to these and other effects and foregrounds and describe them in more detail. Now the CMB-part can be Taylor expanded around its blackbody temperature:

$$T(\hat{r}) = T_0 + \Delta T_{CMB}(\hat{r}), \tag{3.2}$$

which gives

$$B_{CMB}(\hat{r}, \nu) \approx B_{T_0}(\nu) + \Delta T_{CMB}(\hat{r}) \left.\frac{dB(\nu)}{dT}\right|_{T=T_0}. \tag{3.3}$$

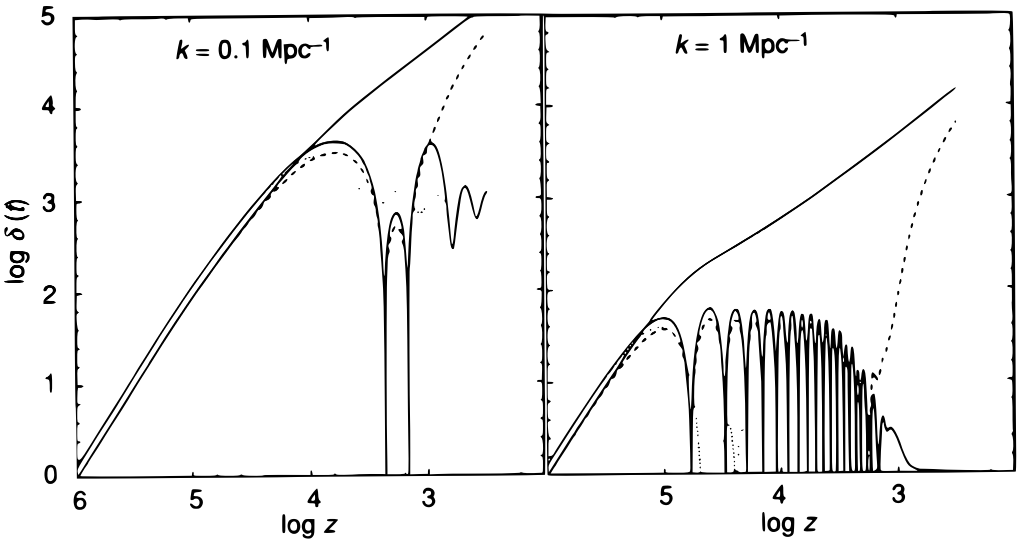


Figure 3.1: Illustration of Silk damping of an evolution of adiabatic perturbations in a cold dark matter model. Left panel: perturbations of co-moving scale 10 Mpc ($\Leftrightarrow M \sim 10^{14} M_{\odot}$); right panel: perturbations of co-moving scale 1 Mpc ($\Leftrightarrow M \sim 10^{11} M_{\odot}$). Reprinted from **?**.

The quantity measured by Planck (in the future) and many other instruments is only the relative excess over B_{T_0}, i. e. ,

$$\frac{B - B_{T_0}}{T_0 (dB/dT)_{T_0}} = \frac{\Delta T_{CMB}}{T_0} + \frac{B_{CMB} + B_{SZ} + B_{dust} + B_{free-free} + ...}{T_0 (dB/dT)_{T_0}}$$
$$\equiv \frac{\Delta T_{CMB}(\nu) + \Delta T_{SZ}(\nu, \hat{r}) + \Delta T_{dust}(\nu, \hat{r}) + ...}{T_0}. \quad (3.4)$$

The measured anisotropies consist of the $\Delta T_X(\nu, \hat{r})/T_0$ terms in the expression above.

3.1 Primary Anisotropies

The primary anisotropies can be divided into three main categories: gravitational, adiabatic and Doppler. Other anisotropies, like topological defects, could also exist, but these are not considered to be very important and are beyond the scope of this introduction. The gravitational and adiabatic terms are combined on large angular scales ($\gg$ 1 degree) and are then called the Sachs-Wolf effect, see **?**.

Furthermore, since the decoupling is not instantaneous, what we observe will be a weighted average over the thickness of the decoupling surface (also called the last scattering surface, LSS). This means that primary anisotropies smaller than this thickness ($\Leftrightarrow \theta \sim 0.1^{\circ}$) will be washed out.

Another effect is the so called Silk damping, **?**, which means that small matter perturbations will not survive, see figure 3.1. The reason for this damping is the fact that in small structures the photons will have time to diffuse out of the dense region before the end of decoupling. The typical mass scale of this effect is $10^{11} M_{\odot}$, the mass of an ordinary galaxy.

3.1.1 Gravitational Anisotropies

As the CMB photons climb out of a gravitational potential, they are redshifted by the gravity. In terms of and equivalent temperature this is given by

$$\left(\frac{\Delta T}{T}\right)_e = -\frac{\Delta\Phi_e}{c^2} \tag{3.5}$$

where $\Delta\Phi_e$ is the gravitational potential in excess of the background.

3.1.2 Adiabatic Anisotropies

In a gravitational potential the number of photons is expected to be larger than normal and their temperature higher. At large angular scales ($\gg 1$ degree), the induced anisotropies will be

$$\left(\frac{\Delta T}{T}\right)_e = \frac{2}{3}\frac{\Delta\Phi_e}{c^2}, \tag{3.6}$$

but on small scales, this is no longer the case due to *acoustic oscillations*.

This means that the Sachs-Wolf effect, which on large scales is the gravitational plus the adiabatic term, is

$$\left(\frac{\Delta T}{T}\right)_e = -\frac{1}{3}\frac{\Delta\Phi_e}{c^2}, \tag{3.7}$$

i. e. the photons are effectively redshifted by the gravitational potential. By measuring the size of these anisotropies and their relative strength we can estimate the matter distribution at the time of decoupling.

3.1.3 Doppler Anisotropies

Due to local movement of the plasma at the time of decoupling, there will be a kinetic Doppler shift

$$\left(\frac{\Delta T}{T}\right)_e = \frac{\vec{v}(\vec{r})\cdot\hat{r}}{c}, \tag{3.8}$$

where $\vec{v}(\vec{r})$ is the local velocity vector of the plasma at the point $\vec{r}$. This effect generally occurs at rather small scales compared to the Sachs-Wolf effect.

3.2 Secondary Anisotropies

The secondary anisotropies are effects that changed the CMB photons between decoupling and now. They can be divided into three types; gravitational effects, local ionization and global ionization. These will be described one by one below.

3.2.1 Gravitational Effects

There are three types of gravitational effects that affect the CMB; the early and the late integrated Sachs-Wolf effects, the Rees-Sciama effect and gravitational lensing.

The integrated Sachs-Wolf (ISW) effect comes into action when there is a change in a gravitational potential as a function of time:

$$\frac{\Delta T}{T} = \frac{\int \Delta\dot{\Phi}\left(\vec{r}(t), t\right)}{c^2}, \tag{3.9}$$

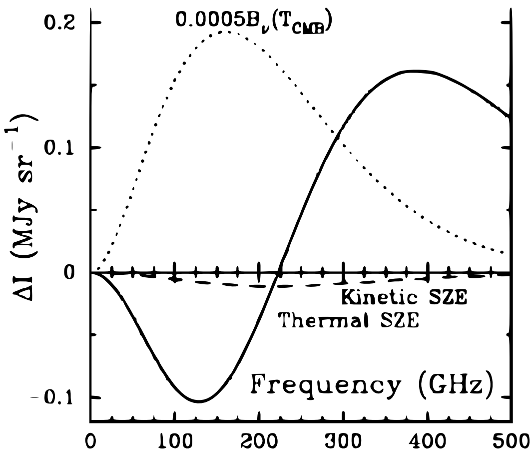


Figure 3.2: Illustration of the thermal and kinetic Sunyaev-Zel'dovich Effect (SZE). The graphs shows the intensity as a function of frequency. The thermal SZ effect increases the photons frequencies, through thermal excitation. The kinetic SZ effect decreases the intensity of the photons in this case because the gas cloud is moving from us.

where $\Delta\dot{\Phi}$ is the time derivative of the gravitational potential in excess of the background potential.

The *early ISW effect* is due to the fact that the photon contribution to the gravitational potential. Since the photon energy decreases with time, this will induce an integrated Sachs-Wolf effect.

The *late ISW effect* comes from the dark energy term that will become more and more important as time passes. This increase in energy also leads to an integrated Sachs-Wolf effect.

The Rees-Sciama effect is also called local ISW. It consists of galaxy clusters and other structures that evolve during the passage of the photons.

Gravitational lensing is an ISW effect perpendicular to the line of sight, affecting the angular distribution of the CMB and smearing it somewhat.

3.2.2 Local Reionization

The local reionization effect is when the reionization affects the CMB through the presence of ionized gas through which the CMB photons must pass. This effect comes about when energetic electrons hit the photons and transfer energy to the photons, and it is called inverse Compton scattering. The impact on the CMB of the inverse Compton scattering is called the Sunyaev-Zel'dovich (SZ) effect, **?**, **?** and **?**. There are two types of the Sunyaev-Zel'dovich effect, thermal and kinetic, see figure 3.2.

The thermal SZ effect is due to energetic free electrons and will have the effect of shifting the CMB spectrum towards higher frequencies since each photon subject to the inverse Compton scattering will gain energy, but not in any particular direction.

The kinetic SZ effect is due to the global motion of a galaxy cluster or other large structures. Since there is a favored direction (in the direction of the velocity of the cluster), this will cause a Doppler shift of the CMB spectrum.

3.2.3 Global Reionization

There are three types of global reionization; suppression of small scales, new Doppler effect and the Vishniac effect.

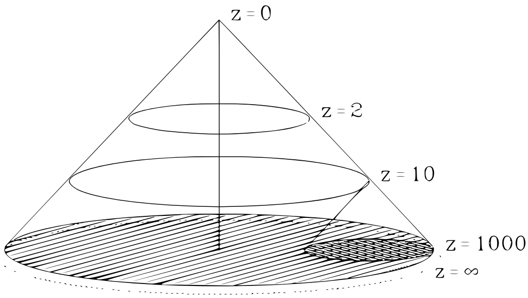


Figure 3.3: Illustration of the suppression of small scales due to the reionization. If photons scatter at reionization, they could come from anywhere within the lightcone projection at $z = 1000$. Through the finite speed of light, we know that they cannot have come from anywhere outside of this projection, which corresponds to and angle $\sqrt{\Omega_0/z_i}$.

The suppression of small scales comes from the fact that the photons scattering during reionization loose their original direction. The amplitude of this effect depends on the time when the reionization occurred, the later time the higher amplitude, see figure 3.3. It also depends on the degree of reionization, in other words, on the *optical depth*. In fact, this effect suppress all scales smaller than

$$\theta \leq \sqrt{\frac{\Omega_0}{z_i}}, \tag{3.10}$$

where Ω_0 is the total relative energy density of the universe and z_i is the *redshift* at reionization. The suppression of the *power spectrum* on these scales is $e^{-2\tau}$.

The new Doppler effect is due to local velocity and density perturbations, and the Vishniac effect is caused by electrons falling in gravitational potential wells, but it is only active on scales $\theta \sim 0.02°$ and even then it is quite feeble.

3.3 Foregrounds

Foregrounds are light sources in the universe emitting in the same frequency range as the CMB. There are three basic types of foregrounds; extragalactic, galactic and local.

3.3.1 Extragalactic Foregrounds

The extragalactic foregrounds are point sources having an origin outside our galaxy. A point source has a very small angular extension. However, their total integrated effect can still be considerable. There are point sources that are active mostly in the radio domain, like e. g. radio galaxies, but there are also sources active mostly in the IR domain, like dusty galaxies.

As I have shown in my second paper, there is also a kind of continuous IR source all over the sky with a bias for mass concentrations – the emission from the early dust.

3.3.2 Galactic Foregrounds

The galactic foregrounds are all diffuse, meaning that they have a certain angular extension. The principal galactic foregrounds are emission from dust, free-free emission and synchrotron radiation. The angular correlations, see section 3.4, of these foregrounds are all roughly $\propto \theta^3$.

The dust in our galaxy has been shown to have a Planck spectrum of temperature ~ 17 K, **?**.

The free-free emission comes from free electrons that are accelerated, thus emitting thermal *bremsstrahlung*. The free-free emission is almost independent of frequency.

The synchrotron radiation is due to acceleration of plasmas and is a sort of global bremsstrahlung. The synchrotron radiation is most effective for frequencies below 70 GHz.

3.3.3 Local Foregrounds

Local foregrounds are perturbations from the solar system, like the planets, the moon, the Sun, the atmosphere and instrumental noise. The solar system perturbations are well known and the instrumental noise is instrument specific.

3.4 Power spectrum

In the previous section we saw that the measured anisotropies can be separated into several components, equation 3.4, each anisotropy with its specific spectral and spatial signature. In this section we will explore the *power spectrum*, which is a powerful tool to quantify the spatial signature of the signal.

The spatial signature is often expressed in terms of the Legendre spherical harmonics

$$\Delta T_X(\vec{r}, \nu) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} Y_{\ell m}(\vec{r}) a^X_{\ell m}(\nu), \tag{3.11}$$

where the spherical harmonics $Y_{\ell m}$ are the basis functions and $a_{\ell m}$ are their components. In order to determine correlations on different angular scales, the correlation functions are used:

$$C^X_\ell(\nu) = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} \left\langle \left| a^X_{\ell m}(\nu) \right| \right\rangle . \tag{3.12}$$

This is also called the (angular) power spectrum. In the case of isotropic fluctuations the above equation simplifies to $\langle a_{\ell m}(\nu)^* a_{\ell' m'}(\nu) \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$. To convert from ℓ to θ a good rule of thumb is $\theta \approx 180^\circ / \ell$.

It is customary to plot the quantity $\ell(\ell + 1)C_\ell / 2\pi$ in units of μK^2, cf figure 3.4. The reason for this choice is so that the root-mean-square (r.m.s.) of the temperature variations becomes visually apparent:

$$\left\langle \Delta T(\nu)^2 \right\rangle = \sum_{\ell=0}^{\infty} \left(\frac{2\ell + 1}{4\pi} \right) \approx \int_1^{\infty} \left(\frac{\ell(\ell + 1)}{2\pi} \right) C_\ell d(\ln \ell), \tag{3.13}$$

where we have used $\frac{l(2\ell+1)}{4\pi} \approx \frac{\ell(\ell+1)}{2\pi}$ for $\ell \gg 1$. This means that in order to estimate the $(\text{r.m.s.})^2$ of the anisotropies in the range $\ell_1 < \ell < \ell_2$ we need to take only the r.m.s. height of the curve times $\ln(\ell_2 / \ell_1)$.

3.4.1 Acoustic Oscillations

Prior to decoupling, the matter and the photons were tightly coupled and effectively formed a baryon-photon fluid. Because of the density perturbations, this fluid started to oscillate. These oscillations are called acoustic. Each mode in these oscillations will give rise to a correlation at a given angular scale in the power spectrum. The acoustic oscillations are a natural consequence of inflation and thus serves to corroborate the inflation theory.

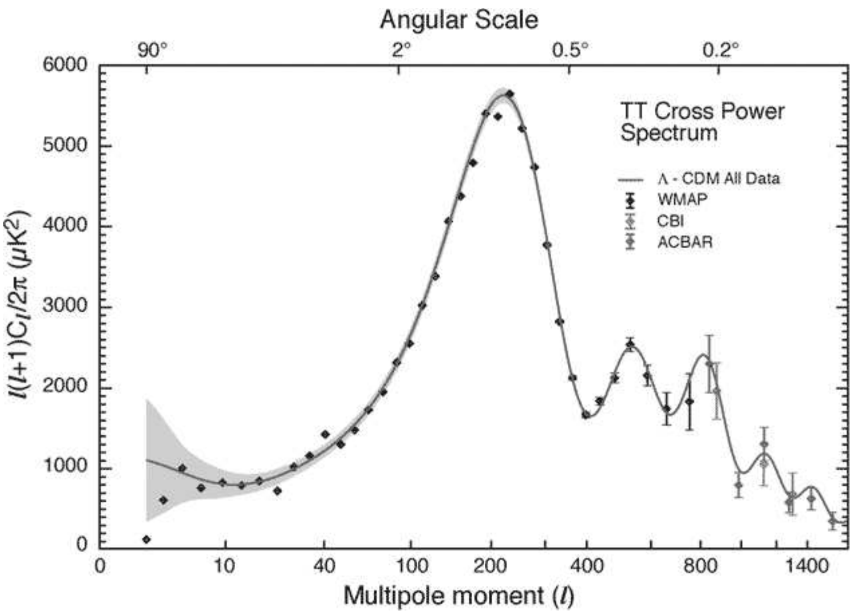


Figure 3.4: The power spectrum as measured by WMAP, CBI and ACBAR. On the x-axis, the inverse angular scale, on the y-axis, the correlation on that scale. The dots are data points and the curve is the theoretical curve.

3.4.2 Simulations of the CMB

A program named CMB-fast is used to estimate the CMB from theory. The program is versatile, allowing the user to test different scenarios with different types of cosmologies and see what the expected power spectrum would become. In figure 3.5 we can see the different components of the CMB and how they are affected by some cosmological parameters.

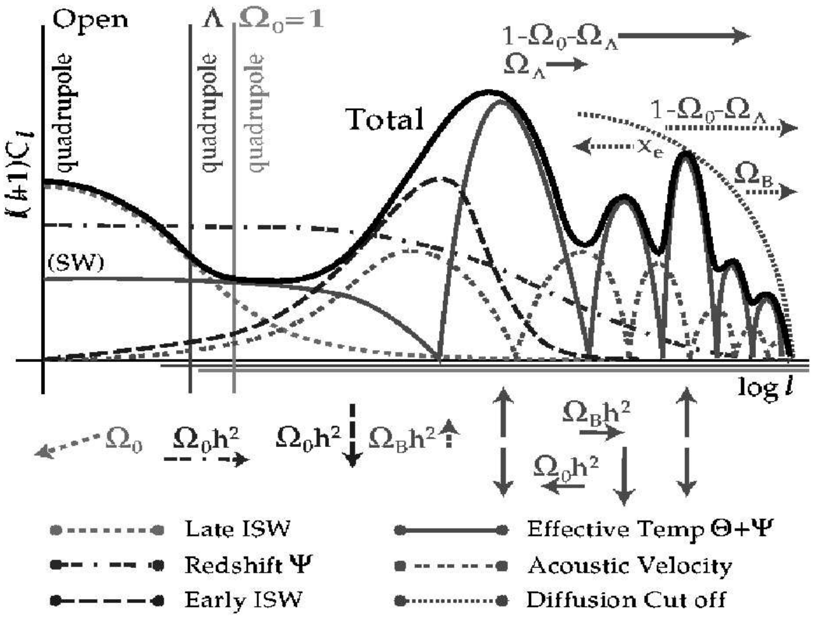


Figure 3.5: The power spectrum as calculated by CMB-fast. Reprinted from **?**. The contribution from different types of anisotropies (see section 3.1 and 3.2) is shown. On the x-axis is the inverse angular scale, and on the y-axis the correlation on that scale. We see the characteristic platau of the Sachs-Wolf effect at large angles and the acoustic oscillations at small angles. We can also see the impact of different cosmological parameters on the power spectrum.

Chapter 4

Short Introduction to the Papers

This chapter is included to give the reader some background information that may be useful for the understanding of the particularities of the appended papers. Section 4.1 describes the dust, which is the principal object of study in this thesis, and section 4.2 introduces dark matter, which is important for Paper II.

4.1 Dust

The abundance of dust in the universe can be calculated by estimating its production and destruction rate. These figures are not well known even of the nearby universe and even less so of the early universe. In this section the properties of this early dust are briefly discussed along with some general properties of the nearby dust. The section is included as a complement to my first paper, **?**, where the specifics of early dust are used. For a more complete review of dust in general, see **?**.

4.1.1 Production

In section 2.4 we treated the formation of light elements through the nucleosynthesis, but most of the terrestrial material is made of heavier elements. The only known source of such heavy elements are *supernovæ*. During its life, a star fuses hydrogen into helium and then onto carbon, nitrogen and other heavy elements. If the star finishes as a supernova, these elements are released into the interstellar medium (ISM), and then serve to produce new planets and stars.

On their way out, many of these elements are ionized. When the ions meet they tend to form ionic bonds, and in this way tiny crystals are formed. These crystals form that we call cosmic dust.

For an overview of dust production in the early universe, the reader is referred to **?**.

4.1.2 Properties

The composition of interstellar dust grains is still largely unknown. While meteorites provide us with genuine specimens of interstellar grains for examination, these are subject to severe selection effects, and cannot be considered representative of interstellar grains. Our only direct information about the composition of interstellar dust comes from spectral features of extinction, scattering, or emission.

By means of spectral measurements and stellar nucleosynthesis it is found that dust grains are composed mainly of elements like silicon, oxygen, nitrogen, carbon and iron. Dust grains are formed of molecules like CO, SiO_2, Al_2O_3, Fe, Fe_3O_4, $MgSiO_3$, Mg_2SiO_4 and amorphous carbon. These grains form at different temperatures. CO form at $\approx$ 2500 K (**?**), amorphous carbon at $\approx$ 1800 K, Al_2O_3 at $\approx$ 1600 K and the other grain types at $\approx$ 1100 K (**?**).

The polarization of starlight was discovered more than 50 years ago, and was immediately recognized as being due to aligned dust grains. Two separate alignments are involved: (1) alignment of the grain's principal axis of largest moment of inertia with its angular momentum J, and (2) alignment of J with the galactic magnetic field.

As has been shown by **?**, the chemical composition can be found of different types of supernovæ with masses of 11-40 $M_\odot$ and metallicities $Z/Z_\odot = 0$, 10^{-4}, 0.01, 0.1 and 1.

Galactic dust is found mostly in nebulæ, where it is an important factor in the star formation process.

4.1.3 Destruction

The destruction of dust particles is not very well understood, due to the fact that the dust is found in a variety of environments of rather complicated nature. In this section, some important mechanisms for dust destruction are touched upon. Their exact impact, especially at the time of the early dust, remains unclear, see **?**.

There are a number of phenomena that destroy dust (or rather erode it into negligible pieces). The destruction mechanisms include *sputtering* and grain-grain collisions in interstellar shocks, *sublimation* during supernovæ radiation pulses, sputtering and sublimation in H II regions, photodesorption by UV light and sputtering by cosmic rays. A classic paper on dust destruction is **?**.

This plethora of processes makes it difficult to calculate the lifetime of the dust. For a hot ionized medium the lifetime can be estimated to 10^8 years, in a cold neutral medium, to 10^9 years and in a molecular cloud, to 10^{10} years, **?**. The actual environment of the dust from the first stars is pretty much unknown. What we do know, however, is that the universe was denser at that time than it is today, but also less clumped. There were no real galaxies, and in the beginning no ionized gas either.

4.2 Dark Matter

Dark Matter (DM) is not very well understood but there are several properties that are known. There are also a multitude of particles that could possibly constitute this mysterious DM. DM has not yet been directly seen neither in astronomical telescopes, nor in particle accelerators.

The DM was originally conceived to explain the velocities of stars in galaxies as a function of their distance from the center. For each of the stellar, galactic, and galaxy cluster/supercluster observation the basic principle is as follows. If we measure velocities in some region, there has to be enough mass present for gravity to stop all the objects flying apart. When such velocity measurements are done on large scales, it turns out that the amount of inferred mass is much more than can be explained by the luminous stuff. Hence we infer that there is DM in the Universe.

DM is also required in order to enable gravity to amplify the small fluctuations in the Cosmic Microwave Background enough to form the large-scale structures that we see in the universe today, as mentioned in section 2.6.

DM candidates are usually split into two broad categories, with the second category being further sub-divided:

- Baryonic
- Non-Baryonic
  - Hot Dark Matter (HDM) and
  - Cold Dark Matter (CDM),

depending on their respective masses and speeds. CDM candidates travel at slow speeds (hence ”cold”) or have little pressure, while HDM candidates move rapidly (hence ”hot”).

Since the DM has yet eluded detection, it is supposed that it will only interact very weakly with ordinary matter. This means that simulations of the structure evolution of the universe can be greatly simplified. Since we know that the gravitationally dominant form of matter in the early universe was DM, and its only interaction is gravitation, the equations of evolution are rather simple to solve. This means that huge simulations can be done including millions of DM particles and covering hundreds of Mpc (mega parsecs). In simulations each “particle” weighs in the order of 10^{10} solar masses.

Chapter 5

Summary and Outlook

5.1 Summary

The universe truly is a marvelous place, and it is astonishing how much we can learn about its history and evolution just by observing some light that happens to fall on the surface of the Earth.

One of the things we might learn in the near future is the impact of dust from the first generation of stars. Since the dust will have a particular spatial and spectral signature it could very well be detected by the Planck satellite, planned to be launched in 2007.

This dust could help us better understand two important things in the universe, the Cosmic Microwave Background and the formation of structures like galaxies and stars in the early universe.

The evolution of the universe has been treated in chapter 2 in order to set the stage for the place of the dust in the history of the universe. The most important points were: (1) The decoupling of matter from radiation (section 2.5), leaving the universe with an omnipresent radiation with an imprint of the properties of universe when it was 300,000 years old; (2) The first generation of stars (section 2.7), which exploded as supernovæ and sprayed out heavy materials that condensed to form dust.

In chapter 3 follows a description of the properties and benefits of the Cosmic Microwave Background. This CMB radiation contains a wealth of cosmological information, which can be extracted with the help of the power spectrum (section 3.4).

Chapter 4 contains a description of our current knowledge of interstellar dust (section 4.1) and gives an introduction to dark matter (section 4.2). Neither of these subjects are particularly well known to us today, but there is a lot of circumstantial evidence that helps us understand the basics.

In the first appended paper, **?**, a simple method is used to determine the dust density as a function of time. The ambient radiation from the first generation of stars will heat this dust and it will reemit a different spectrum. When this emission is integrated along the line of sight through all the dust, a unique spectrum is obtained that could be measured here on Earth. Unfortunately, the current generation of intruments is not capable of identifying the dust signal merely by using the dust spectrum.

In the second paper, **?**, the spatial distribution of dust is the object of study. Since very little is known about this time in the history of the universe, a crude method for the density distribution of the dust is used. The method simply consists of letting the dust be proportional to the dark matter density, since dark matter is believed to have played a key-role in the evolution of large-scale structures like galaxy clusters. Through computer simulations of the evolution of dark matter, the distribution of the dust in space is thus obtained. The knowledge of the spatial distribution is then compared to the sensitivity of the planned Planck satellite. The results are promising but depend on model parameters like the lifetime of this early dust.

The goals of this Licentiate thesis, as presented in the Introduction, have thus been satisfyingly accomplished. The thickness, density and distribution of the dust from the first generation of stars have been estimated, and the impact of this dust on the CMB measurements has been evaluated.

5.2 Outlook

There are still numerous exciting problems to be solved in order to consolidate our understanding of the universe. In particular, the impact of dust on the history of the universe is still an open question. It would be interesting to see some detailed simulations of the evolution of the first galaxies, with dust production and destruction taken into account. This dust has important implications for the spectra emitted by these galaxies, which eventually could be detected, for example with the Hubble telescope. Hubble Ultra Deep Field observations have been carried out but are not yet published, and these observations should show us the universe at an age of 0.3-0.7 billion years. This would mean that we could even get a glimpse of the first generation of stars and find out some more direct evidence of their properties.

Aside from the implications of dust in the early universe, gravitation is still a hot subject. Our present understanding of what takes place with dynamics in the vicinity of a black hole is still poor, and there are other aspects of gravitation that are not fully understood either.

Another interesting path is to study the large scale structure of the universe. There are some tantalizing evidence that the universe might not be as isotropic and homogeneous as has been previously presumed.

New instruments are continously being developed and our understanding of the universe is growing rapidly. All in all, the prospects of astrophysics are excellent in the future, and I look forward to take part in the exploration of the universe.

Appendix A

Cosmology

A.1 Basic Introduction

This appendix contains some explanations for those not so familiar with cosmology but with some knowledge of physics in general. The symbols are explained in appendix B.

First, it is important to know that distance and time are used interchangeably. Since light moves with a constant speed, c, we know that the distance travelled will be $c \cdot t$. So, if we say that something is 100 light years away this means that it was 100 years ago.

Another important measure of distance is (cosmological) redshift, z. The relation between time, t, and redshift, z, is given in section A.2 and is also plotted in figure A.1. Astronomers and astrophysicists often mean distance when they speak about redshift, cosmologists often mean time.

In fact, the definition of redshift is:

$$z = \frac{\lambda_0 - \lambda_e}{\lambda_e} \tag{A.1}$$

where λ_0 is the observed wavelength and λ_e is the emitted wavelength. The reason why $\lambda_0 \neq \lambda_e$ is the expansion of the universe – the light waves also expand and thus their wavelength increases. Consequently the redshift can also be expressed as $z + 1 = 1/R$, where R is the expansion of the universe. Note that light emitted nearby will not have been subject to any expansion of the universe and thus is at $z = 0$.

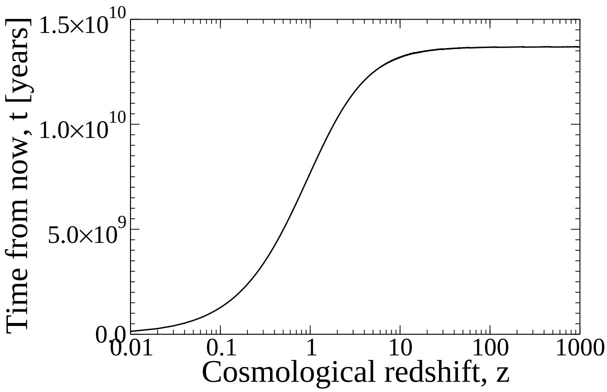


Figure A.1: Time versus redshift.

A.2 Cosmological Equations

Relation between temperature, T, expansion of the universe R and time since the Big Bang, t:

Radiation dominated universe:

$$T \propto 1/R \propto 1/t^{1/2}. \tag{A.2}$$

Matter dominated universe:

$$T \propto 1/R \propto 1/t^{2/3}. \tag{A.3}$$

Evolution of matter and radiation density:

Matter density:

$$\rho_M \propto R^{-3}. \tag{A.4}$$

Radiation density:

$$\rho_R = \sigma T^4/c^2 \propto R^{-4}. \tag{A.5}$$

General:

Time/redshift (for $z < 1000$):

$$\frac{dz}{dt} = -H_0 \sqrt{(1+z)^2(1-\Omega_m+\Omega_m(1+z)^3)}. \tag{A.6}$$

Measured angles:

$$\frac{\pi}{\ell} \approx \theta[rad] = \frac{D_c}{L_c} = \frac{D_c}{c \cdot \int_{t_i}^{t_0}(1+z)dt} = \frac{D_c}{c\int_z^0 dz(1+z)\frac{dt}{dz}}, \tag{A.7}$$

where D_c denotes the co-moving distance and the other symbols are explained in appendix B.

Spectra:

Blackbody spectrum:

$$B_\nu = \frac{2h\nu^3}{c^2}(e^{h\nu/k_BT} - 1)^{-1}. \tag{A.8}$$

Conversion $\nu \leftrightarrow \lambda$:

$$f(\nu)d\nu = f(\lambda)d\lambda, \quad \forall f. \tag{A.9}$$

Appendix B

Explanations

B.1 Glossary

For further descriptions of astronomical terms, the interested reader is referred to http://factguru.com/.

Acoustic oscillations The oscillations due to density variations in the photon-baryon fluid prior to decoupling.

Antimatter Antimatter is constituted of *antiparticles*.

Antiparticle An antiparticle is defined as having the opposite *quantum numbers* of the corresponding particle, but it has the same mass.

Baryonic matter "Ordinary matter" consisting of baryons, i. e. protons and neutrons.

Big Bang The origin of the universe - see section 2.1.

Bremsstrahlung Radiation emitted due to acceleration of charged particles.

CMB Cosmic Microwave Background. The fossil radiation left from the *decoupling* of radiation from matter, $\sim$ 300,000 years after the *Big Bang*. The CMB radiation has a blackbody spectrum with a temperature of $T_{CMB} = 2.725 \pm 0.002$ K, **?**.

Dark Matter Exotic dark matter is believed to constitute $\sim$ 25% of the total mass (energy) of the universe. Ordinary (*baryonic*) matter only constitutes $\sim$ 5% of the total mass (energy) of the universe. The domination of dark matter is inferred from the rotations of galaxies and the evolution of large scale structures (e. g. galaxy clusters) in the universe. Note, however, that ordinary matter invisible to us also is dark matter. It is still and unsettled question, what dark matter actually is. For more information, see section 4.2.

Decoupling When there was not enough thermal energy to excite hydrogen, the energy of the photons did not change anymore and they continued virtually unhindered.

Early ISW effect This is due to the fact that the photons contribute to the gravitational potential. Since the photon energy decreases with time, this will induce an integrated Sachs-Wolf effect.

Foregrounds Other signals that (partly) hide the primordial CMB. Examples: Our galaxy and point sources like nearby planets and distant galaxies and dust, cf section 3.3.

GalICS A computer program used to simulate dark matter and the evolution of galaxies and their spectra.

Integrated Sachs-Wolf effect When a gravity potential changes over time. See section 3.2.

Late ISW effect This comes from the dark energy term that will become more and more important as time passes. This increase in energy also leads to an integrated Sachs-Wolf effect.

Metallicity The mass proportion of elements heavier than helium, denoted Z. The Sun has a metallicity of $Z_\odot \approx 0.02$, **?**.

Optical depth, τ The probability of a photon passing through a medium without scattering is $e^{-\tau}$.

Planck A satellite, which will be launched in 2007 and which is planned to measure the CMB over the entire sky with unprecedented precision.

Population III stars The first generation of stars with extremely low *metallicity* and probably a high mass and a short life.

Power spectrum A plot of the angular correlations of the measured CMB, cf section 3.4.

Quantum numbers The numbers, which can be said best to describe the state of a particle. Examples: electric charge (Q), lepton number (L), baryon number (B), parity (P), spin (S), isospin (I), strangeness (S), and charge conjugation (C).

Quasar Extremely distant and luminous astronomical objects, which are much smaller than a galaxy and much more luminous.

Redshift Used to measure distance from us to a source (a star, a galaxy etc). Equivalently redshift measures time from now and backwards. Today the universe has $z = 0$. A billion years ago correspond to $z \sim 0.1$, ten billion years ago to $z \sim 2$, thirteen billion years ago to $z \sim 8$. The redshift is due to the expansion of the Universe. Contrary to popular belief, this is not a Doppler shift. Most galaxies move away from us, but this is not the cause of their redshifts. Instead, as a light wave travels through the fabric of space, the universe expands and the light wave gets stretched and therefore redshifted. See also appendix A.

Reionization This happened when the first generation of stars formed, emitting high energy photons capable of ionizing the hydrogen and helium gas. The reionization lasted for some five billion years.

Sachs-Wolf effect When a photon has to climb out of a gravity well and thereby gets redshifted.

Silk damping Damping of density perturbations up to $10^{11} M_\odot$ prior to *decoupling*, due to photon diffusion.

Sputtering Bombarding a target material with energetic (charged) atoms, which release atoms from the target, thus eroding it.

Sublimation The change of a solid substance directly into a vapor without first passing through the liquid state.

Sunyaev-Zel'dovich effect When an electron hits a photon and gives it energy. See section 3.2.

Supernova A gigantic stellar explosion in which the luminosity of the star suddenly increases by as much as a billion times. Most of the its substance is blown off, leaving behind, at least in some cases, an extremely dense core, which may become a neutron star.

B.2 Abbreviations

BBN	Big Bang Nucleosynthesis
CDM	Cold Dark Matter
CMB	Cosmic Microwave Background
DM	Dark Matter
GalICS	Galaxies In Cosmological Simulations
HDM	Hot Dark Matter
IGM	InterGalactic Medium
ISM	InterStellar Medium
ISW	Integrated Sachs-Wolf effect
PAH	Polycyclic Aromatic Hydrocarbon
SN	SuperNova
SZ	Sunyaev-Zel'dovich effect
WMAP	Wilkinson's Microwave Anisotropy Probe

B.3 List of Variables

$B(\hat{r}, \nu)$	Measured intensity in W/m^2 in direction $\hat{r}$.
$B_X = B_X(\hat{r}, \nu)$	Intensity of component X.
$\Delta\Phi$	Gravitational potential excess over background.
z	The *redshift*, which is dimensionless, is often used to describe time or length through the intermediary of the expansion of the universe R. See also figure A.1.
R	The expansion of the universe is $\propto R$, see z.
T	Temperature in Kelvin.
t	Time in seconds.
θ	Angle on the sky.
N_p	Number density of protons.
N_γ	Number density of photons.
E_γ	Energy of photons.
z_i	Redshift of the reionization.
$\vec{r}$	Spatial coordinate vector.
$\vec{v}$	Velocity vector.
ΔT_X	Anisotropy for component X.
ℓ	Inverse angle scale, $\theta \approx 180^\circ/\ell$.
C_ℓ	Angular correlation on scale ℓ.
ν	Frequency in Hz.
$Y_{\ell m}(\theta, \phi)$	Angular basis function for the Legendre spherical harmonics.
$a_{\ell m}$	Component of $Y_{\ell m}$.
$\sqrt{\langle \Delta T(\nu)^2 \rangle}$	Root mean square of temperature differences.

B.4 List of Cosmological Constants

h_0	0.72±0.03	Hubble's relative constant (**?**).
$H_0 = 100 \cdot h_0 \frac{\text{km/s}}{\text{Mpc}}$	$2.33\times10^{-18}\text{s}^{-1}$	Hubble's constant.
$\rho_c = \frac{3H_0^2}{8\pi G}$	$(0.97 \pm 0.04) \times 10^{-26}$ kg/m^3	Critical density of the universe.
$\Omega_{tot} = \rho_{tot}/\rho_c$	1.02 ± 0.02	Total relative energy content of the universe, (**?**).
$\Omega_m = \rho_m/\rho_c$	$(0.133 \pm 0.006)/h^2$	Relative matter content of the universe, (**?**).
$\Omega_b = \rho_b/\rho_c$	$(0.0226 \pm 0.0008)/h^2$	Relative baryon content of the universe, (**?**).
$M_\odot$	1.99×10^{30} kg	Mass of the Sun.

B.5 List of Physical Constants and Units

c	299792458 m/s	Speed of light in vacuum, from Latin "celeritas"=speed.
G	$6.6742(10) \times 10^{-11}$ m^3/kg·s^2	Newton's constant of gravitation (**?**).
k_B	$1.3806505 \times 10^{-23}$ J/K	Boltzmann's constant.
1 erg	10^{-7} J	Unit energy in the cgs (centimeter-gram-second) system of units.
1 eV	1.602×10^{-19} J	Electron volt, energy.
1 pc	3.086×10^{16} m	A parsec is defined as the distance from the Sun which would result in a parallax of 1 second of arc as seen from Earth.

Appendix C

Appended Papers