Large Scale Anomalies of the Cosmic Microwave Background with Planck

Ph.D. thesis by Anne Mette Frejsel

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Abstract

This thesis focuses on the large scale anomalies of the Cosmic Microwave Background (CMB) and their possible origins. The investigations consist of two main parts. The first part is on statistical tests of the CMB, and the consistency of both maps and power spectrum. We find that the Planck data is very consistent, while the WMAP 9 year release appears more contaminated by non-CMB residuals than the 7 year release. The second part is concerned with the anomalies of the CMB from two approaches. One is based on an extended inflationary model as the origin of one specific large scale anomaly, namely point-parity asymmetry. Here we find that a modified curvaton model can reproduce an asymmetric behavior of the power spectrum at low multipoles. The other approach is to uncover whether some of the large scale anomalies could have a common origin in residual contamination from the Galactic radio loops. Here we find evidence that the Planck CMB maps contain residual radiation in the loop areas, which can be linked to some of the large scale CMB anomalies: the point-parity asymmetry, the alignment of quadrupole and octupole and the dipole modulation.

Resume

Denne afhandling omhandler stor-skala anomalier i den kosmiske mikrobølgebaggrundsstråling (CMB), og deres mulige oprindelse og natur. Afhandlingen har to hovedområder. Det første har fokus på statistiske tests af CMB, og konsistensen af både billeder og powerspektrum for baggrundstrålingen. Vores resultater viser at dataene fra Planck har god overenstemmelse, mens WMAPs 9 års data ser ud til at være mere forurenet end 7 års dataene. Det andet hovedområde omhandler anomalierne i CMB, som undersøges fra to vinkler. Den ene er baseret på en udvidet inflationsmodel, som vi viser kan reproducere paritets asymmetri af powerspektrummet for lave multipoler. Den anden vinkel er undersøgelser af hvorvidt anomalierne på store skalaer kan have en fælles oprindelse i forgrundsforurening fra de Galaktiske radio cirkler. Vi har fundet beviser for at Plancks CMB indeholder rester af forurening i cirkler-områderne, som kan kædes sammen med nogle af stor-skala anomalierne: punkt-paritets asymmetri, de parallelle axer for kvadrupolen og oktupolen samt dipols modulation.

PREFACE

It is with both great satisfaction and some degree of wistfulness that I here present the culmination of three years of Ph.D. studies at the Niels Bohr Institute. It has been a journey of hard work, learning, collaboration, education and fun, and has been an immensely rewarding time. I have been very happy to be part of the Discovery Center for Particle Physics and Cosmology, which has broadened my horizon of physics beyond cosmology and astrophysics.

A warm thanks to my supervisor, Pavel Naselsky, for discussions, advice and a guiding hand through the community of CMB science and academia. During my Ph.D. studies I have also spent time at Stanford University, where I was working with Igor Moskalenko and Troy Porter on a project of cross-correlating Planck and Fermi-LAT data. I am very grateful for their wonderful hospitality, and thoroughly enjoyed the atmosphere and intellectual stimulus of my stay. Thanks to my colleagues and co-authors, who have given me much inspiration, food for thought and fun collaboration during my three years of Ph.D. studies. Especially my office mates, Martin and Sebastian, have made Ph.D. life in the F-building a thoroughly enjoyable experience. I am also immensely grateful to my proof-readers, Sebastian, Assaf, Amel, Per and my Dad, without whom this thesis would have been much less complete. Lastly a big thank you to my partner, Lars, and my friends and family, who have been a great support both during my studies as well as for the final stretch.

While this thesis is written as a connected story, it is based on many separate projects, some of which were born of each-other and some of which were only peripherally connected. Some projects never made it to publication, but rather morphed into new ones that did. I am happy with the end result that came out of it, and I believe this thesis tells a coherent story about the CMB from Planck and the anomalies that it contains. and I hope that you will enjoy reading it.

Contents

PREFACE						
C	ONTE	NTS	iii			
1	INTRODUCTION					
	1.1	This thesis	3			
2	Тне	E COSMIC MICROWAVE BACKGROUND FROM PLANCK	5			
	2.1	A brief history of the CMB	6			
	2.2	Observing cosmic microwaves	8			
	2.3	CMB data	14			
	2.4	CMB anomalies	22			
3	INVESTIGATING STATISTICAL PROPERTIES OF THE CMB					
	3.1	Consistency tests for Planck and WMAP in the low multipole domain	34			
	3.2	Consistency of the SMICA power spectrum	42			
	3.3	Consistency test conclusions	46			
4	SEA	RCHING FOR A COSMOLOGICAL EXPLANATION	47			
	4.1	Large-scale anomalies of the CMB in the curvaton scenario	48			
	4.2	Cosmological conclusions	60			
5	UNVEILING GALACTIC CONTAMINATION					
	5.1	Zodiacal light and the Kuiper Belt	64			
	5.2	Impact of Galactic loops on the low- ℓ CMB anomalies $\ldots \ldots \ldots \ldots$	65			
	5.3	Galactic radio loops in the Fermi-LAT data	89			
	5.4	Galactic conclusions	94			

DISCUSSING THE ORIGINS OF THE CMB ANOMALIES			
6.1 Future outlook	99		
ACKNOWLEDGEMENTS	101		
LIST OF FIGURES	103		
LIST OF TABLES			
BIBLIOGRAPHY	107		
A Harmonic Coefficients of the Loops	121		

1

INTRODUCTION

For anyone, turning one's gaze to the heavens on a dark night can be breathtaking, fascinating, and may even foster philosophical thoughts. For an astrophysicist there is an extra layer of awe, beauty, and sense of overwhelming vastness about the view, brought on by knowledge of what all those twinkling dots and hazes actually represent. The thought of burning gas giants, exoplanets, gas which is billions of degrees hot, and the unbelievable distances involved, takes the experience of stargazing to a new level.

All the light that we see on such a night comes from sources that emit at optical wavelengths. If our eyes were able to see a wider range of the spectrum than just the optical, we would see an even richer picture of our galaxy. Stars shining at a multitude of wavelengths, warm gas in X-rays, dust in the infrared part of the spectrum and free electrons in radio (see Figure 1.1). Focusing our view on the microwave domain we would see the Milky Way shining brightly, with an almost uniform radiation dominating the rest of the sky. This uniform emission does not originate in our own olar system nor galaxy, but is an ancient cosmic radiation from the earliest era of the Universe. It is called the Cosmic Microwave Background, or just CMB, and was first observed in 1964 [1]. On Earth, however, the oxygen and water in our atmosphere absorb most of the microwave emission, leaving only limited frequency windows open to this primordial radiation. This means that one preferably wants to go into space to get a clear view of the CMB, unobstructed by absorption.

The Planck mission [2] of the European Space Agency (ESA) is a satellite that went to space in order to observe the CMB. Building on the results from its predecessors, the Wilkinson Microwave Anisotropy Probe (WMAP) [3] and the COsmic Background Explorer (COBE) [4] satellite, it confirmed and enforced our beliefs in the standard concordance model of cosmology [5] which describes the content, history and future of the Universe.



*Figure 1.1: The Milky Way at different wavelengths. From top to bottom: radio continuum (408 MHz), atomic hydrogen, radio continuum (2.5 GHz), Molecular hydrogen, infrared, mid-infrared, near infrared, optical, x-ray and gamma-ray. Image credit: NASA*¹.

The main focus of my Ph.D. studies has been the statistical properties of the CMB as observed by the Planck mission, and the anomalies which the CMB has been found to contain. While experiments like WMAP and Planck have built a strong case for how the cosmological concordance model paints the picture of the Universe, these anomalies present themselves as blemishes upon that picture. The anomalies are tiny deviations of the observational data from what is expected from the concordance model. Although collectively referred to as anomalies, the term spans a wide range of different statistically abnormal signatures in the CMB, which are not necessarily connected in their nature and origin. Some of the anomalies are connected to very localized features of the CMB, while others relate to large-scale statistical properties of the signal. These large-scale anomalies are the ones that are taken under investigation in this thesis. We have two goals: firstly, to identify which regions of the sky are connected to the statistically anomalous signatures, and secondly, what their origin may be. We can categorize the possible origins of the CMB anomalies into five main categories,

¹http://adc.gsfc.nasa.gov/mw

- Statistical happenstances
- Systematics or data-processing
- Cosmological/primordial
- Galactic or Solar System
- Extragalactic

The last two could also be grouped together under the label foreground contamination. The main question to be answered is then: what are the large-scale anomalies, are they connected in origin and do we need to revise our model of the Universe, or foregrounds, to accommodate for their existence?

1.1 This thesis

In this thesis I present some of the results from three years of work, where I (and my collaborators) have worked on the consistency of the CMB maps and power spectra, as well as investigations into the nature of some of the large-scale CMB anomalies. It is overall comprised of three types of components: published papers, unpublished work which complements the papers, and text which wraps everything into context. The content of the papers has been incorporated into a coherent and connected form with the rest of the thesis, but the text and results from the papers are presented almost as published.

During most of my Ph.D. studies I have been a member of the Planck collaboration, first as an associate, and after the 2013 release as a full Planck Scientist. Some of the work I have done for the collaboration has not yet been published, and some has contributed to internal analyses for the better understanding of our data, but has not been a direct part of a published paper. I have also spent time working with two Fermi-LAT scientists on a project of cross-correlations between Planck and Fermi. While there are interesting results from that stay that invite for a larger analysis, the results have not reached publication maturity yet.

The structure of the thesis is as follows. Short introductions to the CMB, the CMB anomalies, as well as the COBE, WMAP and Planck experiments are given in Chapter 2. In Chapter 3 are presented statistical tests of the CMB data and their consistency. This primarily follows the paper *Consistency tests for Planck and WMAP in the low multipole domain* [6], as well as internal Planck work, *Consistency tests of the SMICA power spectrum*. In Chapter 4 we turn our attention to the possibility of a theoretical cosmological

explanation of a specific large-scale CMB anomaly, which was discussed in our paper *Large-scale anomalies of the CMB in the curvaton scenario* [7]. Lastly, in Chapter 5, we investigate the possibility of local astrophysical foregrounds as the origin of the large-scale anomalies, based on the paper (in preparation) *Impact of Galactic Radio Loops on the low-l CMB anomalies* [8] and the unpublished work, *Galactic loops in the Fermi-LAT data*.

2

THE COSMIC MICROWAVE BACKGROUND FROM PLANCK

In cosmology, key data for testing hypotheses of properties of the Universe is the Cosmic Microwave Background. It is relic radiation permeating the Universe, bearing information on the state of the Universe when it was only 380,000 years old. The story of the discovery of the CMB has already taken on the patina of legend, starting with the accidental observation of it in 1964 by A. Penzias and R. Wilson. Penzias and Wilson were operating the Bell Telephone Laboratories radio antenna in New Jersey, which they hoped to use for satellite communication and radio astronomy. Here they detected an excess temperature of 3.5K, which was "isotropic, unpolarized, and free from seasonal variations" [1]. With the help of R. Dicke, J. Peebles, P. Roll and D. T. Wilkinson, the CMB was identified as the perpetrator of the excess temperature [9]. While Penzias and Wilson discovered the CMB by accident, many before them had predicted and searched for this background of early Universe photons. In 1948, R. Alpher and R. Herman predicted the presence of the CMB [10] and estimated it to at the level of a few degrees Kelvin. Others published predictions for this background of cosmic microwaves during the decades leading up to 1964. However, the general opinion was that actual detection could be very difficult if not impossible [11]. The first to claim that detection was feasible were A. G. Doroshkevich and I. Novikov, who in 1964 stated that not only should such a cosmic background exist, it should also be observable [12]. A big shift in our understanding of the Universe caused by the observation of the CMB, was the support it gave to the theory of a hot Big Bang as the beginning of the Universe.

Arno Penzias and Robert Wilson were awarded the Nobel prize in 1978 for their discovery. In his Nobel lecture [11], Arno Penzias concluded with words that hold true even today in describing modern CMB science, "Thus, the total picture seems close to complete, but puzzling gaps remain (...) One thing is clear however, observational cosmology is now a respectable and flourishing science."

This Chapter presents an overview of the physical origin of the CMB (section 2.1), the COBE, WMAP and Planck experiments that have observed it (section 2.2), the data used (section 2.3) and finally a review of the anomalies of the CMB (section 2.4).

2.1 A brief history of the CMB

In order to understand why the CMB is important for cosmology, we need to go all the way back to the Big Bang, and the very beginning of the Universe.

Since the laws of physics as we know them break down at the imagined time t = 0, we cannot say anything about this initial condition of the Universe. Amazingly enough, we can say something about the Universe when it is only a tiny fraction of a second old. At this point, we believe that the Universe expanded exponentially, during a period we call inflation. After this inflationary period, the Universe was effectively cold and empty, since all initial densities of particles and radiation had been diluted completely away by the expansion. However, the field driving the inflationary expansion decayed, spawning matter and radiation back into the Universe. Quantum fluctuations of the inflationary field during inflation play an important role in this story of the earliest Universe. These fluctuations lead to a local delay in the ending of inflation, which in turn gave rise to local density perturbations when the field decayed. These density perturbations were the initial fluctuations in the gravitational potential into which matter could accumulate and cluster into over-dense areas. The over- and under-densities in the early Universe were in turn the seeds that later evolved into all structure that we know today [13, 14].

After the inflationary field had decayed, the Universe was dominated by extremely high densities and temperatures, with a hot, relativistic plasma of particles and photons. As the Universe continued to expand, albeit no longer at an exponential rate, it cooled, allowing for the combination of quarks and gluons into hadrons. After further cooling and expansion, the next step was the combination of protons and neutrons into nuclei, which is called the Big Bang Nucleosynthesis.

We know that by looking at galaxies farther and farther away, we are looking further and further back in time. One could imagine that if we looked back far enough, we could see these earliest eras. However, this requires the path between us and the object we are trying to observe to be (relatively) unobstructed. Unfortunately, the Universe at these earliest time was not transparent to radiation. Photons had a very short mean free path, and would continuously scatter off particles, making a direct observation impossible. This also prevented the combination of nuclei into atoms, since energetic and abundant photons would break apart newly formed atoms instantly. The energy of a photon is $E = hc/\lambda$, where h is the Planck constant, c is the speed of light and λ is the wavelength. When the Universe expands, the matter density falls as the volume, R^3 , while the density of photons falls as R^4 , since their wavelength is also redshifted. As the wavelength increases (becomes redshifted) the energy decreases. At some point, the photons were thus no longer energetic enough to split apart the forming atoms. This time is called recombination, where protons and electrons combined into hydrogen atoms, and a few heavier elements. After this, the photons effectively decoupled from the matter. This is the time of Last Scattering, when the Universe changed from being opaque to being transparent to photons. From our observation point in space-time we see the relic radiation as a sphere with a "surface" of no depth, therefore denoted the Last Scattering Surface.

After decoupling, the photons traveled more or less freely through the Universe, while still losing energy (redshifting) due to cosmological expansion. Thus the radiation we see today has been redshifted to microwave frequencies, and has a thermodynamic temperature of 2.73K. We therefore call it the Cosmic Microwave Background. Could we observe this radiation again some time in the distant future, the photons would be shifted to even lower energies, well into the radio domain.

The CMB is highly uniform, but contains anisotropies at the level of $\sim 10^{-5}$ K. These anisotropies carry almost all the information we are interested in. They are fluctuations in temperature (energy) of the CMB photons, and directly reflect the structure of the gravitational potential, and thus over- and under densities, at the time of decoupling. Because photons get gravitationally redshifted when leaving a gravitational potential well, photons from over-dense areas get redshifted more than the mean, while photons leaving underdense areas get redshifted less than the mean. The early Universe density perturbations are thus imprinted into the photons released from the Last Scattering Surface. This is called the early Sachs-Wolfe effect. In this way, the CMB anisotropies are a key source of information on the early Universe. The quantity of interest when discussing the CMB signal is thus $\Delta T/T$, which describes the anisotropies: the temperature difference from the mean with respect to the mean. The CMB as observed by Planck (2015) [15] is shown in Figure 2.1.



Figure 2.1: A Mollweide projection of the Planck 2015 SMICA map of the $\Delta T/T$ CMB sky [15].

2.2 Observing cosmic microwaves

As mentioned in Chapter 1, one must go to space in order to observe the CMB, unimpaired, in many frequency bands and over the full sky. The first satellite experiment to do this was the Russian RELIKT-1 [16] launched into Earth orbit in 1983. However, they only managed to set upper limits on the anisotropy (although later re-examination of the data revealed anisotropy [17]). The first satellite experiment to actually observe the anisotropies was COBE [4], which was sent into Earth orbit in 1989 by NASA. COBE had three main instruments on board: the Differential Microwave Radiometer (DMR) for observing the anisotropies of the CMB in the bands 31.5, 53 and 90 GHz, the Far-Infrared Absolute Spectrophotometer (FIRAS) for obtaining the spectrum of the CMB and the Diffuse Infra-Red Background Experiment (DIRBE) which observed the Cosmic Infrared Background. In 2006, two of the principal investigators for the COBE experiment, J. Mather and G. Smoot, were awarded the Nobel prize in physics "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"².

While COBE was the first to observe the CMB anisotropies, the resolution of the experiment was not very high (see Figure 2.2). Spurred on by the success of COBE in observing the CMB and its anisotropies, the WMAP mission was launched in 2001 by NASA [3]. WMAP had a much better angular resolution and sensitivity than COBE, as well as the ability to observe in polarization. WMAP observed in five different frequency

²http://www.nobelprize.org/nobel_prizes/physics/laureates/2006/



Figure 2.2: Visual comparison of the resolution for the COBE, WMAP and Planck satellites. Image credit: NASA/JPL-Caltech/ESA.

bands, K (23 GHz), Ka (33 GHz), Q (41 GHz), V (61 GHz) and W (94 GHz). Building on the results from COBE and numerous balloon-borne experiments, WMAP helped revolutionize our knowledge of the CMB, and make cosmology transition into a precision science. One of the main results from WMAP and the numerous balloon-borne experiments was the temperature power spectrum of the CMB, as shown in Figure 2.3. The power spectrum is a function of multipole, ℓ , which is inversely proportional to angular scale.

After WMAP, there were multiple reasons for a new space experiment. For one, several anomalous features had presented themselves in the CMB (some already from the COBE mission, and confirmed by WMAP), which prompted discussions on whether systematics were properly eliminated. Secondly, the WMAP polarization measurements were highly contaminated by our Galaxy, and much better polarization observations in more frequency bands were needed to complement the temperature data.

Planck was a space telescope sent up by the European Space Agency in 2009, in collaboration with NASA [2]. The aim of the Planck mission was to observe the CMB with unprecedented precision in both temperature and polarization. Planck had 9 frequency bands, observed by two instruments: The Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI). The LFI observed in three frequency bands centered on 30 GHz, 44 GHz, 70 GHz. The HFI observed in six frequency bands centered on 100 GHz, 143 GHz, 217 GHz, 353 GHz, 545 GHz and 857 GHz. The detectors from



Figure 2.3: Summary of the experimental results for the CMB power spectrum, as of February 23, 2004 (figure by Max Tegmark³).

30 GHz to 353 GHz observed both temperature and polarization, whereas the 545 GHz and 857 GHz detectors only observed temperature.

The temperature power spectrum as observed by Planck 2015 is shown in Figure 2.4. Especially the small angular scales (high multipoles) are much better constrained than for WMAP. By the standard Λ CDM concordance model of the Universe, we mean a Universe comprised of dark energy (Λ), cold dark matter, baryons and radiation. This model is parametrized, and the CMB is a powerful tool to determine these parameters [5]. This model is exactly the fit we compare the observed CMB power spectrum to.

³http://space.mit.edu/home/tegmark/cmb/experiments.html



Figure 2.4: The Planck 2015 temperature power spectrum. The best-fit base ΛCDM theoretical spectrum fitted to the Planck likelihood is plotted in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1 \sigma$ uncertainties [5].

2.2.1 From temperature to polarization

While the temperature data of the CMB for many years completely dominated the scene of discoveries for CMB cosmology, one of the main objectives of Planck was to complement the temperature data with multi-frequency precision polarization observations. The CMB is expected to be linearly polarized due to Thomson scattering of the CMB photons off electrons at the time of Last Scattering.

Polarization of the CMB photons can be characterized by the Stokes parameters, Q and U, describing linear polarization. These parameters are not invariant under rotation, however, and we can therefore not create a meaningful power spectrum of the polarization from them. Instead it is possible to create a linear combination of them (as described by M. Zaldarriaga and U. Seljak in [18]), which is invariant under rotation, called E- or B-mode polarization instead of Q and U. The Planck 2015 polarization power spectra (TE and EE cross-spectra) are shown in Figure 2.2.1.

In the context of the evolution of the Universe, cosmological gravitational perturbations are an important concept. These come in three variants: scalar, vector and tensor



Figure 2.5: The Planck 2015 polarization TE and EE power spectra. The theoretical TE and EE spectra plotted in the upper panel of each plot are computed from the best-fit model of Figure 2.4. Residuals with respect to this theoretical model are shown in the lower panel in each plot. The error bars show $\pm 1 \sigma$ errors [5].

perturbations, which evolve independently of each other. Here, density and tensor perturbations are the important ones, since for most simple models of inflation, vector perturbations are not generated or decay rapidly. Density perturbations of the early Universe are scalar, and produce only E-mode polarization of the CMB. Primordial B-mode polarization, however, can only be generated through tensor perturbations. Tensor perturbations also give rise to primordial gravitational waves. An important constraint from the Planck polarization results are thus on the tensor-to-scalar polarization ratio, r. The 2015 results for r are shown in Figure 2.6, comparing the limits set by data to predictions by various inflationary models.



Figure 2.6: Constraints on the tensor-to-scalar ratio. The contours show the marginalized joint 68% and 95% CL regions from Planck in combination with other data sets, compared to the theoretical predictions of selected inflationary models [19].

The work in this thesis only considers CMB temperature data, and not polarization data. This is in part because the temperature dataset is so rich that it is a source of continuing investigation, but also due to a time constraint: the Planck polarization data came out in February/March of 2015, only a few months before the deadline of this thesis. A lot of the analyses and papers presented in this thesis could in principle be repeated with polarization data. However, a problem that was presented in relation to the Planck 2015 data release, was large angle systematics in the polarization data, which were not well understood. The polarization angle [20],

$$\Phi = \frac{\arctan(U/Q)}{2} \tag{2.1}$$

13

for the Planck 2015 SMICA polarization Q and U maps, smoothed by 1 degree is shown in Figure 2.7. The low multipoles ($\ell < 50$) are highly contaminated by systematics, apparent through the very non-random structure of the signal, whereas only the Galactic plane appears peculiar for the higher multipole range. While most of the polarization data has been released by Planck in 2015, much work still remains to be done, e.g. regarding the systematics of low multipoles. Another data release and corresponding papers will come out, probably in 2016, shedding even more light on full sky polarization in the Planck frequencies. This will also be crucial for the investigation of low multipole anomalies in the polarization data, as well as the observation of primordial B-modes.



Figure 2.7: The Planck 2015 SMICA map polarization angle. Left: $\ell < 50$. Right: $\ell = 50 - 200$.

2.3 CMB data

When we observe in the microwave domain, the resulting maps of the sky at the observed frequencies (mentioned in Section 2.2 for the different experiments) also contain other emission than just the primordial CMB. Especially the Galactic plane is highly dominated by other emission, see Figure 2.8. The main source of extra emission besides the CMB comes from our own Galaxy, where dust and free electrons emit photons in the microwave frequency range. Thus, before one can do statistical tests on the CMB data, a separation of these components from the true CMB signal is needed.

There are several versions of the CMB data set available from different experiments, both for small patches and for the full sky. Although the observed quantity, the CMB, is the same, the systematics and methods of cleaning differ from experiment to experiment. It is crucial for drawing conclusions on the cosmology that the data set used is reliable and unbiased by contaminants. Here, we therefore review the component separation methods used to isolate the CMB signal, and touch upon the data that has been used for the various analyses in this thesis. The data used include frequency maps, component



Figure 2.8: Frequency maps from Planck 2015. The maps are shown in galactic coordinates.

maps, constructed CMB maps and masks from the Planck and WMAP missions. Also used are Fermi-LAT gamma-ray data. Due to the extent in time of the work presented, the data used are not the same versions. For the Planck maps, both the 2013 data release and the 2015 data release have been used. For WMAP, the 7 year data and 9 year data were used. Many of the analyses presented in this thesis compare with simulations of the CMB for assessment of significance. Since the Planck CMB simulations were not accessible outside the collaboration, some of the published work compares to random Gaussian simulations created with HEALPix based on the CMB power spectrum. Some of the work—either internal Planck work or work done after the release—compares with the official simulations from Planck.

2.3.1 Foregrounds

Observing in many frequency bands allows for a separation of components present in the maps by using information on their frequency dependence. For low frequencies, synchrotron radiation and free-free emission are the main contributors, together with spinning dust. At high frequencies thermal dust dominates, see Figure 2.9. These components also play an important role for the study of astrophysical objects as well as the Interstellar Medium in our own Galaxy, for example in [21–23], with Planck. The frequency maps are scaled to the thermodynamical temperature of the CMB, K_{CMB} , and the CMB is thus

approximately constant for all of the frequency maps. This means that subtracting two frequency maps should give a CMB free difference map. For 545 GHz and 857 GHz the CMB is effectively not present, and thus these maps are presented in surface brightness, $MJy \ sr^{-1}$ (for example in Figure 2.8).



Figure 2.9: Brightness temperature as a function of frequency and astrophysical foreground components. Each component is smoothed to an angular resolution of 1° *FWHM, and the lower and upper edges of each line are defined by masks covering 81 and 93% of the sky, respectively [24].*

Component separation takes advantage of the frequency dependence of these components, to separate them from each other. Planck uses four different methods to separate out the CMB signal from the foregrounds: SMICA, NILC, SEVEM and Commander. As opposed to the other three, Commander (see below) also produces templates of the other components, which is very important for studying the nature and morphology of the different foregrounds. This naturally requires that one has enough frequency bands of observation for each component. If the spectral index (the slope of the curves in Figure 2.9) varies over the sky for one or more components, one can quickly run into a deficit of frequency bands with regards to the degrees of freedom. Details of the component separation methods can be found in *Planck 2013 results. XII. Component Separation* [25] and *Planck 2015 results. X. Diffuse component separation: Foreground Maps* [24].



Figure 2.10: The Planck AME 1 (top) and AME 2 (bottom) maps. Both maps are smoothed with a 1° Gaussian kernel. AME 1 is at the reference frequency of 22.8 GHz while AME 2 is at the reference frequency of 41 GHz, with a peak frequency of 33.35 GHz.

Spinning dust

The Commander component separation method (see below) produces two "Anomalous Microwave Emission" (AME) maps, see Figure 2.10. AME was discovered at the time of COBE as an excess emission that correlated spatially with thermal dust [26, 27]. It was suggested that it could be connected with tiny spinning dust grains which produce electric dipole emission [28–30], and also that these tiny dust grains could be Polycyclic Aromatic Hydrocarbons (PAHs). The polarization of AME is difficult to determine since the AME regions are dominated by polarized synchrotron emission, but the best Planck estimate is at a few percent [21]. The spectral energy distribution of the spinning dust has been very successful to explain AME in Galactic clouds [31]. It is thus believed that a spatial map of the spinning dust component shown in Figure 2.9 could be the AME map [31]. The spinning dust has recently come into discussion, however. In *A Case Against Spinning PAHs as the Source of the Anomalous Microwave Emission* [32], B. T. Draine and B. S. Hensley argue that magnetic dust [33, 34], rather than the spinning dust, is the origin of the AME.

2.3.2 CMB maps from component separation

The four component separation methods for constructing the CMB map are outlined in Table 2.1, and described in more detail below. The resulting maps (from Planck 2013) can be seen in Figure 2.11. These maps are supposed to represent the true CMB signal, in principle free from foreground contamination. In reality we know that at least the Galactic plane is contaminated, which can even be seen in the maps. Each map comes with a confidence mask, which shows which parts of the constructed CMB map can be trusted to be free of contaminants, see Figure 2.12.

Characteristic	Commander-Ruler	NILC	SEVEM	SMICA
Method	Bayesian parameter estimation	Internal linear combination	Internal template fitting	Spectral parameter estimation
Domain	Pixel	Needlet	Pixel	Spherical harmonic
Channels [GHz]	30–353	44-857	30-857	30-857
Effective beam FWHM [arcmin]	~ 7.4	5.0	5.0	5.0
ℓ_{\max}	none	3200	3100	4000

Table 2.1: Overview and comparison of component separation algorithms [25].



Figure 2.11: The Planck 2013 CMB maps produced by the four different component separation methods. Note that SMICA has been inpainted by a constrained Gaussian realization in the Galactic plane, the large Magellanic cloud and other extended point sources [25].



Figure 2.12: Confidence masks by Planck 2015. Left: The SMICA confidence mask. Right: The common mask, a combination of the confidence masks for all four component separation methods. Blue areas are zero, green areas are 1.

WMAP ILC The Internal Linear Combination map (ILC) is the WMAP CMB product [35]. It uses weighting of the observed frequency maps by minimizing the variance in pixel space to obtain a map that is as clean as possible of foregrounds. A frequency map can be expressed as,

$$y_i(p) = s(p) + f_i(p) + n_i(p)$$
 (2.2)

where s(p) is the CMB, $f_i(p)$ are the foregrounds and $n_i(p)$ is the noise, for each channel *i* [36]. We may then try to reconstruct the CMB, s(p), through combinations of these frequency maps,

$$\hat{s}(p) = \sum_{i} w_i(p) y_i(p) \tag{2.3}$$

For the WMAP ILC method, the weights are not pixel dependent, and $\sum_i w_i = 1$. The method then employs minimization of the variance of the $\hat{s}(p)$ map to construct the least contaminated map of the CMB. For the WMAP ILC method, The w_i 's are calculated in 12 different regions, 11 of which are inside the galactic plane.

There are several versions of the ILC map provided by the WMAP team, one for each release. WMAP has released 5 data-bundles: 1 year data, 3 year data, 5 year data, 7 year data and 9 year data, all cumulative, taking advantage of more and more mission observations. However, one should note that the pipeline used to produce the ILC maps has differed from year to year, which makes direct comparison difficult.

Planck SMICA The SMICA map uses spectral parameter estimation in the spherical harmonic domain. It also uses minimization of the variance, but in multipole space instead of pixel space. Figure 2.13 the resulting weights given to the Planck 9 frequency maps as a function of multipole are shown.

Planck NILC The Needlet Internal Linear Combination method (NILC) uses the minimization of variance in needlet space rather than pixel space. This means that weights are allowed to vary over the sky and also in multipole space.

Planck SEVEM The Planck SEVEM method uses a template fitting method to fit foregrounds and isolate the CMB signal in pixel space. The templates are constructed from combining neighboring frequency maps.

Planck Commander Commander uses Bayesian Gibbs sampling to do parametric component separation in pixel space. Besides a map of the CMB, the Commander method also provides component maps of Galactic astrophysical foregrounds.



Figure 2.13: The SMICA weights assigned to the 9 Planck 2015 frequency maps, as a function of multipole [37].

2.3.3 Spherical harmonics decomposition

The CMB is a signal on a sphere, and therefore a natural thing to do is to decompose it into spherical harmonics,

$$S(\theta,\phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\phi)$$
(2.4)

and equivalently,

$$a_{\ell m} = \int_{\Omega} S(\theta, \phi) Y^*_{\ell m}(\theta, \phi) d\Omega$$
(2.5)

where $S(\theta, \phi)$ is the signal in direction (θ, ϕ) on the sky. The $a_{\ell m}$'s are the spherical harmonic coefficients. ℓ is the multipole of the spherical harmonic. The anisotropies of the CMB are believed to originate from random Gaussian quantum fluctuations. Thus the spherical harmonic coefficients are therefore supposed to be independent, and obey

$$\langle a_{\ell m} \rangle = 0 \tag{2.6}$$

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = \tilde{C}_{\ell} \delta_{\ell \ell'} \delta_{m m'}, \qquad (2.7)$$

where the average is taken over an ensemble of universes and \tilde{C}_{ℓ} is the power spectrum. We do not have the opportunity to observe an ensemble of universes however. Instead we can estimate the power spectrum of the signal by

$$C(\ell) = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2.$$
(2.8)

If the signal is randomly Gaussian, the power spectrum fully contains all information. The variance of the observed power spectrum can, under the assumption of Gaussianity, be expressed as,

$$\operatorname{Var}(C(\ell)) = \frac{2}{2\ell+1}C(\ell)^2.$$
 (2.9)

This is the inherent uncertainty due to the fact that we only have one observable Universe, and not an ensemble to average over, and is called cosmic variance.

2.4 CMB anomalies

Other properties of the CMB that we may fit to our model of the Universe, apart from the power spectrum, is the assumption that on large scales the Universe is homogeneous and isotropic, and that the CMB fluctuations are Gaussian. Statistical tests of the CMB are performed to test the assumptions of exactly Gaussianity, isotropy and other properties [38]. Some of these tests have revealed the so-called CMB anomalies, mentioned in Chapter 1. These anomalies are statistical deviations from the Λ CDM model of the Universe, all at the level around $\leq 3\sigma$.

Some of these anomalies have been reported as early as for the COBE data, but most were discovered and discussed in connection to WMAP data. In the review article *Large-Angle Anomalies in the CMB* [39] C. J. Copi, D. Huterer, D. J. Schwarz and G. Starkmann discuss the anomalies pertaining the large scales of the sky. Not long after, together with the 7 year WMAP release, a paper titled "*Seven-year WMAP Observations: Are There Cosmic Microwave Background Anomalies*" [40] was published. Here the WMAP team also reviewed and discussed the probability and significance of the reported anomalies of the CMB. In table 2.2 an overview of reported anomalies is given.

There are many attempts in the literature to attribute these anomalies to systematics, primordial origin, foreground emission, or simply cosmic variance. A major result from Planck was actually the confirmation of a collection of the WMAP anomalies, namely the quadrupole-octupole alignment, hemispherical power asymmetry, dipolar modulation, parity asymmetry, and the WMAP Cold Spot. This confirmation from an experiment

Name	Description	References
Lack of large an- gular correlations	The two-point correlation function is close to zero on large angular scales.	[38, 41–45]
WMAP cold spot	Unusually cold area with respect to its sur- roundings, in the vicinity of the south eclip- tic pole.	[46-49]
Low $\ell = 2$ power	The power of the quadrupole is very low, compared to the Λ CDM power spectrum (see however [50])	[51, 52]
Point-parity asym- metry	Asymmetry between the power in even and odd multipoles in the temperature power spectrum.	[53, 54]
Axis-of-evil	The peculiar alignment of the quadrupole $(\ell=2)$ and octupole $(\ell=3)$.	[55–60]
Hemispherical power asymmetry	Asymmetry between the total power on the North/South ecliptic hemispheres.	[42, 61–65]
Dipole modulation	Cosine modulation of the CMB signal, with direction close to the south ecliptic pole.	[42, 65, 66]

Table 2.2: CMB anomalies.

with completely different systematics, scan strategy and observation techniques led to the belief that systematics were probably not the culprits of the anomalies. Although the anomalies have been observed in the temperature data, their origin, if not cosmological, could also prove to be main sources of contamination in polarization data. Therefore, the understanding of their origin is potentially crucial for investigating the E-modes and B-modes and potential primordial non-Gaussianities.

There is an even more fundamental question: whether (some of) these anomalies have a common origin or are statistically independent. If we believe that all the anomalies originate from the same source, it would be even more important to discover their origin. In the opposite case, where all the anomalies are statistically independent, the problem is how one peculiar realization of the primordial random field can contain all these anomalies. It is important to note, though, that there is some degree of a-posteriori bias involved when it comes to the study of the CMB anomalies. Paraphrasing Ronald Coase, *"if you torture the data long enough, it will confess to almost anything"*. It is thus important to exercise care when interpreting anomalous statistical results of the CMB.

2.4.1 Large scale anomalies

Most of the anomalies mentioned in table 2.2 are connected to the largest scales of the sky, i.e. to the lowest multipoles. This thesis mainly concerns itself with the possible origins of this category of anomalies, and thus a review of the large scale anomalies is appropriate. Chapter 4 mainly looks at the point-parity asymmetry, while Chapter 5 takes a broader perspective and also includes considerations on the impact of Galactic foregrounds on the dipole modulation, the quadrupole-octupole alignment and amplitude, as well as the point-parity asymmetry.

Missing large angular correlation

The two-point angular correlation function, $C(\theta)$ is the pixel space equivalent of the power spectrum. Given that the signal is isotropic, it is invariant under all rotations, and the two-point correlation is defined as,

$$\langle T(\hat{\mathbf{n_1}})T(\hat{\mathbf{n_2}})\rangle \equiv \tilde{C}(\theta) = \frac{1}{4\pi} \sum_{\ell} (2\ell+1)C_{\ell}P_{\ell}(\cos\theta),$$
 (2.10)

where again $\langle \rangle$ indicates an average over universes [43]. For our own Universe we may estimate this quantity by,

$$C(\theta) = \overline{T(\hat{\mathbf{n_1}})T(\hat{\mathbf{n_2}})}.$$
(2.11)

The anomaly is not so much a mismatch between the predicted two-point correlation function and the observed one, with and without masking, although at the very largest scales there seems to be some discrepancy. Rather it is the peculiar feature that at angles of > 60° the correlation is consistent with zero. Like many of the other anomalies, it is at the level of a few σ . The missing correlations at angles of $\theta > 60°$ was first reported as an anomaly in [41], in agreement with previous COBE results [67]. It has been discussed in connection with every CMB map release since. In [40], however, the WMAP team claimed that the missing large angular correlation is simply a chance alignment effect, combined with a bad a-posteriori choice of statistics.

The Planck 2013 results claim no inconsistency between model and data (*p*-value of ~ 85%), but these Planck results did not test for the lack of correlations at $\theta > 60^{\circ}$, but rather of the general fit between model (black line) and the CMB maps. In [45], Copi et al. test exactly the lack of large-angle correlation for the Planck 2013 data and find a *p*-value for the Planck 2013 SMICA map of 0.202%. This is consistent with previous results that reported a significance at the level of < 5% (E.g. in [44] they find a *p*-value

of 0.025%). The Planck 2015 results are shown in Figure 2.14. Again Planck find no inconsistency between model and observation, in this paper actually testing the lack of large-angle correlations. They do however comment that the fit seems to be too good (*p*-value of 98.1% for SMICA) and that this indicates an overestimation of the variance of the two-point correlation function.

Future testing of the two-point correlation function for polarization will be important for determining whether this is a true anomaly or a statistical fluke [68].



Figure 2.14: Two-point correlation function for the Planck 2015 CMB maps at $N_{side} = 64$ [69]. The black solid line indicates the mean determined from 1000 SMICA simulations. The shaded dark and light gray regions indicate the corresponding 68% and 95% confidence regions, respectively.

Dipole modulation and North/South hemispherical asymmetry

Dipole modulation refers to the observation that the CMB seems to be modulated by a dipole, i.e. a cosine function [42, 65, 66]. The CMB itself has no intrinsic dipole, since it is fully attributed to the motion of the satellite with respect to the CMB rest-frame.

Dipole modulation is a violation of statistical isotropy, and the notion that there is no preferred direction in the Universe—also known as the Copernican principle. Following [40] and [65] dipole modulation is defined as,

$$T(\mathbf{n})_{modulated} = (1 + \mathbf{w} \cdot \mathbf{n})T(\mathbf{n})_{unmodulated}, \qquad (2.12)$$

where $T(\mathbf{n})$ is the CMB signal in the direction \mathbf{n} . The modulation is parametrized by \mathbf{w} , with a direction \hat{w} and amplitude A, $\mathbf{w} = A\hat{w}$.

Planck employs several methods to study the dipole modulation. One of them (from the 2015 results) follows the use of local variance, implemented for Planck 2013 by Y. Akrami et al. in [70]. It considers discs of various sizes placed on the (masked) CMB sky, and calculates the variance in each disc. From this a local-variance map is produced, with correction for the average variance. One can then fit a dipole to these local-variance maps [69]. In Figure 2.15 the result for the direction of this modulation for the 2013 and 2015 Planck results is shown. The direction is the same as was found for the WMAP releases.

Planck finds the amplitude of the dipole modulation to be significantly deviating from expectation, albeit depending on the component separation method and smoothing scale. The significance goes from 1.1σ for SMICA smoothed by FWHM=8° up to 3.5σ for Commander at a smoothing scale of FWHM=5° for the 2013 results [38]. In the Planck 2015 results [69] they employ a Butterworth high-pass multipole filter instead of Gaussian smoothing,

$$H(\ell) = \frac{(\ell/\ell_0)^4}{1 + (\ell/\ell_0)^4}.$$
(2.13)

They report a *p*-value of < 0.1% for all methods at a $\ell_0 = 5$ and disc size of 8°. The highest *p*-value is for $\ell_0 = 30$ where they obtain a *p*-value of 1.8% for Commander and SEVEM.

The North/South hemispherical asymmetry is naturally connected to the dipole modulation, but refers to the lack of large scale power on the northern ecliptic hemisphere. In the 2013 Planck *Isotropy and statistics of the CMB* paper [38] they claim a significant hemispherical power asymmetry with a *p*-value at the level of $\sim 1 - 3\%$. For 2015 they confirm the results of the 2013 analysis, with *p*-value ranging from 0.8% for SEVEM at $N_{side} = 32$ to 2.9% for Commander at $N_{side} = 16$.


Figure 2.15: Top: Dipole modulation direction for Planck 2013 [38]. The colored area indicates the 95% confidence region for the Commander solution, while the dots shows the maximum-posterior directions for the other maps. Bottom: local-variance dipole directions for the Planck 2015 SMICA map. The colors, as indicated by the color bar, correspond to different values of the high-pass filter central multipole ℓ_0 . The size of a marker disc corresponds, from small to large, to the size of the disc used in the analysis [69].

Alignment of the quadrupole and octupole

Popularly known as the "axis of evil", the alignment of the quadrupole (ℓ =2) and octupole (ℓ =3) is a peculiarity in directions [55, 56]. Using multipole vectors [58] one can define ℓ directions for a multipole which span out $\ell(\ell - 1)/2$ planes. For the quadrupole this gives one plane, whereas the octupole has three planes. For the observed CMB these three planes are very aligned, meaning that the octupole is very planar. The (almost) single octupole plane aligns almost perfectly with the quadrupole plane, which can even be seen by eye in Figure 2.16. The alignment angle for the Planck 2013 data is 12.3° at a *p*-value of 3.2%. Another peculiar thing about this alignment of quadrupole and octupole is that it appears to be aligned with the ecliptic plane, and orthogonal to the direction of the dipole modulation.



Figure 2.16: The alignment of axes of the quadrupole (top) and octupole (bottom) for the Planck 2013 SMICA map (left) and Planck 2015 SMICA map (right). The plus indicates the axis of the quadrupole, the star the axis of the octupole plane. The diamonds represent the axis of the quadrupole after kinematic quadrupole corrections [38]. Temperature range is $\pm 35\mu K$.

In Figure 2.16 (right) the quadrupole and octupole for Planck 2015 are shown. Their alignment angle is 11.2° , with a *p*-value of 1.4%, see Section 5.2.2.⁴

Another reported anomaly related to the quadrupole is the low power compared to the Λ CDM expectation value. In the WMAP 9 year "*Final maps and results*" paper [50], the

⁴The Planck 2015 *Isotropy and Statistics* paper does not quote the alignment nor the significance. The numbers quoted here are from the analysis presented in Section 5.2.

WMAP team claims that the level of the quadrupole power is not significantly low. However, if some of the large scale emission in the CMB map is actually due to foregrounds or other systematics, the power of the quadrupole could be even lower than its current level.

Point-parity asymmetry of the power spectrum

Point-parity asymmetry describes the observation that there is more power in odd multipoles than in even ones in the CMB temperature power spectrum. The estimator of point-parity asymmetry, as introduced in [53, 54], is given by

$$g(\ell) = \frac{\sum_{L=2}^{\ell} L(L+1)C(L)^{+}}{\sum_{L=2}^{\ell} L(L+1)C(L)^{-}}$$
(2.14)

where $\ell \geq 3$. $C^{+/-}$ denotes the power spectrum of even (+) or odd (-) multipoles, respectively. The estimator is cumulative. In Figure 2.17 the results for this estimator for the Planck 2013 data are shown [38]. The *p*-value, the probability to obtain the same value of $g(\ell)$ or lower for simulations, is lowest around $\ell = 25$, with a value of $\sim 0.5\%$ for SMICA.

In the Planck 2015 results the estimator in Eq.(2.14) has been slightly revised, in order to compensate for the fact that for each ℓ , an uneven number of even and odd multipoles are summed over. They use the $R(\ell_{max})$ estimator [71],

$$R(\ell_{max}) = \frac{\ell_{tot}^{-}}{\ell_{tot}^{+}} \frac{\sum_{\ell=2}^{\ell_{max}} \ell(\ell+1)C(\ell)^{+}}{\sum_{\ell=2}^{\ell_{max}} \ell(\ell+1)C(\ell)^{-}},$$
(2.15)

where $\ell_{max} \ge 3$, $C(\ell)^{+,-}$ is the CMB power spectrum for even (+) or odd (-) multipoles, and $\ell_{tot}^{+,-}$ is the total number of even or odd multipoles in the summation up to ℓ_{max} . The results are shown in Figure 2.17 with the lowest *p*-value again $\ell \sim 25$ with a value of 0.2%.

The investigation of the origin of point-parity asymmetry is central in this thesis, since the work presented was the natural continuation of previous projects where we looked for either signatures or possible origins of the point-parity asymmetry. In [72] we found a non-randomness of the CMB phases, which is not expectable, and support for the claim of parity asymmetry in the power spectrum. In [73] we found evidence of Solar System contamination of the CMB due to Kuiper Belt Objects, which when cleaned out of the CMB maps influences both parity asymmetry, dipole modulation and quadrupoleoctupole alignment. Since these investigations led us to believe that Galactic or Solar System foregrounds possibly still contaminated the CMB, we broadened our scope to see the influence on other anomalies than the parity asymmetry. This is the subject of Chapter 5.



Figure 2.17: Planck 2013 point-parity asymmetry results. Top: The $g(\ell)$ estimator from Eq.(2.14). Bottom: the corresponding p-value when comparing to simulations [38].



Figure 2.18: Planck 2015 point-parity asymmetry results. Top: The $R(\ell_{max})$ estimator from Eq.(2.15). Bottom: the corresponding p-value when comparing to simulations, reported in percentages [69].

3

INVESTIGATING STATISTICAL PROPERTIES OF THE CMB

The prerequisite for determining properties of the CMB, as well as the anomalies, is that the data under investigation is consistent and as clean as possible. This starts with the consistency and calibration of the frequency maps, but also for the derived CMB maps themselves. This chapter concerns itself with the statistical consistency of the CMB data. The approach that presented here does not concern itself with the technical process of map-making itself, but rather with the manifestations systematics may have in the end products. In this way, we investigate consistency of the CMB maps delivered by Planck 2013 and WMAP, as well as a preliminary Planck CMB temperature power spectrum.

The work presented here partly consists of a project done in the Winter of 2012/2013, during the final months before the first Planck release. This resulted in the paper *Consistency tests for Planck and WMAP in the low multipole domain* [6], done in collaboration with Hao Liu and Martin Hansen. The paper investigated the internal consistency of the three published 2013 Planck CMB maps (SMICA, NILC and SEVEM), and the consistency between the Planck and WMAP CMB maps. The contents of this paper is presented in Section 3.1.

At the time of publication, the first Planck data [74] had just been released, as had the 9 year data from WMAP [50]. Since the publication of the paper others have also discussed the consistency and possible problems relating to this. In the paper *Large-scale alignments from WMAP and Planck* [75], Copi et al. discuss the alignment anomaly of the CMB in the context of discrepancies between data releases for WMAP and Planck. In *On the coherence of WMAP and Planck temperature maps* [76], A. Kovács et al. looked at the consistency of phase coherence for WMAP and Planck CMB maps. They found good consistency of the SMICA map with the WMAP Q,V and W maps. They also confirmed one of the findings in our paper of the dipole-like signature in the SMICA-ILC9 difference map.

The other part of the work presented here are tests that were performed in late 2013 for the Planck collaboration. These involved doing internal testing of the consistency of the statistical properties of the SMICA power spectrum, and determining whether they were in agreement with the results from Monte Carlo simulations. This work resulted in an unpublished internal report that was used for the further optimization of internal products. In Section 3.2 some of the results from this report are shown.

3.1 Consistency tests for Planck and WMAP in the low multipole domain

Since Planck and WMAP employ two different instrumental approaches to the observation of the sky, we want to do consistency checks between experiments as well as internally in a single experiment, to verify that the maps we believe to represent the clean CMB are not contaminated by instrumental effects and systematics. We therefore test the internal consistency and differences between the three released Planck 2013 CMB maps (SMICA, SEVEM and NILC, see Figure 3.1) and the differences between the WMAP ILC 9 year and 7 year maps (ILC9 and ILC7) [77]. Furthermore, we wish to test the external consistency between the WMAP ILC9 map and the Planck NILC map. The basic assumption here, is that the difference between two constructed CMB maps (the 'difference map') contains any residual non-CMB contributions (such as noise, systematic errors, foregrounds etc.) that ought to be uncorrelated with the true, primordial CMB signal.

Since we are faced with several different sky maps all in principle depicting the CMB signal (see Section 2.3.1), we must take under consideration that they contain some element of contamination. Thus, the three Planck maps as well as the WMAP ILC maps are likely not perfect representations of the true primordial CMB, but contain an intrinsic CMB component, c, and a small non-cosmological component, n, which is due to noise, foregrounds, systematics etc. If we subtract two maps we will be left with a difference map, d, which is only composed of a difference in contaminants, Δn . In a spherical harmonics decomposition we can write this as

$$a_{\ell m}^{map} = c_{\ell m} + n_{\ell m}$$

$$d_{\ell m} = a_{\ell m}^{map1} - a_{\ell m}^{map2} = \Delta n_{\ell m},$$
 (3.1)

where $a_{\ell m}^{map}$ refers to a specific map (WMAP or Planck). If the map is clean of contaminants (i.e. $n_{\ell m}^{map1} = 0$) we would not expect a significant correlation between $a_{\ell m}^{map1}$ and $d_{\ell m}$, because a pure CMB signal should not be correlated significantly with noise, systematics or foreground residuals.

We calculate the level of cross-correlation in pixel space,

$$K_p = \frac{\sum_{i} (x_i - \bar{X})(y_i - \bar{Y})}{\sqrt{(\sum_{i} (x_i - \bar{X})^2)(\sum_{i} (y_i - \bar{Y})^2)}},$$
(3.2)

where x_i and y_i are the values of pixel *i* for the two maps respectively and \bar{X} and \bar{Y} are the mean pixel values for the two maps. As some residuals of the Galactic plane are definitely still present in the maps, we mask out the Galaxy using the WMAP KQ85 9yr mask [50], in order to see the effect of contaminants in the rest of the map. Thus, the sum over *i* is only over unmasked pixels. Note that the sign of the correlation coefficient is not relevant, since the choice of which map to subtract from the other is interchangeable. Also, bear in mind that the power of the difference map is not very important for this investigation. What we are truly testing here is the morphology of the maps, and the estimator K_p shows the level of similarity of the morphology of the two maps.

We estimate the significance of the correlations by comparing with the correlation between randomly simulated CMB maps and the difference maps: NILC-SMICA, NILC-SEVEM, SMICA-SEVEM. We thus repeat the cross-correlation procedure using 10,000 random Gaussian simulations based on the Λ CDM theoretical power spectrum created using HEALPix.

3.1.1 Consistency tests of Planck maps

For the consistency tests of the three Planck 2013 CMB maps SMICA, NILC and SEVEM (shown in Figure 3.1) we first create the difference map by subtracting the three Planck maps from each other in pixel space. We have three combinations of difference maps: the difference between NILC and SMICA (denoted NILC-SMICA), the difference between NILC and SEVEM (denoted NILC-SEVEM) and the difference between SMICA and SEVEM (denoted SMICA-SEVEM). The three difference maps have $l_{max} = 100$, and a resolution corresponding to $N_{side} = 128$. In Figure 3.2 both the unmasked difference maps and the same maps with the WMAP KQ85 9yr mask applied are shown. Similar maps can be found in [25], albeit with a different color scheme and other temperature bounds.



Figure 3.1: Top: Planck 2013 NILC map. Middle: Planck 2013 SMICA map. Bottom: Planck 2013 SEVEM map. All with an $\ell \leq 100$.



Figure 3.2: The difference maps (left), and masked with the WMAP KQ85 9yr mask (right). Top: the NILC-SMICA difference map. Middle: the NILC-SEVEM difference map. Bottom: the SMICA-SEVEM difference map.

Using Eq. (3.2) we now calculate K_p , the cross-correlation coefficient between each input map and the relevant difference map. We assess the significance of K_p by comparing with the results for 10,000 random simulations. The results are presented in Figure 3.3. We see that the Planck maps only correlate weakly with their respective difference maps, and are well consistent with simulations. We attribute this to the high similarity between the Planck maps (see Figure 3.2) outside the Galactic mask, making the numerator in Eq.(3.2) small. In conclusion, the three Planck maps are very consistent with each other. The numerical values are shown in Table 3.1.



Figure 3.3: Cross-correlation coefficients compared to 10,000 simulated maps. Top left: NILC-SMICA. Top right: NILC-SEVEM. Bottom: SMICA-SEVEM. Red line: NILC, green line: SMICA, light blue line: SEVEM.

	NILC-SMICA		NILC-SEVEM		SMICA-SEVEM	
	K_p	Percentage	K_p	Percentage	K_p	Percentage
NILC	0.02294	23.4%	0.01485	36.0%		
SMICA	-0.007667	41.0%			0.01518	35.4%
SEVEM			-0.03536	20.6%	-0.04156	16.7%

Table 3.1: Numerical values of the cross-correlations for Figure 3.3. For each difference map, the table shows the value of K_p , and the percentage of the 10,000 simulations that have a higher (or for $K_p < 0$: lower) value of K_p .

3.1.2 Consistency tests of WMAP ILC9 and ILC7 maps

We now turn our attention to the ILC9 in comparison with the ILC7. The weights in the construction of the ILC9 have been improved from the ILC7 through refinement of the estimations for pixel noise, calibration and beam profiles (see [50] for details). The ILC9 map is thus expected to be superior to the ILC7 through 2 additional years of data taking as well as optimization of the method of construction.

The ILC9-7 difference map is shown in Figure 3.5 (top). The map is dominated by a dipole (see bottom figure), which is closely aligned with the well known kinematic dipole. The same feature is present in the difference map between the 7 year and 5 year ILC map, as reported in [78]. The Galactic plane is clearly visible in the map, as are selected point sources. Therefore we mask it with the KQ85 9yr mask before doing the cross-correlation, as we did in the case for the Planck maps.

We compute the cross-correlation between the ILC9-7 difference map and ILC9 and ILC7, respectively. The results are presented in Figure 3.4, and the numerical values for the cross-correlation are presented in Table 3.2. We see that ILC9 cross-correlates much stronger with the difference map than ILC7, and that the ILC7 is in agreement with the distribution of the 10,000 random simulations, while the ILC9 is not.



Figure 3.4: Cross-correlation coefficient compared to 10,000 simulated maps with the ILC9-7 difference map. Red: ILC7. Purple: ILC9.

	K_p	Percentage		
ILC9	0.1120	< 0.01%		
ILC7	0.01597	26.5%		

Table 3.2: Numerical values for Figure 3.4. K_p is the total cross-correlation coefficient for the map. Right: the percentage of 10,000 simulations with a higher value of K_p .



Figure 3.5: Top: The ILC9-7 difference map. Middle: the masked difference map (WMAP KQ85 9yr mask). Bottom: Dipole (l = 1) of the ILC9-7 difference map.

3.1.3 Consistency tests of Planck NILC and WMAP ILC9 maps

We now turn to an investigation of the difference map between the Planck NILC map and the WMAP ILC9 map. We select the Planck NILC map for the comparison, since the NILC method is the most similar in nature to the ILC method (see for instance [25] and Section 2.3.1). Since the WMAP ILC9 map has been smoothed at the level of 1°, we smooth the NILC at the same level. The difference map is shown in Figure 3.6.



Figure 3.6: Top: the NILC-ILC9 difference map. Bottom: the masked difference map.

In the difference map we clearly see the Galactic plane, and some features in the lower left quadrant of the map. This is similar to the dipole clearly seen in Figure 3.5, but since we are now subtracting the ILC9 map, the sign of the dipole is changed. It is evident that the ILC9 contains an enhanced dipole, both in comparison with the WMAP ILC7 and with the Planck NILC map.



	K_p	Percentage		
NILC	-0.0606	5.24%		
ILC9	-0.2362	< 0.01%		

Figure 3.7: Cross-correlation coefficients compared to 10,000 simulated maps for the NILC-ILC9 difference map. Red: NILC. Purple: ILC9.

Table 3.3: Numerical values for Figure 3.7. K_p is the total cross-correlation coefficient for the map, compared to the percentage of the 10,000 simulations with a lower value of K_p .

In Figure 3.7 we show the result of the cross-correlations for the difference map and the NILC and ILC9 map respectively, in comparison to the 10,000 simulated maps. Numerical values are presented in Table 3.3. The resolution, mask and maximum *l*-value are similar to those of the previous tests. We see a strong (anti-)correlation between the ILC9 and the NILC-ILC9 map, in comparison with the simulations. The cross-correlation coefficient for the NILC is in reasonable accordance with the simulations. Taken together with the results for ILC9-7 in the previous section, this indicates that the ILC9 map includes a larger amount of non-CMB residuals than the ILC7.

3.2 Consistency of the SMICA power spectrum

Following the work on consistency in pixel space, we are interested in the consistency of the CMB power spectrum. This is especially interesting, since the point-parity asymmetry of the CMB power spectrum is one of the CMB anomalies. Consistency and quality of the power spectrum is thus crucial for determining the origin of the point-parity asymmetry. Since point-parity asymmetry is concerned with the difference in power between even and odd multipoles, we do our consistency analysis on even and odd multipoles separately. The data used for this analysis was the Planck internal data version δ DX9 (which were not published). The simulations used were the FFP6 Monte Carlo simulations of SMICA. The Planck 2015 published data are version DX11, and FFP8 or FFP9.

In order to determine the consistency between the SMICA power spectrum and corresponding simulations we looked at three statistical properties, namely variance, skewness and kurtosis. Since the theoretical CMB power spectrum is the average of a hypothetical statistical ensemble of universes, the actual observed power spectrum fluctuates around it, as can be seen in Figure 3.8. We therefore performed these statistical tests on the distribution of the residuals between the theoretical power spectrum and the observed one, $\sqrt{\ell + 0.5} \Delta C_{\ell} / C_{\ell}^{th}$, where $\Delta C_{\ell} = C_{\ell}^{th} - C_{\ell}^{TT}$ and $\sqrt{\ell + 0.5}$ suppresses the spread due to cosmic variance.



Figure 3.8: The Planck Λ CDM best fit curve C_{ℓ}^{th} (black) with the δ DX9 SMICA TT power spectrum C_{ℓ}^{TT} (green). Bottom panel: The residual $\sqrt{\ell + 0.5} \Delta C_{\ell} / C_{\ell}^{th}$.

We wish to investigate the statistical properties of the residuals $\sqrt{\ell} + 0.5 \Delta C_{\ell}/C_{\ell}^{th}$, because we expect no systematic deviation from random fluctuations about the theoretical power spectrum. We take a histogram over $\sqrt{\ell} + 0.5 \Delta C_{\ell}/C_{\ell}^{th}$ (Figure 3.9), over the range $\ell = 2-700$, and calculate the variance, skewness and kurtosis. In order to determine the significance of these properties for the histogram, we compare with the 1000 FFP6 MC simulations. For each simulation we calculated the variance, skewness and kurtosis of the corresponding $\sqrt{\ell} + 0.5 \Delta C_{\ell}/C_{\ell}^{th}$ histograms for even and odd multipoles respectively. This results in the distributions shown in Figure 3.10 for even (blue) and odd (red dashed) multipoles. This we compare to the value for Planck SMICA (green lines). We see a good agreement for all three statistical properties between the SMICA power spectrum and that of the simulations, and no significant discrepancy between even and odd multipoles.



Figure 3.9: The distribution of $\sqrt{\ell + 0.5} \Delta C_{\ell} / C_{\ell}^{th}$ for SMICA. Solid green line: Gaussian fit.



Figure 3.10: Properties of $\sqrt{\ell} + 0.5 \Delta C_{\ell}/C_{\ell}^{th}$. Histograms show 1000 FFP6 MC simulations, split into odd ℓ (red dashed) and even ℓ (blue). The green lines show the corresponding value for SMICA for the property for even (dash-dotted) and odd (solid) respectively.

Choosing $\ell_{max} = 700$ is in principle arbitrary, although motivated by the need to minimize noise contribution which increases for smaller scales, but one could choose other ranges of ℓ to test. Choosing a lower ℓ_{max} further reduces the contribution from noise, and we therefore investigate $\ell_{max} = 500$, $\ell_{max} = 300$ and $\ell_{max} = 100$. The effect on the variance, skewness and kurtosis results from Figure 3.10 when changing ℓ_{max} is shown in Figure 3.11.



Figure 3.11: Same as Figure 3.10, but varying ℓ_{max} . From left to right: $\ell_{max} = 100$, $\ell_{max} = 300$ and $\ell_{max} = 500$.

For all three ranges there is a good consistency between the expectation from simulations and the SMICA values observed. Only in the variance plot for $\ell = 500$ (upper right corner of Figure 3.11) there is a slight tendency towards the Planck values being in tension with the simulations. The corresponding values and significances for this are shown in Table 3.4.

	Planck value	# sims	<i>p</i> -value
Odd	3.25407	25	2.5%
Even	3.15057	16	1.6%

Table 3.4: Significance of the variance for $\ell = 500$. The Planck value is the corresponding green line (solid or dashed) in Figure 3.11. The "# of sims" is the number of simulations out of 1000 that have a higher value for the variance than the Planck value.

In the Planck 2013 *Isotropy and Statistics* paper, not only the anomalies are reviewed. A plethora of statistical tests of the Gaussianity of the map and consistency of the CMB data are presented. Three of these tests is on the variance, skewness and kurtosis of the data. It is worth noting that those tests were done on the map itself, not the power spectrum. The tests show that of these statistical properties, the variance of the map is anomalously low. This is not to be confused with the variance tests performed here.

3.3 Consistency test conclusions

We have investigated the consistency of the Planck 2013 NILC, SMICA and SEVEM maps as well as the consistency of the WMAP ILC9 and ILC7 maps, and performed a cross test between NILC and ILC9. The basic assumption was that the difference between two maps—the difference map—consists only of a non-cosmological signal, which a pure CMB map should not correlate strongly with. We found that the Planck 2013 NILC, SEVEM and SMICA maps are in very good agreement with each other, and none of them show a significant correlation with their respective difference maps outside the mask. On the other hand, the ILC9 map correlates significantly with the difference map, both in comparison to ILC7, in comparison to Planck NILC and in comparison to random simulations. Thus ILC9 appears to be more contaminated than the ILC7. This should be taken into consideration when using WMAP maps for cosmological analyses.

For the SMICA power spectrum we find good consistency between data and simulations. We also investigated whether changing the range of multipoles for the power spectrum had any effect on this agreement. Here we found that for an ℓ_{max} of 500, the variance of the SMICA map is higher than simulations at the level of 1.6% (for even multipoles) and 2.5% (for odd multipoles). For the ranges $\ell_{max} = 100$ and $\ell_{max} = 300$ there is good consistency.

4

SEARCHING FOR A COSMOLOGICAL EXPLANATION

As was discussed briefly in Chapter 2, the origins of the large-scale, low-multipole CMB anomalies are unclear. If the anomalies are not just statistical happenstances of our particular realization of a hypothetical ensemble of universes, we can search for an answer in either primordial physics, systematics or astrophysical foregrounds. Here, we turn our attention to the search for a cosmological explanation. If (some of) the large scale anomalies turn out to have a primordial origin, this would give insight into the physics of the earliest times of inflation.

The Cosmological Principle states that the Universe should be isotropic and homogeneous on scales above 100 Mpc, which is widely accepted as a basic principle of most cosmological scenarios. This principle can be experimentally tested by galaxy surveys and CMB observations. The results from the Sloan Digital Sky Survey of the large scale structure of the Universe, indicated that the galaxy distribution becomes isotropic and homogeneous at large scales [79, 80], which supports the Cosmological Principle well. However, if we believe that the anomalies have a cosmic origin, there is a possibility that the Cosmological Principle will be challenged.

The curvaton scenario discussed in this chapter considers exactly a change in the Cosmological Principle. The paper which is presented in this chapter, *Large-scale anomalies of the CMB in the curvaton scenario* [7] was done together with Hao Liu and Pavel Naselsky, after investigations into the effect of a super-horizon dipolar perturbation as a possible primordial origin of the point-parity asymmetry. It is an extension of the work done by Erickcek et al. in Super horizon perturbations and the cosmic microwave background and *A scale-dependent power asymmetry from isocurvature perturbations* [81, 82]. They discuss how perturbations on scales larger than the horizon could affect the CMB. Among other things, they arrive at the conclusion that super horizon perturbations do not contribute to the CMB dipole, and they discuss these perturbations in reference to the hemispherical power asymmetry in the CMB. We extended the analysis to an investigation of whether one could reproduce the parity asymmetry of the CMB temperature power spectrum by implementing an inflation model with such super horizon perturbations.

4.1 Large-scale anomalies of the CMB in the curvaton scenario

In the standard inflationary scenario, the large-scale structure is generated by the initial perturbations due to quantum fluctuations of the inflation field. However, if we further consider the possibility that the standard inflation field is not the only field in the inflation stage (the inflation field is still dominating), then by adding some extra components to the nearly scale-invariant spectrum we can introduce a seed of asymmetry to the theoretical expectation, not just to a specific realization by a particular observer. One way of adding such an extra component is through the curvaton scenario [83, 84].

In the this scenario we can see that additional non-isotropic perturbations can be generated by the curvaton field. The curvaton field, σ , is supposed to have negligible energy density compared to the inflaton field. It is also non-interacting with the inflaton field, and thus its initial value σ_* is kept during inflation. The quantum fluctuations of the curvaton field $(\delta\sigma)_{rms} = H_{inf}/(2\pi)$ (H_{inf} is the Hubble parameter during inflation) contributes part or all of the primordial perturbations [85–88]. If the curvaton potential is $V(\sigma) = (1/2)m_{\sigma}^2\sigma^2$ with $m_{\sigma} \ll H_{inf}$ (m_{σ} is the mass of the curvaton), then after inflation (when $m_{\sigma} \simeq H$) the curvaton will oscillate and decay into radiation and will interact with matter. The sequence of curvaton decaying and decoupling of particle species gives different curvaton interacting scenarios, like curvaton-dark matter interacting [82].

The aim of this chapter is to see if we can mimic the even-odd multipole parity asymmetry of the CMB power spectrum through the curvaton scenario. This would give a cosmological explanation to this CMB anomaly. Whereas Erickcek et al. [81, 82] focus on super horizon perturbations (the wavelength of the perturbation they consider is very large), we have discovered that if the wavelength of the curvaton perturbation is comparable to or smaller than the horizon, then the model could be used for the explanation of some of the CMB anomalies.

The outline is the following. We present the extended model in Section 4.1.1. In Section 4.1.2, we apply this model to the WMAP data to see if it can, at least partly,

explain the power spectrum parity asymmetry and the temperature space anomalies. In Section 4.1.3 we show how a plane wave component can affect the CMB power spectrum. In the end, a brief discussion is given in Section 4.2.

4.1.1 Extended model based on the curvaton scenario

Based on the curvaton scenario, we have constructed a model with three parameters to see if it can generate some of the observed anomalous features of the CMB, in particular power asymmetry in the power spectrum. The model is presented below.

J. Kim and P. Naselsky find in [54] that if there is a primordial perturbation in Fourier space $\Psi(\mathbf{k})$, then the low multipole ($2 \leq \ell \leq 30$) spherical harmonic decomposition coefficients ($a_{\ell m}$) are connected to $\Psi(\mathbf{k})$ through

$$a_{\ell m} = 4\pi (-i)^{\ell} \int \frac{d^3 \mathbf{k}}{(2\pi)^3} \Psi(\mathbf{k}) \, T_{\ell}(k) \, Y_{\ell m}^*(\hat{\mathbf{k}}), \tag{4.1}$$

where $T_{\ell}(k)$ is the radiation transfer function. For odd multipoles, $\ell = 2n + 1$ with n = 0, 1, 2, ... we have

$$a_{\ell m} = -\frac{(-i)^{\ell-1}}{\pi^2} \int_0^\infty dk k^2 \int_0^\pi d\theta_{\mathbf{k}} \sin \theta_{\mathbf{k}} \times \int_0^\pi d\phi_{\mathbf{k}} T_\ell(k) Y_{\ell m}^*(\hat{\mathbf{k}}) \operatorname{Im}[\Psi(\mathbf{k})], \qquad (4.2)$$

and for the even multipoles, $\ell = 2n$,

$$a_{\ell m} = \frac{(-i)^{\ell}}{\pi^2} \int_0^\infty dk k^2 \int_0^{\pi} d\theta_{\mathbf{k}} \sin \theta_{\mathbf{k}} \times \int_0^{\pi} d\phi_{\mathbf{k}} T_{\ell}(k) Y_{\ell m}^*(\hat{\mathbf{k}}) \operatorname{Re}[\Psi(\mathbf{k})].$$
(4.3)

From Eq.(4.2) and (4.3), we can see that e.g. odd-parity preference might be produced, provided that

$$|\operatorname{Re}[\Psi(\mathbf{k})]| \ll |\operatorname{Im}[\Psi(\mathbf{k})]| \quad (k \lesssim 22/\eta_0), \tag{4.4}$$

where η_0 is the present conformal time. As is seen from 4.4 the phases of metric perturbations ($\xi = \arctan\left[\frac{\operatorname{Im}(\Psi(\mathbf{k}))}{\operatorname{Re}(\Psi(\mathbf{k}))}\right]$) have to be localized in the vicinity of $\xi \propto \pi/2$; $3\pi/2$, at least for the range $k \leq 20/\eta_0$ to $30/\eta_0$. This shows the possibility of generating even-odd parity asymmetry from specific primordial perturbations.

The squeezed space of phases indicates that for spatial scales $x \gtrsim 4$ Gpc [54] the homogeneity and isotropy of the perturbations is abnormal. Namely, parity arguments of the CMB leads to the parity asymmetry of the metric perturbations, $\Psi(\vec{x}) \approx -\Psi(-\vec{x})$. Let

us assume that the origin of those anomalies can be associated with unusual properties of the curvaton field [53, 81, 82]. The potential perturbation at decoupling due to a curvaton field perturbation is given in [81], using a real space form $\Psi(\tau_{dec}, \vec{x})$, as:

$$\Psi(\tau_{dec}, \vec{x}) \simeq -\frac{R}{5} \left[\frac{\Psi(\tau_{dec}, \vec{x})}{\frac{9}{10} \Psi_P} \right] \left[2 \left(\frac{\delta_{\sigma}}{\overline{\sigma}} \right) + \left(\frac{\delta_{\sigma}}{\overline{\sigma}} \right)^2 \right], \tag{4.5}$$

where $\overline{\sigma}$ is the homogeneous curvaton background, and $\sigma(\vec{x}) = \overline{\sigma} + \delta\sigma(\vec{x})$. $R \equiv \rho_{\sigma}/\rho_{total}$ is the fraction of the curvaton contribution to the total energy density just before the curvaton field decays. The curvaton decay is assumed to be early enough so that we get $\Psi_P \simeq -(2R/9)\delta\rho_{\sigma}/\rho_{\sigma}$.

We set the time-dependent coefficient of $[2(\frac{\delta_{\sigma}}{\overline{\sigma}}) + (\frac{\delta_{\sigma}}{\overline{\sigma}})^2]$ as $\psi(\tau)$. If we suppose that $\frac{\delta_{\sigma}}{\overline{\sigma}} = r \sin(\vec{k} \cdot \vec{x} + \delta)$ (sinusoidal fluctuation for curvaton perturbation, see also Sec. 4 of [82], and δ is the phase), then we have the spatial distribution of the real space potential as:

$$\Psi(\tau, \vec{x}) = \psi(\tau) [2r\sin(\vec{k} \cdot \vec{x} + \delta) + r^2\sin^2(\vec{k} \cdot \vec{x} + \delta)].$$
(4.6)

The low order CMB power spectrum consist of early Sachs-Wolfe (SW) and Integrated Sachs-Wolfe (ISW) effects. According to [81] the induced SW effect is given by $\left[\frac{\Delta T}{T}(\hat{n})\right]_{SW} = \Psi(\tau_{dec})/3$. Therefore, we only have to calculate the ISW effect. According to Equation 16 of [81], the ISW effect is given by:

$$\left[\frac{\Delta T}{T}(\hat{n})\right]_{ISW} = 2\int_{a_{dec}}^{1} \frac{d\Psi\{a, H_0^{-1}[\chi_0 - \chi(a)]\hat{n}\}}{da}da,$$
(4.7)

where $\chi(a) \equiv H_0[\tau(a) - \tau_{dec}]$ and $\chi_0 \equiv \chi(a = 1) = H_0 x_{dec}$. If we assume that r is constant this gives:

$$\left[\frac{\Delta T}{T}(\hat{n})\right]_{ISW} = 2[2r\sin(\vec{k}\cdot\vec{x}_{dec}+\delta) + r^2\sin^2(\vec{k}\cdot\vec{x}_{dec}+\delta)]\Psi(a)\mid^1_{a_{dec}}.$$
 (4.8)

Combining the SW and ISW effect, and letting $\vec{k} \cdot \vec{x}_{dec} = q\pi [1 - \cos(\theta)] = q\omega$ (q is the wave number, θ is the polar coordinate, and we choose the system of coordinates so that \vec{k} is oriented along $-\vec{Z}$), we have gotten the CMB fluctuations due to curvaton perturbations as:

$$\left[\frac{\Delta T}{T}(\hat{n})\right] = 4r\Psi_c[\sin(q\omega+\delta) + \frac{r}{2}\sin^2(q\omega+\delta)],\tag{4.9}$$

where $\Psi_c = \Psi(a) \mid_{a_{dec}}^{1} + \Psi(\tau_{dec})/3$ is a constant and is related only to the overall amplitude.

Now it is clear that in our plane-wave model, the structure of CMB fluctuations due to curvaton perturbations are determined by only three parameters: q, r and δ . At the current stage, we consider only the structural term of Equation 4.9:

$$\left[\frac{\Delta T}{T}(\hat{n})\right] \propto \sin(q\omega + \delta) + \frac{r}{2}\sin^2(q\omega + \delta), \qquad (4.10)$$

and let the amplitude from Eq.(4.9) be a free parameter. From this equation we can get the curvaton component power spectrum.

Equation 4.10 can also help us understand why the curvaton-based perturbations are so different to the ordinary adiabatic perturbations. The curvaton-based perturbations are proportional to a linear combination of $\sin(q\omega + \delta)$ and $\sin^2(q\omega + \delta)$. Such sin-functions have intrinsic power spectrum odd-even parity asymmetry, and, since there are both first and second orders of the sin-function in the combination, different parity asymmetry patterns can be easily produced according to their ratio. Moreover, the linear combination in Equation 4.10 is rotationally symmetric around the wave vector \vec{k} of the sinusoidal perturbation, which provides an axis of rotation symmetry along \vec{k} . Globally speaking, such an axis due to the curvaton scenario could be a potential source of asymmetry and/or anomaly, even if the exact direction of the axis can not be predicted by the curvaton scenario alone.

4.1.2 Implementation of the curvaton model

The curvaton model can now be implemented and compared to CMB data. The model is determined by three parameters: the wave number q, the curvaton fluctuation strength r and the initial phase δ . Note that changing δ is very similar to choosing a special spatial position of a particular observer. Firstly, in Section 4.1.2 we determine the model parameters by fitting the WMAP power spectrum. Then in Section 4.1.2 we proceed to find the most optimal orientation of the model based on the WMAP data.

Determining model parameters

We apply the model to the WMAP ILC7 CMB power spectrum, in order to determine the model parameters. The best fit Λ CDM power spectrum does not have power asymmetry, but the observed power spectrum does. Thus, assuming that the WMAP ILC7 CMB power spectrum is a combination of Λ CDM and an extra component due to the curvaton field,

the power spectrum of this extra component (C_{extra}) should display power asymmetry. Therefore we fit our model to the difference between the Λ CDM best fit power spectrum and the observed power spectrum.

With each parameter set (q, r, δ) , we calculate the CMB temperature distribution according to Equation 4.10 as well as the CMB power spectrum, and then linearly fit the derived power spectrum to C_{extra} to determine the constant Ψ_c (Equation 4.9). The χ^2 statistic of fitting is recorded for this parameter set, and the best guess of (q, r, δ) is determined by the minimal χ^2 . The resulting CMB power spectrum is given in the top of Figure 4.1. It seems as though the characteristic power asymmetry structure has been fairly well reproduced by the model, and only the $\ell = 2$ (quadrupole) component is not particularly well fitted. To quantitatively estimate whether parity asymmetry is actually produced, we use the parity estimator $g(\ell)$, as defined in Section 2.4.1, Eq.(2.14). In Figure 4.2 we see that the parity asymmetry ($g(\ell) < 1$) is indeed reproduced for the model for low multipoles, as expected.

We also give a contour plot of the likelihood of fitting in the parameter space. The likelihood of fitting can be calculated as $\mathcal{L}_{fit} = P(\chi^2 > \chi^2_{fit})$. We have tested that the model CMB power spectrum is not sensitive to r and thus we choose to fix r at its best guess value, r = 2.6, to plot a 2D-contour of $\ln(\mathcal{L}_{fit})$ over q and δ . This is given in the bottom figure of Figure 4.1. We can see that there is a double-peak structure along the δ axis, separated at about 0.7π . We have confirmed that these two peaks give very similar resulting power spectra. It is not strange to see a double-peak separated by 0.7π , because all large-scale perturbations are more or less spatially periodic.

Although the fitting in Figure 4.1 looks good, we must be careful about concluding that the entire large-scale CMB asymmetry is generated by our model. At least now, we can only say that part of the large scale power asymmetry could be explained by our toy-model. For example, when we look at the quadrupole ($\ell = 2$) component, we see that the fitting here is not good enough. However, the fitting at $\ell = 2$ can actually be made much better than Figure 4.1, but at the cost of worse fitting on all other components. Therefore, it's more likely that the quadrupole anomaly is more or less affected by a different origin, which cannot be explained in the curvaton scenario.

Finding the best orientation of the model

Since the temperature fluctuations caused by plane wave curvaton perturbations are rotationally symmetric around the wave vector \vec{k} (see Figure 4.5 for an example), its spherical harmonic components $\alpha_{\ell m}$ should not have the same strength at different m. Especially, if



Figure 4.1: Application of our model to WMAP data. Top: The best fit model power spectrum (dotted) and the difference between the Λ CDM best fit power spectrum and the observed WMAP 7-yr power spectrum (solid). Bottom: A 3-level contour plot of $\ln(\mathcal{L}_{fit})$ at 0.5, 0.75, 0.96 (black, blue, red), where $\ln(\mathcal{L}_{fit})$ is normalized to (0, 1).



Figure 4.2: Parity parameter for observed WMAP 7-yr power spectrum (solid line) and for the curvaton model (dashed line).

k is in the direction of the $\pm Z$ -axis, then $\alpha_{\ell m} = 0$ for all $m \neq 0$ components. Therefore, the orientation that minimizes the $m \neq 0$ spherical components for the real CMB data is very likely the best orientation of the model. In Figure 4.1, we see that for $\ell = 3 - 7$ components are fairly well fitted by the model, while also exhibiting parity asymmetric behavior (more power in odd multipoles than in even ones). Thus if we try to optimize the orientation of the model based on this range, it may increase the accuracy of determining the orientation of the model.

Our approach is like this: First we rotate the WMAP 7-year ILC map around the Yaxis (Galactic plane) to find an angle θ_{ℓ} that minimizes $\sum_{m\neq 0} |\alpha_{\ell m}|^2$ for each ℓ in range $\ell = 3 \sim 7$ respectively. The average value $\langle \theta_{\ell} \rangle$ tells us the latitude of the orientation in the Galactic coordinate system, which is -53° . Interestingly, as discovered by [56] the preferred axis of the WMAP quadrupole ($\ell = 2$) and octupole ($\ell = 3$) both point to $(l, b) \sim (110^{\circ}, 60^{\circ})$ in Virgo. Since the preferred axis does not distinguish between \hat{n} and $-\hat{n}$ ($b = \pm 60^{\circ}$), we see that the axis we have found is only 7° away in latitude from the well known "axis-of-evil". Moreover, as discovered by [47, 48], the non-Gaussian WMAP cold spot at (l, b) = (209, -57) is also only 4° away in latitude from our axis here. Thus our model may play an important role not only in the parity asymmetry problem, but also in relation to other large-scale CMB anomalies, and perhaps even be connected to some CMB non-Gaussianities.



Figure 4.3: Overlapping of belts corresponding to $|\theta - \pi/2| = \langle \theta_{\ell} \rangle$ for $\ell = 3 - 7$, plotted in Galactic coordinates. Top: derived from WMAP ILC. Bottom: derived from Planck NILC. The two poles of the axes with the strongest overlap are marked out by "1A", "1B", and the two poles of the secondary axes are marked out by "2A", "2B".

The standard deviation of θ_l in range $\ell = 3 - 7$ is $\sigma_0 = 15.4^\circ$. Such a small value means that these harmonic components have clustered orientations. To confirm that σ_0 is really small, we did a test with 5000 simulations, and for each *i*-th simulation, the standard deviation of θ_l in range $\ell = 3 - 7$ was calculated as σ_i . We only got 41 out of 5000 simulations that had $\sigma_i < \sigma_0$. This means that for the WMAP data the clustering of θ_ℓ in the range $\ell = 3 - 7$ is significant at a level of 99.2%.

After determining the latitude of the orientation, we change the coordinate system of the ILC map by rotating the Z-axis to all 192 directions defined by the HEALPix resolution $N_{side} = 4$ [89]. For each new coordinate system, we do the same as we did above and get $\langle \theta_{\ell} \rangle$ for this coordinate system. If the harmonic components are sufficiently clustered (i.e. if $\sigma_0 < 20^\circ$) we draw a belt at $\langle \theta_{\ell} \rangle$ with a width of 12° for this coordinate system. The overlapping of these belts are shown in Figure 4.3 (all turned to Galactic coordinates). The hottest spots give the possible orientations of the model. The two poles of the strongest orientations are marked out by "1A", "1B". The coordinate of the axis is $(l, b) = (189^\circ, -55^\circ)$. We can also see an orientation at $(l, b) = (346^\circ, -50^\circ)$ from Figure 4.3, whose poles are marked out by "2A", "2B". To determine the most optimal orientation of the model we calculated the correlation coefficients (for $\ell = 3 - 7$) between the multipole components of our model and the ILC, when the model was rotated to directions "1B" (axis-1) and "2A" (axis-2) respectively. As is seen from Table. 4.1 we have determined that axis-1 is the most optimal orientation.

l	2	3	4	5	6	7
Axis-1	-0.13	0.55	-0.16	0.60	0.59	-0.05
Axis-2	0.15	0.15	0.09	-0.08	-0.01	0.14

Table 4.1: The model-to-ILC correlation coefficients between their multipole components when the model temperature map is rotated to the "1B" (axis-1) and "2A" (axis-2) directions.

As also shown in Figure 4.3, we have tested the direction calculation using the Planck NILC map [74], and seen that the result is quite close to WMAP. By also taking into consideration the Planck official results on the low- ℓ anomalies [38], it seems that the directions shown in Figure 4.3 is not due to systematics, but more likely intrinsic cosmic features or at least residual foreground.

We show the similarity between the large-scales components of the model (rotated to axis-1) and the WMAP ILC map in Figure 4.4 (the result for Planck NILC is close to this). Let us take the $\ell = 5$ component (fourth row) as an example: both model and the ILC have one cold spot located at -90° to -60° . We also see a band of cold spots between

 -30° and 0° and between 30° to 60° . There is one hot spot located at 60° to 90° , and hot spots in the band between 0° and 30° , and the band between -60° and -30° . We cannot hope to reproduce the components of the ILC completely with just this model, but we can look for the best fit possible. The 1B direction seems to be the best of the directions determined.

Stability of the model to contaminations

We have tested the stability of our method by using an input map derived from Equation (4.9) with q = 3, r = 0, $\delta = 0$, $\hat{k} = (1,0,0)$ (neglecting the coefficient $4r\Psi_c$). By using the same method mentioned in the previous section, the resulting axis is found to be $(l, b) = (4.5^\circ, 6^\circ)$, well consistent with expectation, and validates the stability of our method. Then we added two contaminations to test the stability of this method: The contaminations are similar to the source but with 1/10 strength and different wave vector directions: $\hat{k} = (0, 0, 1), \sqrt{3}/3(1, 1, 1)$ respectively. With the same approach, we got a resulting axis at $(b, l) = (10^\circ, 357^\circ)$, also close to expectation. Thus we have shown that our approach is insensitive to weak contaminations with "misleading" axes (e.g. due to other sources of asymmetry).

4.1.3 The effect on the power spectrum of a plane wave component

Here we show an example from simulation, in which we can see how the power spectrum power asymmetry can be generated from a plane wave component due to the curvaton model discussed above. First we generated a simulated CMB map from a Λ CDM power spectrum. Then we generated a map of a plane wave component with the same parameters as shown in Figure 4.1 (the direction of the plane wave is not important for a simulated map, so we choose the Ecliptic north/south poles as the direction). The summation of them resembles the " Λ CDM + curvaton" scenario, see Figure 4.5. We then calculate the power spectrum of both the original and combined map, and plot them together with the WMAP CMB low- ℓ power spectrum in Figure 4.6. We can see that the odd-even multipole power asymmetry of the WMAP low- ℓ power spectrum can be somewhat reproduced in this way, especially in the range $\ell \sim 5 - 9$.

Certainly, with more simulations we can also see cases in which the combined power spectrum (blue line in Figure 4.6) isn't similar to the real data (red line in Figure 4.6). The reason is simple: the CMB and curvaton components can have different directions and phases, thus the summation of them can make the power spectrum either higher or lower. This fact makes the problem much more complex. However, with more simulations



Figure 4.4: Maps of l = 2 - 7 (top to bottom). Left: components of the model with the best-fit parameters shown in Figure 4.1 rotated to the direction of "1B" (axis-1). Middle: the WMAP 7-year ILC map. Right: the model components rotated to the direction of "2A" (axis-2). The lines indicate latitudes in the coordinate system of the model (the lines on the ILC maps correspond to the coordinate system of axis-1).



Figure 4.5: Top: The original simulated CMB map with Λ CDM power spectrum. Middle: The plane wave component due to a curvaton field. Bottom: The summation of the two top panels. All in μ K.



Figure 4.6: The harmonic power spectrum of: theoretical Λ CDM (Black dash), simulated map without plane wave (black solid), with plane wave (blue), and WMAP low- ℓ power spectrum (red).

we can see that with the curvaton component presented in Figure 4.1, the probability of getting similar result to real data will increase.

The power spectrum similarity is evaluated by the cross-correlation coefficient between the power spectrum for WMAP data and simulations in the range $\ell = 4 - 12$ for 10,000 simulations:

$$K_{4-12} = Corr(C_{\ell}^{sim}, C_{\ell}^{WMAP}), \qquad \ell = 4 - 12.$$
(4.11)

If the simulations are pure Λ CDM (no curvaton component is added), only 2.6% \pm 0.16 of the simulations have a $K_{4-12} > 0.6$. For the simulations with Λ CDM + curvaton component 18.4% \pm 0.43 of the simulations have a $K_{4-12} > 0.6$. This fact supports the curvaton scenario presented in this work quite well.

4.2 Cosmological conclusions

In the work presented in this chapter we introduced a model based on the curvaton scenario, which has only three parameters, and applied it to the WMAP data. The model was an extension of [81, 82], but we have discovered that if the wavelength of the curvaton perturbation is comparable to or smaller than the horizon $(q \ge 1)$, then the model can be used to explain point-parity asymmetry and perhaps even more power asymmetry problems of the CMB. Our results show that such a simple model can fit the CMB power spectrum difference between the Λ CDM expectation and the experimental observation to some degree for low multipoles. The spatial structure can also be fitted, fairly well for $\ell = 5$. This tells us that at least part of the CMB large-scale asymmetry could be attributed to an extra component of the inflation field, which can thus provide a possible cosmic explanation to the CMB asymmetry problems. However, these morphological features could also be mimicked by some combination of foreground residuals, as discussed in [73], and which will be covered in the next chapter. In this work our goal was to investigate a theoretical model based on the curvaton scenario, and to see which constraints we have to apply to it in order to explain the observed point-parity asymmetry in the CMB. It will also be interesting to see what comparison of this method with the Planck polarization data will yield, as discussed in [71].

A recent paper has placed limits on the semi-classical fluctuations in the primordial Universe [90]. Although the fluctuation amplitude of our model has not been discussed here, we notice that they have obtained nearly the same direction as we do in their figure 3 (compare to the "1A" direction in our Figure 4.3). Therefore, the limits on the fluctuation amplitude discussed in their paper may also apply to our model.

After the publication of this work, G. Aslanyan and R. Easther in *Large Scale Anomalies in the Microwave Background: Causation and Correlation* [91] also show how a significant part of point-parity asymmetry of the power spectrum can have its origin in a large plane wave inhomogeneity.
5

UNVEILING GALACTIC CONTAMINATION

Another possible source of the CMB anomalies are more local phenomena, namely our own Galaxy and Solar System. From the outset, however, we do not expect to find significant contributions using this approach. The component separation algorithms (see 2.3.1) are supposed to weed out all other components than the CMB from the final maps, absorbing the Galactic or Solar System emission into other components. Nevertheless, we know that the Galactic plane in the CMB maps is in fact contaminated by residual radiation. We therefore normally mask it out with a confidence mask (see Figure 2.12). Once this mask is applied, our assumption is that the rest of the sky is reliable. However, the presence of anomalies in the CMB raises the question whether somehow some residuals outside the Galactic plane have escaped the component separation methods. This could be, for example, due to some new unknown foreground, mimicking the spectral behavior of the CMB. Without knowing the exact mechanism for how such residuals may have propagated into the CMB map, one may still test the hypothesis of the presence of Galactic or Solar System foregrounds in the CMB maps.

The question we wish to answer in this chapter is then whether Galactic or Solar System residuals are present in the CMB maps, and if so, whether they are connected to the CMB anomalies. Our approach is to identify peculiar zones or areas on the sky that could be responsible for some, or all, of the CMB anomalies. Any correlations between these areas and known Galactic emission sources could indicate possible contamination of the CMB maps. As opposed to the approach of the previous chapter where we look at adjustments of the standard cosmological models, here we are essentially testing the component separation of the foregrounds from the CMB—thus we will be challenging either the methods or our understanding of the foregrounds themselves.

The Solar System contributions from zodiacal light and Kuiper Belt objects are discussed in Section 5.1 below. The indications of the presence of a possible Galactic contamination, specifically the Galactic radio loops, and the effect on the low multipole anomalies is discussed and shown in Section 5.2. This section is based on a paper (in preparation) from 2015, *Impact of Galactic Loops on the low-l CMB anomalies* together with Diego Molinari, Hao Liu, Sebastian von Hausegger, Assaf Ben-David and Pavel Naselsky. It follows the recent claim of Liu et al. [92] that they had detected an imprint of the Galactic radio Loop 1 in the WMAP 9yr ILC map. Extending the analysis of Liu et al. to Planck data was a logical next step. We therefore looked at signatures of the radio loops in the Planck CMB maps. Going further than the Liu et al. paper, we also looked into the impact a presence of these Galactic radio loops in the Planck SMICA map would have on the low multipole CMB anomalies.

5.1 Zodiacal light and the Kuiper Belt

In an earlier paper, *Can residuals of the Solar system foreground explain low multipole anomalies of the CMB?* [73], we looked at point-parity asymmetry in the context of Kuiper Belt Objects (KBO) in our Solar System, which are small asteroid-like remnants from its formation. We found that they could, at least partly, explain some of the parity asymmetric behavior of the power spectrum, due to the Kuiper Belt's asymmetric structure in Galactic coordinates.

In the Planck 2015 maps a new correction for Zodiacal light, also connected to the KBO's, has been implemented in the data analysis. In Figure 5.1 is shown the difference maps between 2013 and 2015 Planck CMB maps. Especially in the NILC, SEVEM and SMICA the ecliptic belt is clearly visible. However, Planck uses the Kelsall model [93] to estimate the emission from Zodiacal light. In the paper *The Microwave Thermal Emission from the Zodiacal Dust Cloud Predicted with Contemporary Meteoroid Models* [94] by V. D. Dikarev and D. J. Schwarz, a new take on modeling the Zodiacal light is presented, and they argue that the Kelsall model is not enough to model the Zodiacal light properly. A future repetition of the investigations undertaken in [73] with the new Planck data would be interesting, and would hopefully reveal that ecliptic emission has been sufficiently removed.



Figure 5.1: Planck 2013-2015 CMB difference maps, at $N_{side} = 128$ smoothed by 80 arcminutes, as presented in figure 3 of [37]. Especially for NILC and SMICA the ecliptic belt (zodiacal light) is very clear.

5.2 Impact of Galactic loops on the low- ℓ CMB anomalies

Recently, Liu et al. [92] claim to have detected an imprint of the Galactic radio Loop 1 in the WMAP 9yr ILC map. The four Galactic radio loops were originally discovered during the 1960s and 1970s in radio surveys [95-97], and are the remnants of old supernova explosions. A more recent determination of the loop parameters in radio was done by V. Borka for 408, 840 and 1420 MHz in [97]. Supernova explosions accelerate material into the interstellar medium (ISM), creating a shock front which compresses the gas and dust of the ISM. This shock front also amplifies the turbulent magnetic field of the ISM, which gives rise to increased (polarized) synchrotron radiation. The loops are thus very dominant at low frequencies dominated by synchrotron radiation. In Figure 5.2 is shown the Haslam 408 MHz map [98], which is essentially a map of Galactic synchrotron emission, with the loops super-imposed. The compressed, heated dust radiates thermal emission at higher frequencies. We do not expect Loop 1, nor the other loops, to be present in the CMB map, since cleaning of synchrotron and dust emission is part of the component separation algorithms. However, by investigating correlations between the Planck 2015 SMICA map and the Galactic radio loops, we may uncover evidence of residual foregrounds or previously unknown foreground components.

In [99], W. Zhao argues through directional statistics that the CMB point-parity asymmetry, the dipole modulation and the anomalies connected to the quadrupole and octupole of the CMB may have a common origin. In the present work we investigate the possible role of local foregrounds, specifically the four Galactic radio loops, as a common source of the large scale CMB anomalies. For the point-parity asymmetry, we examine the impact on the significance of the anomaly when masking out the loop regions. We also investigate the effect of cleaning the SMICA map by a template of the loops on the alignment of the quadrupole and octupole. Lastly, we look at the dipole modulation after masking out a peculiar loop-like region found through an analysis of the squared map. We use the Planck SMICA 2015 temperature map and corresponding 1000 Planck FFP9 simulations [37, 100].



Figure 5.2: The Haslam 408 MHz map with the four Galactic loops super-imposed (Loop 1, center. Loop 2 lower left. Loop 3 upper left. Loop 4 inside Loop 1). Also outlined, in white, is the area attributed to the NPS [92].

5.2.1 Detection of the loops in SMICA

One of the most prominent features at radio frequencies is the North Polar Spur (NPS), which is part the Galactic radio Loop 1. It is very dominant in the 408 MHz Haslam map [98] (Figure 5.2), and can also be seen in the WMAP and Planck low frequency polarization and temperature maps [50, 101, 102](see Figure 5.3).

In [92], Liu et al. investigate the average temperature along a ring of width $\pm 10^{\circ}$ following Loop 1, as well as clusterization of peaks along the loop. They found a probability



Figure 5.3: Polarization intensity, $\sqrt{Q^2 + U^2}$, of the Planck 2015 30 GHz map, which is dominated by polarized synchrotron emission. Smoothed by 3°. The NPS stands out very clearly. Loop 3 is also slightly visible.



Figure 5.4: The four Galactic radio loops plotted on the Planck 2015 SMICA map.

of getting the level of clusterization of peaks observed along Loop 1 of only 0.018% (or up to 3.3% if the criteria are slightly relaxed). They suggest that the origin of this contamination of the CMB map could be magnetic dipole emission from ferro- or ferrimagnetic dust grains, a component of the ISM not previously observed. We update the analysis of [92], by repeating it with the Planck 2015 SMICA map. In Figure 5.4 the Planck 2015 SMICA map is shown with the four radio loops superimposed.

We take the average temperature of the SMICA signal along Loop 1 with a width of $\pm 2^{\circ}$ (see Figure 5.5), and find $\overline{T}_{L1} = 22.76 \,\mu$ K. In Figure 5.6 the average temperature is shown as a function of Φ . It is clear that the NPS (between the dashed lines) is neither the sole, nor primary, contributor to the mean temperature, and thus we also have indications that more of Loop 1 might be contributing. We use 1000 Planck FFP9 MC simulations to calculate the probability of obtaining an average temperature equal to or higher than the observed \overline{T}_{L1} along Loop 1. Here we find a *p*-value of 1.8%.



Figure 5.5: The SMICA map at $\ell \leq 20$ in the Loop 1 ring of $\pm 2^{\circ}$. The direction of the angle Φ is indicated in the middle (Blue is zero, red is 360°).



Figure 5.6: The average temperature of the SMICA signal along the $\pm 2^{\circ}$ ring, as a function of the angle Φ . The area between the two dashed lines is the NPS.

The squared CMB map makes highly positive or highly negative areas stand out visually, and we would therefore expect the Loops to be apparent if they are present in the SMICA map. The squared SMICA map is shown in Figure 5.7 with imposed thresholds of 1000 μK^2 and 2000 μK^2 respectively. The four radio loops are marked in the background, as well as a fifth peculiar area which stands out. The other area which stands out very clearly is the Galactic Cold Spot, which has previously been attributed to be a genuine feature of the CMB, despite its apparent peculiarity [40].



Figure 5.7: Top: Pixels of the squared SMICA map with values above 2000 μK^2 at $N_{Side} = 16$. Bottom: Same as top, but for values above 1000 μK^2 . Loops are indicated for visualization.

The morphology of this new peculiar area is fairly well described by a loop structure, and we therefore denote it Loop A. We note that this "loop" is not a known Galactic radio loop, but it does partially coincide with the Orion-Eridanus Super bubble, a region of active star formation, supernovae and cold molecular clouds [103, 104]. When comparing

Loop A with the IRAS loops [105]—detections of old supernova remnants in infrared data—a possible explanation for its presence is a cumulative effect of projections from these supernova shells, see Figure 5.8. In Figure 5.9 we over plot Loop A and the Orion-Eridanus Super bubble on the Planck 857 GHz data, where the overlap of supernova shells is even more apparent.



Figure 5.8: The Planck 2015 SMICA map, with the four Galactic radio loops and Loop A superimposed. Also shown is the outline of the Orion-Eridanus Super bubble in lower right quadrant, to the right of Loop A. In black, the 462 IRAS loops [105].



Figure 5.9: A cut-out of the Planck 2015 857 GHz temperature map. The black rings are the IRAS loops, the white small circle in the center is the Orion-Eridanus Super bubble. Loop A is the white partial ring in the lower left corner.



Figure 5.10: Left: Loop A superimposed on SMICA ($\ell \leq 20$). Also outlined is the Cold Spot. Right: the average temperature of the SMICA signal along a $\pm 2^{\circ}$ ring of the Loop A region. The solid line marks our chosen boundary between the asymmetric parts. The dashed lines indicate the area of the Cold Spot.

We apply the same analysis along the Loop A as was used for Loop 1. A peculiar feature is that the loop-like region is comprised of two distinct regions: one part is strongly positive, the other part strongly negative. Some of this negative part is the well known Cold Spot, indicated in Figure 5.10 by the small white circle. The other cold area along the Loop coincides with the Orion-Eridanus region. The average temperature along Loop A, $\overline{T}_{LA} = 21.24 \,\mu\text{K}$ is comparable to that of Loop 1, but has a *p*-value of 8.1%. If we instead look at the two distinct parts separately (divided by the solid line in Figure 5.10), we get an average temperature for the hot part of $\overline{T}_{LA}^H = 70.2 \,\mu\text{K}$ with a *p*-value of only 0.2%, and for the cold part $\overline{T}_{LA}^C = -39.5 \,\mu\text{K}$ with a *p*-value of 5.2%. In [106], J. D. McEwen et al. identify highly non-Gaussian areas of the CMB. One of the regions they find to be highly non-Gaussian is exactly the Loop A region, which is also what we see in the temperature distribution.

Interestingly, the negative part of Loop A is exactly π displaced from the NPS, see Figure 5.11. Such a positive/negative structure is highly parity asymmetric, which implies that masking just one of the two areas will have impact on the point-parity asymmetry. Taking the displacement of the positive part of Loop A, we see that the counterpart is also dominantly negative.



Figure 5.11: Top: displacement of the NPS (yellow) by π (light blue). Middle and bottom: displacement by π of the mirror image of the positive and negative part of Loop A, respectively.

5.2.2 Impact of the loops on the CMB anomalies

In this section we investigate whether the five identified regions of the sky (Galactic radio Loops 1-4, and the new Loop A) may be connected to the CMB anomalies. We investigate the possibility of the loops being the source of the following specific low multipole anomalies: the odd-parity preference of the power spectrum, quadrupole-octupole alignment, and the dipole modulation.

Point-parity asymmetry

While point-parity asymmetry is an asymmetry of the power spectrum, the surplus of power in odd over even multipoles reflects some asymmetry of the map itself. Since the loops are large scale features, they would especially affect the low multipoles, which is where point-parity asymmetry is observed. Thus the loops could induce an asymmetric imprint on the CMB map, leading to point-parity asymmetry. We may test their impact by imposing masks on the SMICA map before extracting the power spectrum.

The Planck common mask⁵ is a combination of the confidence masks for the four derived CMB maps, and one can expect it to cover all possibly contaminated regions the CMB maps. We consider various extensions of the common mask, in which we cover one or more of the four loops shown in Figure 5.4, as well as Loop A. The masks are summarized in Table 5.1 and shown in Figure 5.12.

Mask	Region covered	f_{sky}
0	Common mask	63.8%
1	Common + WMAP 9 yr pol mask	59.1%
2	Common + Loop 1	53.6%
3	Common + Loop 1 and 4	49.6%
4	Common + Loop 1 and A	49.6%
5	Common + Loop 1, 2, 3 and 4	39.4%

Table 5.1: Description of the masks we consider in this section. The third column shows the fraction of the sky analyzed.

The width of the loops is chosen to be 20 degrees. We also consider the WMAP 9yr polarization mask⁶, which covers the NPS. All the masks have been generated at high resolution and then degraded to $N_{side} = 32$ with a threshold so that the resulting pixels with a value less than 0.9 are set to zero and all others to 1. The SMICA map

⁵http://pla.esac.esa.int/pla

⁶http://lambda.gsfc.nasa.gov



Figure 5.12: The masks we consider in this section. Mask 0 (top left), mask 1 (top right), mask 2 (middle left), mask 3 (middle right), mask 4 (bottom left), mask 5 (bottom right). Green areas are 1, blue areas are zero.

and simulations considered are smoothed by FWHM=320 arcminutes and also degraded to $N_{side} = 32$. We extract the power spectrum of the masked CMB map using the QML power spectrum estimator [107–109].

The extracted power spectra are then used as an input to the point-parity estimator $R(\ell_{max})$ [53, 54, 69, 71](also shown in Eq.(2.15),

$$R(\ell_{max}) = \frac{\ell_{tot}^{-}}{\ell_{tot}^{+}} \frac{\sum_{\ell=2}^{\ell_{max}} \ell(\ell+1)C(\ell)^{+}}{\sum_{\ell=2}^{\ell_{max}} \ell(\ell+1)C(\ell)^{-}},$$
(5.1)

where $\ell_{max} \ge 3$, $C(\ell)^{+,-}$ is the CMB power spectrum for even (+) or odd (-) multipoles, and $\ell_{tot}^{+,-}$ is the total number of even or odd multipoles in the summation up to ℓ_{max} . In Figure 5.13 the results for $R(\ell_{max})$ are shown, for SMICA masked with each of the 6 masks listed above. We repeat the analysis for the FFP9 MC simulations of the CMB, with the resulting *p*-values shown in the right plot. In agreement with previous results for the common mask [38, 69], we see that the most anomalous range is around $\ell_{max} \sim 25$, where we obtain a *p*-value of 0.3% for the same mask (mask 0).

We observe that when masking Loops 1 and 4 (mask 3) we get a reduction of the significance of the parity asymmetry, to a *p*-value of ~ 3%, with regards to the anomalous level of parity asymmetry at $\ell_{max} = 25$. This can also be seen, although less significantly when masking Loop 1 only (mask 2). Although adding Loops 2 and 3 (mask 5) gives an even larger reduction in significance, the sky-fraction is much smaller. For the other masks we do not obtain similar increase in *p*-value.

While the Loop 1 and Loop 4 regions appear to be the main contributors to the alleviation of the parity asymmetry, one might ask whether this is due to their sizes and shapes, and not their specific locations on the sky. We test this effect by changing the locations of Loops 1 and 4, while keeping the orientation of the common mask fixed. We investigate four different shifts, $(l, b) = ([100^\circ, 0^\circ], [160^\circ, 0^\circ], [90^\circ, -30^\circ], [-30^\circ, -40^\circ])$, respectively, we find that none of them are able to reproduce the same decrease of significance as the original position of Loops 1 and 4.

Since the differences between the four Planck CMB maps at large scales are minor, we expect no differences in the results for the other CMB maps. For robustness we confirm this assumption for the parity analysis, by repeating the analysis for the Planck SEVEM, NILC and Commander maps using mask 0 and mask 3. We find that the effect of using mask 3 (Loop 1 and 4) is the same for each component separation method, although slightly less pronounced for SEVEM. For all maps the *p*-value increases from $\sim 0.3\%$ to $\sim 3 - 4\%$ when using mask 3.

Quadrupole-Octupole Alignment

Another large-scale anomaly worth investigating in connection with the loops is the peculiar alignment between the axes of the quadrupole and octupole of the CMB [38, 56]. In order to do so, we aim to fit a template of the loops to the CMB data. After finding a best-fit template, we can subtract it and test its effect on the anomaly. The alignment angle is calculated in harmonic domain and is consequently sensitive to slight variations in the harmonic coefficients. We therefore refrain from masking the data for this analysis.

In order to fit a template containing the loops to the CMB data, we require a model of their angular profiles in harmonic space. For Loops 1 through 4 we use the angular profiles of [110]. As stated above, Loop A is comprised of a positive, loop-like region and a cold area which coincides with the Orion–Eridanus Super bubble. We



Figure 5.13: Top: The point-parity estimator results of the SMICA map with the masks in Table 5.1 (colored lines). The black line indicates the average for the MC simulations, with $1, 2, 3\sigma$ dispersion levels shown in gray bands. Bottom: the corresponding p-values of the estimator.

therefore model it as the sum of two objects: a hot loop having the same angular profile as the four radio loops, and a cold Gaussian spot. The loop is centered around $(l,b) = (-126^\circ, -31^\circ)$, with angular radius $\alpha = 31^\circ$, as determined from the analysis of the squared SMICA map (see Figure 5.7). We center the cold spot at the location of the Super bubble, $(l,b) = (-160^\circ, -25^\circ)$. This model of Loop A should sufficiently capture its large-scale properties. In addition, motivated by the analysis of the squared SMICA map, we also consider the Galactic Cold Spot (GCS) as a possible contributor to the anomalous features of the large scales. We model it as another Gaussian spot, centered at $(l,b) = (-25^\circ, -6^\circ)$. The harmonic coefficients, $s_{\ell m}^{(i)}(\delta)$, of the object *i* depend on its angular width, δ , and are normalized to unit peak amplitude. The angular profiles used for the loops and spots as well as their harmonic transforms are given in Appendix A.

We model the observed large scales of the CMB as being comprised of the true CMB signal and an additional template consisting of the objects we consider,

$$d_{\ell m} = a_{\ell m} + t_{\ell m}, (5.2)$$

where d, a and t are the observed data, true CMB and template harmonic coefficients, respectively. The template is built from N objects,

$$t_{\ell m}(\lambda_1, \delta_1, \dots, \lambda_N, \delta_N) = \sum_{i=1}^N \lambda_i s_{\ell m}^{(i)}(\delta_i), \qquad (5.3)$$

where λ_i is the amplitude of object *i* and $t_{\ell m}$ is a function of 2*N* parameters. Since without committing to a particular model for the large scale CMB fluctuations we do not know the expected measurement errors of the underlying $a_{\ell m}$ coefficients, we perform an unweighted least-squares fit of the template to the data by minimizing the sum of squared residuals,

$$F = \sum_{\ell=2}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} |d_{\ell m} - t_{\ell m}|^2.$$
(5.4)

The loops are large-scale objects, and so we can choose an ℓ_{max} in the low multipole domain. On the other hand, we should make sure to include all the scales in which the loops have significant power. We have noted above (see Figure 5.13) that at $\ell_{\text{max}} \approx 25$ there is a peak in the level of the point-parity asymmetry anomaly. Aiming to include all those scales in our analysis, we therefore choose a smaller cutoff scale and set $\ell_{\text{max}} = 40$ in Eq.(5.4).

We minimize Eq.(5.4) using the spectral projected gradient algorithm,⁷ which iteratively minimizes a function, given a box domain for the parameters. This allows us to constrain the model parameters. The loop amplitudes are constrained as $0 \le \lambda_{\text{loop}} \le 300 \,\mu\text{K}$, while the width of each loop is constrained according to its angular radius, α , such that $1^{\circ} \le \delta_{\text{loop}} \le 90^{\circ} - \alpha$. Both the spot overlaid on top of Loop A and the GCS are cold, so we constrain their amplitudes as $-300 \,\mu\text{K} \le \lambda_{\text{spot}} \le 0$. The width of each spot is constrained as $5^{\circ} \le \delta_{\text{spot}} \le 70^{\circ}$. The result of the minimization depends of course on the initial guess for the parameters, and the descent in the direction of maximal gradient can result in a local minimum. We start with initial values of $\lambda = 20 \,\mu\text{K}$ and $\delta = 5^{\circ}$ for all the loops, $\lambda = -50 \,\mu\text{K}$ and $\delta = 30^{\circ}$ for the cold spot of Loop A and $\lambda = -50 \,\mu\text{K}$, $\delta = 50^{\circ}$ for the GCS.

It is not clear, a-priori, whether Loop A and the GCS are indeed foreground residuals, or true CMB fluctuations. We therefore consider several scenarios, each including a different subset of the objects we consider: the four Galactic radio loops (GRL), Loop A and the GCS.

The best-fit templates are shown in Figure 5.14. We can see that whenever either Loop A of the GCS are included in the fit, they tend to play a more dominant role than the four GRL, and have much larger amplitudes. Also shown are the residual maps after subtracting each template from the SMICA map. It is apparent that the main large-scale features, visible by eye, are removed by some of the templates. In Figure 5.15 we plot the power spectra of these residual maps.

Since we remove some of the large-scale features of the map, the subtraction of all the templates—except the one which includes only the radio loops and has a significantly lower amplitude—results in a loss of angular power in the lowest multipoles. If either Loop A or the GCS are indeed foreground residuals, the remaining CMB fluctuations will be left with very little large scale power, increasing the level of discrepancy between the expected Λ CDM power spectrum and the observed one. We also note that when choosing lower values of ℓ_{max} , the effect on the results is minor, since, as is apparent in Figure 5.15, the power spectra of the templates themselves are negligible for $\ell \gtrsim 15$.

We now turn to inspect the largest scales, i.e. the quadrupole and the octupole. In Figure 5.16 we plot those multipoles for all the best-fit templates, as well as for the SMICA map. We can see that some of the templates appear to reproduce the quadrupole and octupole of the SMICA map well. A visual inspection of the multipoles suggests that the only templates which fit poorly are the one which contains the GRL alone and the one including the GCS in addition to the GRL. Complementary to Figure 5.16, in Figure 5.17 we

⁷See the Open Optimization Library, http://ool.sourceforge.net/.



Figure 5.14: Left: The best-fit templates. Right: The residual maps after subtraction of each template from the SMICA map. The top row shows the original SMICA map. All maps include only the multipoles $\ell = 2, ..., 40$. The objects included in the fit are named on the left.



Figure 5.15: Angular power spectra of the residual maps after template subtraction. Also shown are the power spectra of the original SMICA map and the best-fit Λ CDM model.

plot the quadrupoles and octupoles of the residual maps, computed by subtracting each template from the SMICA map. If a template indeed represents additional foreground contributions to the CMB data, the residual map associated with it is an estimation of the underlying clean CMB. We can see that the residual quadrupole and octupole no longer seem aligned, at least for all the templates which fit the data well. Moreover, the residual octupoles no longer even seem to be planar.

All these notions can be readily quantified. The most straightforward statistic measuring the multipole alignment, first defined by [56], involves calculating for each multipole the axis which maximize the dispersion of its angular momentum, as

$$\hat{\mathbf{n}}_{\ell} = \arg\max_{\hat{\mathbf{n}}} \sum_{m=-\ell}^{\ell} m^2 \left| a_{\ell m}(\hat{\mathbf{n}}) \right|^2,$$
(5.5)

where $a_{\ell m}(\hat{\mathbf{n}})$ are the harmonic coefficients of the map, calculated in a coordinate system in which $\hat{\mathbf{n}}$ is the *z*-axis. After calculating the quadrupole axis $\hat{\mathbf{n}}_2$ and the octupole axis $\hat{\mathbf{n}}_3$, we define $\theta_{2,3} = \cos^{-1} |\hat{\mathbf{n}}_2 \cdot \hat{\mathbf{n}}_3|$. A small angle corresponds to high alignment between the axes. The alignment angle is then compared to the angles calculated from an ensemble



Figure 5.16: The quadrupole (left), the octupole (middle) and their sum (right). On the top row, the multipoles of the Planck 2015 SMICA map. Below, the multipoles of the best-fit templates.



Figure 5.17: The quadrupole (left), the octupole (middle) and their sum (right) of the residual maps. On the top row, the multipoles of the Planck 2015 SMICA map. Below, the multipoles of the residual maps.

of simulations. We calculate each $\hat{\mathbf{n}}_{\ell}$ by rotating the $a_{\ell m}$ coefficients on a HEALPIX grid and repeatedly evaluating the sum in Eq.(5.5). We do so in two stages, first finding the axis on an $N_{\text{side}} = 16$ grid, and then focusing on an area around the found axis and repeating the search using a grid of $N_{\text{side}} = 512$.

While simple, this statistic is not robust. It assumes that a single plane exists, for each multipole, on which most of its power is concentrated. This is indeed true for the quadrupole, but not necessarily for any other multipole. If such a plane does not exist for the octupole, rendering it not planar, neither the axis \hat{n}_3 nor the angle $\theta_{2,3}$ is very meaningful. The planarity of a multipole with respect to a given direction can be quantified using the statistic defined by [56],

$$p_{\ell}(\hat{\mathbf{n}}) = \frac{|a_{\ell,-\ell}(\hat{\mathbf{n}})|^2 + |a_{\ell\ell}(\hat{\mathbf{n}})|^2}{\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2},$$
(5.6)

i.e. by the fraction of power in the $m = \pm \ell$ modes of that orientation. We apply it to the axis $\hat{\mathbf{n}}_3$ to test the octupole planarity. While the SMICA octupole is rather planar with $p_3(\hat{\mathbf{n}}_3) = 93.5\%$, the residual maps we would like to test are not. Even for a map with a planar octupole such as the SMICA, the alignment angle is not a robust statistic in the way it is usually applied, since the simulations used to assess its significance are not constrained to be planar. We therefore require a more robust statistic, which takes into account both the octupole planarity and its alignment to the quadrupole.

Such is the following statistic, involving multipole vectors [57, 58, 111–114]. We first perform a multipole vector decomposition of the map using the publicly available code⁸ by [58]. Using the two quadrupole vectors, $\hat{\mathbf{v}}_{2,1}$ and $\hat{\mathbf{v}}_{2,2}$, we calculate the normal to the quadrupole plane, $\mathbf{q} = \hat{\mathbf{v}}_{2,1} \times \hat{\mathbf{v}}_{2,2}$ (the direction of which coincides with $\hat{\mathbf{n}}_2$). In a similar manner, the three octupole vectors, $\hat{\mathbf{v}}_{3,i}$, define three normals, $\mathbf{o}_i = \hat{\mathbf{v}}_{3,j} \times \hat{\mathbf{v}}_{3,k}$ $(i, j, k = 1, 2, 3; i \neq j \neq k)$. We normalize these normal vectors to unit length and calculate the statistic⁹

$$S = \frac{1}{3} \sum_{i=1}^{3} |\hat{\mathbf{q}} \cdot \hat{\mathbf{o}}_i|.$$
(5.7)

A high value of S means that the octupole is both planar and aligned with the quadrupole plane. Comparing S to the ensemble of realizations, we then get a p-value that is more meaningful than the one calculated based on the alignment angle alone.

We apply these statistics to all the residual maps attained by subtracting each template from the SMICA map, as well as to the SMICA map itself. The results are shown in

⁸http://www.phys.cwru.edu/projects/mpvectors/

⁹This is the same statistic as S, S_{WW} and $\widehat{S}23$ of [112–114], respectively.

Template	$\theta_{2,3}$ [deg]	$\Pr(\theta_{2,3})$ [%]	$p_3(\hat{\mathbf{n}}_3)$ [%]	S	$\Pr(S)$ [%]
SMICA	11.2	2.2	93.5	0.874	1.4
GRL	10.4	1.6	84.8	0.777	5.1
GRL, Loop A	16.0	4.0	56.1	0.601	23.9
GRL, GCS	30.3	13.8	84.1	0.754	6.7
GRL, Loop A, GCS	55.8	44.1	72.7	0.562	31.5
Loop A	27.3	11.4	69.5	0.678	12.4
Loop A, GCS	35.9	19.6	75.3	0.659	15.0

Table 5.2: Alignment statistics for the residual maps and for SMICA. Also shown are the probabilities to attain more extreme values of $\theta_{2,3}$ and S for the FFP9 simulations.

Table 5.2. We can see that while when the octupole planarity level, $p_3(\hat{n}_3)$, is high the *p*-values given by the $\theta_{2,3}$ and *S* statistics are somewhat consistent, when the planarity level is lower they are not. Focusing on the *p*-values given by the robust *S* statistic, we find them in agreement with our visual inspection of the quadrupoles and octupoles of the templates: when each of the four templates which include Loop A is subtracted from the SMICA map, the planarity of the octupole and its alignment with the quadrupole are destroyed. We conclude that the four Galactic radio loops, the GCS and especially Loop A are the main contributors to the low multipole alignment. Using these objects alone, it is possible to reproduce the quadrupole and octupole to a high degree, such that the map which remains after their removal shows no significant sign of alignment, and has low power on large angular scales.

Dipole Modulation

The last reported anomaly that we investigate in this context is the dipole modulation of the CMB signal (see Section 2.4), seen by both WMAP and Planck [40, 42, 65, 66]. We note that the Loop A region surrounds the direction of the dipole modulation (see Figure 5.18), which motivates an investigation into whether Loop A could be connected to the the dipole modulation anomaly.

We follow the approach of Akrami et al. [70], which was also employed by Planck in 2015. Planck reports a direction of $(l, b)[^{c}irc] = (225, -18) \pm 24$ with amplitude $A = 0.066 \pm 0.021$ for SMICA [69]. We use 3072 discs placed at the pixel centers of a HEALPix $N_{side} = 16$ map, with a disc size of 8°, to calculate the local variance of the SMICA map. Only discs where more $\geq 90\%$ of the pixels are unmasked are used. The variance for each disc is assigned to the matching $N_{side} = 16$ pixel, resulting in a low



Figure 5.18: Dipole modulation direction for Planck maps [38] and WMAP 5yr ILC, with the SMICA loop A area shown.

resolution variance map. From this map we have subtracted the mean variance calculated for the 1000 FFP9 simulations, and done inverse variance weighting by this mean value, as can be seen in Figure 5.19. From the $\Delta\sigma^2/\sigma^2$ map we may extract a dipole, setting the masked pixels to zero. Note that in [69, 70] they do these calculations on the full resolution map, while we use the maps at $N_{side} = 256$ due to computational limitations. However, for the Planck 2015 SMICA map masked with the common mask we obtain a modulation amplitude of A = 0.056 and direction $(l, b)[^\circ] = (217, -26)$, in excellent agreement with both the Akrami et al. and Planck 2015 results. We therefore believe that the results reported here will not change significantly if repeated at full resolution.

We now repeat this procedure using the masks outlined in Section 5.2.2. Since we suspect Loop A could significantly affect the dipole modulation we also test another mask, denoted mask 6, which is the combination of the common mask and Loop A. The directions of the dipole modulation obtained with each mask are shown in Figure 5.20. The directions are consistent with the ones found by Planck (within the 1σ uncertainty, shown in light blue), and do not change much with the masks.

While the direction of the dipole modulation does not change much by employing the masks, the modulation amplitude highly affected. To assess the significance of this we process all 1000 simulations with each of the seven masks, and plot the corresponding distribution of the dipole amplitude together with the SMICA values in Figure 5.21. Each vertical line represents the amplitude for the SMICA map, which should be compared to the distribution of the same color. The p-values—the number of simulations with a higher



Figure 5.19: Local variance map for Planck 2015 SMICA with the common mask.



Figure 5.20: Dipole modulation direction for each of the 6 masks and the Planck 2015 SMICA direction. The light blue area indicates the 1σ (±24°) limit on the SMICA direction given by Planck 2015.

modulation amplitude than the SMICA value—are summed up in Table 5.3. We see that the anomaly is alleviated for both masks that include Loop A. Since mask 2 actually gives a more anomalous result than just the common mask, it seems logical that the *p*-value of mask 4 is lower than for mask 6, although both are no longer significant.



Figure 5.21: Dipole modulation amplitude. The distributions are for the 1000 FFP9 simulations masked with each mask respectively. The dashed vertical lines are the amplitude values for SMICA masked with the six masks. The colors indicate the masks used, as shown in the legend.

Mask	Region covered	<i>p</i> -value
0	common mask	1.4%
1	common + WMAP 9 yr pol mask	1.4%
2	common + Loop 1	0.7%
3	common + Loop 1 and 4	1.3%
4	common + Loop 1 and A	8.1%
5	common + Loop 1, 2, 3 and 4	1.1%
6	common + Loop A	20.5%

Table 5.3: p-values for the dipole modulation amplitude with the six masks.

5.2.3 Discussions

We have investigated possible correlations between the Galactic radio loops and the Planck 2015 SMICA map, and found support for the claim that Loop 1 is present in the map. Analyzing the T^2 SMICA temperature map, we also found indications of a new peculiar region on the sky. Since its morphology is fairly well described by a loop structure, we denoted it Loop A. We note that this "loop" is not a known Galactic radio loop. An interesting feature of this Loop A is that half of it is exactly π displaced from the NPS.

We investigated the impact of the loop regions on several low multipole CMB anomalies previously reported. For the point-parity asymmetry, we found that masking Loop 1 and Loop 4 removes the significant parity asymmetry of the TT power spectrum in the $\ell = 10 - 40$ range. Furthermore, masking only the NPS does not alleviate the anomaly like masking the full Loop 1 does. This implies that not only the NPS but probably the full Loop 1 is present in the SMICA map. The quadrupole-octupole alignment can be very well reproduced by templates of the loops which have been fitted to the low multipole SMICA map. Cleaning the SMICA map with these templates removes the alignment. The best templates appear to be the ones including Loop A. We also investigated the effect of the loops on the dipole modulation amplitude and direction. We found that the regions of Loop 1 and Loop A have the largest effect on the dipole modulation amplitude, but in opposite directions. The *p*-value of the dipole modulation amplitude is no longer anomalous when masking out Loop A (together with the common mask). In conclusion the Loop A region is highly connected to these low multipole anomalies, and its nature requires further investigations.

Some of the other anomalies are the North/South hemispherical asymmetry, the low power of the quadrupole and the WMAP cold spot. While we have not directly addressed these anomalies in this work, it is clear that they could easily be connected to the discussed loops. The North/South hemispherical asymmetry has also previously been connected with the dipole modulation, which we have shown is related to the high power in the area of Loop A. If the surplus of power in this region is attributable to some contamination, this would also affect the power asymmetry. The low power of the quadrupole becomes even lower by the introduction of the loops, which now account for most of the power of $\ell = 2$. The WMAP cold spot is positioned in the Loop A area, and further understanding of why this area impacts other low multipole anomalies could shed light on the nature of the Cold Spot.

5.3 Galactic radio loops in the Fermi-LAT data

In this section we look at a possible morphological connection between Loop 1 at microwave frequencies and at gamma-ray energies. The initial motivations for the work were based in presentations given by Troy Porter and Igor Moskalenko at the Niels Bohr Institute in May 2014. Here, they presented a collection of residual maps-the difference between Fermi gamma-ray data and Galprop¹⁰ [115, 116] models of the diffuse Galactic gamma-ray emission, shown in Figure 5.22. Since the residual maps showed a clear indication of Loop 1, the motivation was to investigate a possible morphological connection between the Fermi-data (and residual maps) and the Planck CMB maps, which we saw in the previous section could be contaminated by Loop 1, in order to quantify a possible contribution of this loop emission. Thus, the main question for this endeavor was whether we could find significant cross-correlation between the Planck SMICA map and the residual map. Another part of the project was to extend the cross-correlations to the frequency maps in both temperature and polarization, which is still ongoing and not presented here.

The Fermi gamma-ray Space Telescope [117] is a spacecraft sent into near-Earth orbit in 2008, with the purpose of observing cosmic rays from our Galaxy and extra-galactic sources. The primary instrument, Large Area Telescope (LAT), does full-sky imaging of the gamma-ray sky from 20 MeV to 300 GeV. The instrument relies on conversion of gamma-rays to electron-positron pairs, which are recorded by a precision tracker and a calorimeter. The instrument can observe in two directions at the same time (front and back). Fermi also carries an instrument for studying gamma-ray bursts from distant galaxies. The Fermi-LAT data¹¹ used here is full-sky, full-mission front events (Pass 7) from 1-100 GeV in four energy bins (Figure 5.22). The residual map is the difference between a Galprop model of the diffuse gamma-ray emission due to the propagation of cosmic rays [115, 116], and the actual Fermi-LAT data. The residual map [118] used was originally the product of Fermi-LAT work on the inner Galaxy [119]. The energy bins in the figures refer to the integrated energy bins for the Fermi residual maps. Energy bin 1 (E1) corresponds to 1-3.16GeV, energy bin 2 (E2) corresponds to 3.16-10GeV, energy bin 3 (E3) corresponds to 10-31.62 GeV and energy bin 4 (E4) is 31.62-100GeV. Note that energy bin 4 (31.62GeV - 100GeV) is too sparse to make reliable cross-correlation analyses. All maps are at HEALPix $N_{side} = 256$. The Planck data used is the DX11 maps and FFP9 (the official 2015 data release).

¹⁰http://galprop.stanford.edu/

¹¹http://fermi.gsfc.nasa.gov/ssc/data/



Figure 5.22: Top: The Fermi gamma-ray data (energy bin 1), unsmoothed. Bottom: the residual map used, smoothed by 1.3 degrees (energy bin 1).

5.3.1 Cross-correlations of Planck and Fermi data

We test the cross-correlation between the Planck 2015 SMICA map and the Fermi data through mosaic cross-correlation. Since our hypothesis is, that some of the structure seen in the Fermi residual map is connected with Loop 1 (see Figure 5.23), we can test if the residuals of Loop 1 we suspect are present in the SMICA map cross-correlate with this difference map.



Figure 5.23: A cut out of Loop 1 (width of 20 degrees) in the residual map from Figure 5.22.

The mosaic cross-correlation method calculates the cross-correlation coefficients for patches of the sky, which in turns gives a picture of the morphology of the cross-correlation. These patches, p, contain a number of pixels, i, which are summed over when calculating the cross-correlation coefficient. This means that we can create a map of the morphology of cross-correlations, albeit at a lower resolution than the input map.

$$K_{p} = \frac{\sum_{i \in p} (x_{i} - \bar{x}_{p})(y_{i} - \bar{y}_{p})}{\sqrt{\sum_{i \in p} (x_{i} - \bar{x}_{p})^{2} \sum_{i \in p} (y_{i} - \bar{y}_{p})^{2}}}.$$
(5.8)

Here we do the summation over pixels in Eq.(5.8), by using the pixelization of the map. We are using HEALPix for the calculations, and thus the number of pixels summed over is $p = \left(\frac{N_{side}^{in}}{N_{side}^{out}}\right)^2$, in HEALPix notation. We start from a resolution of $N_{side} = 256$ and downgrade to $N_{side} = 32$, which gives us p = 64.



Figure 5.24: Mosaic cross-correlation between SMICA and the residual map. Bottom map is smoothed by a 5 degree Gaussian kernel.

Shown in figure 5.24 is the mosaic cross-correlation map for the SMICA map with the residual map for the first energy bin. Smoothing by 5 degrees (bottom) shows the morphological structure of the cross-correlation better, at the expense of the amplitude of correlation.

We can compare the distributions of the cross-correlation coefficient for the full map with the ones for the map outside a mask covering the Galactic plane, for the area only inside Loop 1 (20 degree width) and for the area only inside the NPS. To assess the significance of these cross-correlations between SMICA and the residual map, we repeat the calculations for the 1000 FFP9 Monte Carlo simulations of the CMB. In Figure 5.25 the comparison between the distributions of correlation values for SMICA and the simulations is shown. For all three energy bins we clearly see that SMICA and the simulations are completely in agreement for the full map and the map outside the galactic mask. For Loop 1 and the NPS we see indications that there might be some tendency toward higher correlation values than the distribution from simulations. However, the low number of pixels for the NPS makes the spread in the distribution for the simulations big, and a distinction of a significant discrepancy is not possible. These indication do merit further investigations of Loop 1 in the Fermi residual map, which will be the subject of future work.



Figure 5.25: Distributions for the mosaic cross-correlation between SMICA and the residual map. From left to right: Energy bin 1, 2 and 3. From top to bottom: Full map (red), outside the Galactic mask (green), only inside Loop 1 (20 degree width) (blue) all with bins of 0.05, and lastly: only inside the NPS (yellow), with bins of 0.1.

5.4 Galactic conclusions

On the background of the investigations presented in section 5.2 we have convincing evidence that (some of) the Galactic Loops are present in the Planck CMB maps, and that they impact several large scale anomalies. These are the point-parity asymmetry of the power spectrum, the quadrupole-octupole alignment and the dipole modulation. While we have not directly addressed other these anomalies in this work, they could be connected to the discussed loops.

It has not been the scope of this work to find a physical model of the type of component which might cause a leak of the loops into the CMB, without being picked up by the component separation methods. We note, however, that recent discussions on a magnetic dust component could provide such a source. For example, in Mertsch and Sarkar (2013) [92] it was suggested that in the frequency region between the two dominant components (dust and synchrotron) of a supernova shell, the emission could be dominated by a new component, namely magnetic dust. This is a previously undetected foreground component, predicted in [28, 34, 120], which can emit polarized photons in the range 100 - 200 GHz. The weak frequency-dependence of this component allows it to be absorbed into the derived CMB map (such as SMICA), without being picked up by component separation algorithms. In the Planck intermediate results XXII paper [121], a magnetic dust component has also been discussed. Taking a look at the Planck Anomalous Microwave



Figure 5.26: The AME 1 map from the Planck 2015 Commander component separation [24]. Superimposed are the four Galactic radio loops and Loop A.

Emission (AME) component map from Figure 2.10, we see a strong overlap between the Loop regions and the strongest emission (see Figure 5.26). It has previously been argued that this emission is due to spinning dust, but B. S. Hensley and B. T. Draine argue in [32] that this is probably not the case. Rather, they encourage further investigations into magnetic dust as an explanation for the AME emission.

We have aimed at showing that the Galactic radio loops indeed could be present in the Planck SMICA map, and that they—together with the Loop A region—could be connected to some of the low multipole CMB anomalies. The analysis here is not exhaustive, and future investigations should apply even more sophisticated tests for all the anomalies studied here. However, our aim was to perform an initial investigation, testing if and how the loops could affect the low multipole CMB anomalies. We hope these results will emphasize the need for further investigations into the Loop regions.

6

DISCUSSING THE ORIGINS OF THE CMB ANOMALIES

Three areas have been under investigation through this thesis: tests of the consistency of Planck and WMAP CMB data, a cosmological explanation to one of the large-scale anomalies, and an unveiling of Galactic contamination of the CMB maps in connection with several large-scale anomalies. Here it is time to connect the dots and try to answer the question posed at the beginning: what are the origin(s) of the large-scale CMB anomalies, and are they related or statistically independent? While I do not claim that all possibilities have been investigated exhaustively, I do believe we can present some increased clarity on these matters.

With respect to the consistency, we found that the three 2013 Planck CMB maps were very consistent, both with each-other and with simulations. Our results indicated that the WMAP ILC9 map is actually more contaminated than both the WMAP ILC7 map and the Planck maps. For the unpublished SMICA power spectrum we found good consistency for the range up to $\ell_{max} = 700$. We did see indications that the variance of the residuals of the power spectrum is higher than of simulations for a range up to $\ell_{max} = 500$, with a *p*-value of 1.6% for even multipoles and 2.5% for odd ones. In general, there were no discrepancies between the consistency for even and odd multipoles.

In chapter 4 we fit a curvaton inflationary model with three parameters to the WMAP ILC7 data. The purpose was to test which constraints we would have to impose on the model in order to reproduce the observed point-parity asymmetry of the power spectrum. We discovered that if the wavelength of the curvaton perturbation is comparable to or smaller than the horizon, then the model can fit the parity asymmetry of the CMB power spectrum fairly well. A further possibility, that the scenario could also explain even more asymmetry anomalies, was suggested for future work.

Investigating the Galactic foregrounds, we found evidence of a connection between regions associated with the Galactic radio loops and some of the low multipole anomalies of the CMB. We also identified a new peculiar region, which we denoted Loop A due to its loop-like structure. We investigated the impact of these regions on the CMB anomalies. We fitted templates of the Loops to the Planck 2015 SMICA map, and found that we could reproduce the CMB quadrupole and octupole, as well as their alignment, very well for templates including Loop A. For the point-parity asymmetry we found that masking Loop 1 and 4 strongly alleviates the anomaly. The Loop A area also had an impact on the dipole modulation, whose direction it almost coincides with. Masking Loop A strongly reduces the dipole modulation amplitude anomaly. While it was not the scope of the work to determine a physical model of how the Galactic radio loops, and the peculiar Loop A region, could leak into the SMICA CMB map, we note that recent discussions on magnetic dust could provide an explanation. We also looked at a possible connection between gamma-ray data and CMB data for the Galactic radio loops. We did not find any correlations between the Planck SMICA map and the Fermi-LAT data, but future investigations into the Loop 1 area could provide interesting information on the effect of the loops in gamma-rays.

With regards to the question of whether the CMB anomalies have their origin in systematics, cosmology, foregrounds or simply statistical flukes was raised. This thesis has addressed some of these aspects, testing the impact on anomalies of various approaches. With regards to the option of foregrounds, we may conclude that there are promising results that indicate that the origin of at least some of the anomalies could be associated with Galactic contamination of the CMB maps.

It is my personal belief that we will find that the origin of most of the large-scale anomalies are connected to Galactic and Solar System residuals. Take for example the point-parity asymmetry. While we have shown that it is possible to reproduce asymmetric behavior of the power spectrum through the curvaton scenario, the argument against it is that the curvaton scenario recently has been shown to be disfavored by observational evidence [122] from the Planck data. On the other hand, the point-parity has been shown to be highly affected by the removal of the Galactic radio loops, and to some extend the ecliptic plane. The presence of these foregrounds in the CMB maps has been suggested to be magnetic dust, which in turn makes the need for a cosmological explanation moot.
6.1 Future outlook

The evidence for the presence of Galactic loops in the CMB data, however, is not yet complete. More tests are needed, on both the impact on anomalies as well as the nature of the emission. Future work should focus on determining whether magnetic dust is indeed a (polarized) foreground in the Planck data, as suggested, as well as its spectral properties. The connection of the loops to more anomalies could also be tested further. With regards to the comparison between Fermi and Planck data, an effort to model the contribution from nearby Galactic Loops in gamma-rays into the Galprop models of the diffuse emission would be very interesting. The tests on anomalies in this thesis only consider temperature data, but a logical next step is the investigation of identified peculiar areas in polarization. We know, for example, that the emission in the Galactic radio loops are supposed to be very polarized, and we can thus hope to get a better understanding of the nature of their emission.

After the Planck 2015 polarization results and corresponding constraints on the tensorto-scalar ratio, the future of CMB science seems to lie in B-mode polarization and the hunt for primordial gravitational waves. The challenge is, that the observed B-mode polarization is dominated by lensing of the CMB by galaxy clusters [123], and by polarized dust in our own Galaxy [124, 125]. These components must be constrained and cleaned to very high precision before any primordial signal can be seen. If some of the anomalies are due to Galactic contamination, and perhaps even a new (polarized) component, we cannot hope to achieve the levels of precision needed to observe and constrain primordial B-modes without an understanding of the origin of the anomalies. Although the claim from the BICEP2 experiment in 2014 [126] of the discovery of primordial B-modes was later attributed to be a signature of dust, through a joint analysis with Planck [127], many experiments (BICEP3 included) are still vigorously working towards the observation of primordial B-modes.

For the past decades the CMB has given us a unique window to the earliest Universe, and continues to do so. While much space has been spent on the anomalies in this thesis, they cannot negate the enormous addition to our understanding of the fundamentals as well as intricacies of the Universe that we have gained through these data. An understanding of the origin of the CMB anomalies would be an extra feat in the line of great accomplishments achieved through observations of the Cosmic Microwave Background.

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¹²http://www.esa.int/Planck

¹³http://www.cosmos.esa.int/web/planck/planck-collaboration

¹⁴http://pla.esac.esa.int/pla

¹⁵http://www.glesp.nbi.dk/

¹⁶http://www.eso.org/science/healpix/

List of Figures

1.1	Milky way at different wavelengths.	2
2.1	CMB map	8
2.2	CMB Experiments	9
2.3	2004 CMB power spectrum	10
2.4	Planck temperature power spectrum	11
2.5	Planck polarization power spectra	12
2.6	Constraints on tensor-to-scalar ratio.	13
2.7	Polarization angle	14
2.8	Frequency maps Planck 2015	15
2.9	Frequency dependence of foreground components	16
2.10	AME component maps	17
2.11	The four CMB maps from Planck 2013	19
2.12	Planck confidence mask	19
2.13	SMICA weights	21
2.14	Anomaly: lack of large-scale angular correlation	25
2.15	Anomaly: dipole modulation	27
2.16	Anomaly: alignment	28
2.17	Anomaly: point-parity asymmetry 2013	30
2.18	Anomaly: point-parity asymmetry 2015	31
3.1	Planck 2013 NILC, SMICA and SEVEM maps	36
3.2	Planck difference maps	37
3.3	Planck difference map cross-correlations	38
3.4	WMAP cross-correlations	39
3.5	WMAP difference maps	40
3.6	Planck and WMAP difference maps	41
3.7	Planck and WMAP cross-correlations	42
3.8	SMICA δ DX9 temperature power spectrum $\ldots \ldots \ldots \ldots \ldots \ldots$	43
3.9	Distribution of $\sqrt{\ell + 0.5} \Delta C_{\ell} / C_{\ell}^{th}$ and fit $\ldots \ldots \ldots \ldots \ldots \ldots$	44

3.10	Variance, skewness and kurtosis for SMICA temperature power spectrum	44
3.11	Same as Figure 3.10, but varying ℓ_{max}	45
4.1	Determining curvaton model parameters	53
4.2	Parity of the curvaton model	54
4.3	Best orientation of the model	55
4.4	Maps of $l = 2 - 7$ for the model and ILC7	58
4.5	The effect on the power spectrum of a plane wave component	59
4.6	Power spectra of the model and WMAP ILC	60
5.1	Planck 2013-2015 difference maps	65
5.2	The Haslam map	66
5.3	Planck polarized 30 GHz	67
5.4	SMICA with Galactic radio loops	67
5.5	Temperature analysis in Loop 1	68
5.6	Mean temperature of Loop 1	68
5.7	Thresholds on the T^2 SMICA map	69
5.8	SMICA with loops and IRAS	70
5.9	857 GHz with Loop A and IRAS	70
5.10	Loop A temperature analysis	71
5.11	Displacing Loop A by π	72
5.12	Masks used in the analysis	74
5.13	Point-parity ratio and <i>p</i> -value	76
5.14	Best fit templates of the loops and their residual maps	79
5.15	Angular power spectra for residual maps	80
5.16	$\ell = 2, 3$ and their sum for the templates	81
5.17	$\ell = 2, 3$ and their sum for the residual maps	82
5.18	Dipole modulation directions	85
5.19	Local variance map	86
5.20	Dipole modulation direction for the masks	86
5.21	Dipole modulation amplitude	87
5.22	Fermi data and residual map	90
5.23	A cut out of Loop 1 in the residual map	91
5.24	Mosaic cross-correlation of SMICA with residual map	92
5.25	Distributions for mosaic correlation	93
5.26	Planck AME 1 map	94

List of Tables

2.1	Overview of component separation algorithms	18
2.2	Anomalies	23
3.1	Planck cross-correlation values	38
3.2	WMAP cross-correlation values	39
3.3	Planck and WMAP cross-correlation values	42
3.4	Significance of variance for $\ell = 500$	46
4.1	The curvaton model-to-ILC correlation coefficients	56
5.1	Description of the masks we consider in this section	73
5.2	Alignment statistics	84
5.3	p-values for the dipole modulation amplitude	87

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Appendices

Appendix A

Harmonic Coefficients of the Loops

We present here the expressions used for the harmonic coefficients of the four radio loops, as well as for our toy models of Loop A and the Galactic Cold Spot. As the angular profile of each loop, we use the model suggested by [110],

$$L(\alpha,\beta;\theta) = \frac{1}{\sqrt{\sin^2\beta - \sin^2\alpha}} \begin{cases} \sqrt{\sin^2\beta - \sin^2\theta} - \sqrt{\sin^2\alpha - \sin^2\theta} & \theta < \alpha, \\ \sqrt{\sin^2\beta - \sin^2\theta} & \alpha \le \theta \le \beta, \\ 0 & \theta > \beta, \end{cases}$$
(A.1)

where α is the inner angular radius of the loop, $\beta > \alpha$ is its outer radius and the peak amplitude at $\theta = \alpha$ has been normalized to 1. The harmonic transform of this profile is calculated in detail in [110], and is given by

$$L_{\ell}(\alpha,\beta) = \sqrt{\pi(2\ell+1)} \int L(\alpha,\beta;\theta) P_{\ell}(\cos\theta) \sin\theta \,d\theta$$

= $\sqrt{\frac{\pi}{2\ell+1}} \frac{K_{\ell}(\alpha) \sin\alpha - K_{\ell}(\beta) \sin\beta}{\sqrt{\cos^2\alpha - \cos^2\beta}},$ (A.2)

where

$$K_{\ell}(\alpha) = \frac{\ell+2}{2\ell+3} H_{\ell+2}(\alpha) + \left(\frac{\ell+1}{2\ell+3} - \frac{\ell}{2\ell-1}\right) H_{\ell}(\alpha) - \frac{\ell-1}{2\ell-1} H_{\ell-2}(\alpha), \quad (A.3)$$

and $H_{\ell}(\alpha)$ is the hypergeometric function

$$H_{\ell}(\alpha) = {}_{2}F_{1}\left(\frac{1}{2} - \frac{\ell}{2}, 1 + \frac{\ell}{2}; \frac{3}{2}; \sin^{2}\alpha\right).$$
(A.4)

We set $\beta = \alpha + \delta$, where δ is the angular width of the loop.

121

For the two cold spots, the one overlaid on top of the hot Loop A (the Orion–Eridanus Superbubble) and the GCS, we take a Gaussian profile,

$$G(\sigma; \theta) = \exp\left(-\frac{1-\cos\theta}{\sigma^2}\right),$$
 (A.5)

which has also been normalized to unit peak amplitude. In order to be able to calculate its harmonic transform analytically, we use here a Gaussian in $2\sin(\theta/2)$ instead of a Gaussian in θ . The harmonic transform of the profile is then

$$G_{\ell}(\sigma) = \sqrt{\pi(2\ell+1)} \int G(\sigma;\theta) P_{\ell}(\cos\theta) \sin\theta \,\mathrm{d}\theta$$

= $\sqrt{4\pi(2\ell+1)} e^{-1/\sigma^2} i_{\ell}(\sigma^{-2}),$ (A.6)

where $i_{\ell}(x)$ is the modified spherical Bessel function of the first kind. We use the (approximate) FWHM of the spot, $\delta = 2\sqrt{2\log 2}\sigma$, to parametrize its angular width.

Each of the profiles described above is of an azimuthally symmetric object placed at the north pole of the sphere. In order to place the object at an arbitrary direction (θ, φ) , we simply multiply the coefficients with a Wigner rotation matrix $D_{m0}^{\ell}(\varphi, \theta, 0)$. As the location of each object is known, we are left with δ , the angular width, as the only free parameter apart from the overall amplitude. The harmonic coefficients of the object *i* are therefore

$$s_{\ell m}^{(i)}(\delta) = D_{m0}^{\ell}(\varphi_i, \theta_i, 0) L_{\ell}(\alpha_i, \alpha_i + \delta)$$
(A.7)

if it is a loop, and

$$s_{\ell m}^{(i)}(\delta) = D_{m0}^{\ell}(\varphi_i, \theta_i, 0) G_{\ell}\left(\frac{\delta}{2\sqrt{2\log 2}}\right)$$
(A.8)

if it is a spot. These objects all have unit amplitudes.

Publication list

Presented here is a list of the publications I have co-authored during my Ph.D. studies.

- [1] A. Frejsel, M. Hansen, and H. Liu. *Consistency tests for Planck and WMAP in the low multipole domain*. JCAP, 6:5, arXiv:1305.4033, June 2013.
- [2] H. Liu, A. M. Frejsel, and P. Naselsky. *Large-scale anomalies of the CMB in the curvaton scenario*. JCAP, 7:32, arXiv:1302.6080, July 2013.
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- [4] Planck Collaboration. *Planck intermediate results. XXV. The Andromeda Galaxy as seen by Planck.* arXiv:1407.5452, July 2014.
- [5] Planck Collaboration. *Planck intermediate results. XXVI. Optical identification and redshifts of Planck clusters with the RTT150 telescope.* arXiv:1407.6663, July 2014.
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- [8] Planck Collaboration. Planck intermediate results. XXXIII. Signature of the magnetic field geometry of interstellar filaments in dust polarization maps. arXiv:1411.2271, November 2014.

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- [21] Planck Collaboration. Planck 2015 results. XIX. Constraints on primordial magnetic fields. arXiv:1502.01594, February 2015.
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- [25] Planck Collaboration. *Planck 2015 results. XX. Constraints on inflation.* arXiv:1502.02114, February 2015.
- [26] Planck Collaboration. *Planck 2015 results. XXI. The integrated Sachs-Wolfe effect.* arXiv:1502.01595, February 2015.
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- [35] Planck Collaboration. *Planck 2015 results. V. LFI calibration*. arXiv:1505.08022, May 2015.

- [36] Planck Collaboration. *Planck 2015 results. XVI. Isotropy and statistics of the CMB.* arXiv:1506.07135, June 2015.
- [37] A. Frejsel, D. Molinari, H. Liu, S. v. Hausegger, A. Ben-David, and P. Naselsky. *Impact of Galactic Loops on the low multipole CMB anomalies*. In preparation, July 2015.

Abstract

This thesis focuses on the large scale anomalies of the Cosmic Microwave Background (CMB) and their possible origins. The investigations consist of two main parts. The first part is on statistical tests of the CMB, and the consistency of both maps and power spectrum. We find that the Planck data is very consistent, while the WMAP 9 year release appears more contaminated by non-CMB residuals than the 7 year release. The second part concerns the anomalies of the CMB from two approaches. One is based on an extended inflationary model as the origin of one specific large scale anomaly, namely point-parity asymmetry. Here we find that a modified curvaton model can reproduce an asymmetric behavior of the power spectrum at low multipoles. The other approach is to uncover whether some of the large scale anomalies could have a common origin in residual contamination from the Galactic radio loops. Here we find evidence that the Planck CMB maps contain residual radiation in the loop areas, which can be linked to some of the large scale CMB anomalies: the point-parity asymmetry, the alignment of quadrupole and octupole and the dipole modulation.