

The aim of this section is to provide some more information about the activities summarised above.

I am currently a Staff Research Scientist at the Jet Propulsion Laboratory, JPL, and a Visitor in the California Institute of Technology, Caltech, Physics department, Observational Cosmology group. For the past 3 years I was a Staff Scientist at the Infrared Processing and Analysis Center, IPAC, Caltech. I have been a research fellow for 8 years, as a Postdoctoral Scholar in Physics at the Observational Astronomy Group in the California Institute of Technology, Caltech; and previously as a Leverhulme fellow in the Cavendish Astrophysics Group, University of Cambridge, UK, and beforehand as a Postdoctoral fellow at the Center for Astrophysics of the University of Porto (CAUP), Portugal and also in the Department of Physics, Kansas State University, USA.

The research activity carried out after my PhD has greatly increased my knowledge and understanding and has diversified my interests.

### **1 Supervision experience.**

Throughout my time as a PhD student at Cambridge, as a JNICT research fellow at the University of Cambridge, and as an FCT research fellow in the University of Porto, I have maintained a role in the supervision of students. As a postgraduate student, I tutored the course 'Part IA Elementary Mathematics for Biologists', at New Hall, Cambridge. After finishing my PhD I provided additional input to Anthony Lasenby's PhD student Pia Mukherjee at the start of her PhD. I also took an active interest in the work of Mike Hobson's PhD student Sarah Bridle: the starting point for her research was derived from previous work developed during my PhD. This resulted in a joint paper [6]. I also jointly supervised two undergraduate students at Porto on their parallel project under a grant for initial research work, as well as providing additional input to Paul Scott's PhD student Richard Savage at MRAO, Cambridge and Joe Silk's PhD student Rebecca Bowen at Oxford as a result of my stay as a visitor at the University of Oxford. I tutored the course 'Electromagnetism, Mathematical Tripos Part IB' for Queens, Jesus, Magdalene and Pembroke College as well as 'Introduction to Special Relativity', for Downing and Magdalene college. I also supervised my PhD student, Sarah Smith, from October 2002, on 'Non-Gaussianity in the Cosmic Microwave Background'. By the same time became second supervisor of Gayoung Chon on 'Theoretical Studies of the Cosmic Microwave Background'. Later on became the supervisor of Nutan Rajguru on 'Observations of the Cosmic Microwave Background with the Very Small Array'. I also worked with other PhD students at the Cavendish and IOA namely Jason McEwen and Fergus Simpson, among others. Both my students completed their PhD in 3 years and their thesis have been nominated for the Royal Astronomical Society, Michael Penston, prize. Since 2005 I work actively with students and postdocs such as Kevin Huffenberger, Loris Colombo, Sanjit Mitra, Rajib Saha, etc. from both Caltech, campus and JPL mostly on Planck satellite. I also work with students and postdocs of the BICEP collaboration as well as with other collaborators on other experiments such as CBASS, QUIET, etc. I participate actively in the weekly Planck Algorithm Development Group, ADG, meetings at JPL as well as in the weekly BICEP group meetings and several Planck core and working group telecons.

### **2 Academic lecturing experience.**

After the conclusion of my first degree in Theoretical Mathematics I taught a mathematics course for 5 years. I also ran classes in the 'Theory of Manifolds' final year option course for the Mathematics degree in the University of Porto. This course involves the understanding of differential geometry as well as topology of manifolds. During this period I simultaneously took a degree in Physics and Applied Mathematics. For the academic year of 1998 I prepared the fourth-year option in Astronomy course on "Extragalactic Astronomy" for the Physics and Applied Mathematics degree at the University of Porto. This course provided a general overview of extragalactic astronomy and particularly highlighted its observational aspects.

I also provided a postgraduate course on 'Comparison of Microwave Background Predictions and Observations', held at CAUP, University of Porto, during 1999. This course covered most topics of my PhD thesis and was intended to provide an understanding of both CMB theory and observations and their implications for Cosmology.

The course covered the mathematical tools commonly used in CMB analysis, a description of CMB experiments, procedures to simulate CMB maps, Bayesian data analysis as applied to the Tenerife CAT and PYTHON experiments, comparison of experiments with theory and constraints on the cosmological parameters using current CMB observations.

Finally, I gave lectures at the Cavendish Astrophysics Group during lent terms, a graduate course on 'The Cosmic Microwave Background and Structure Formation'. This course comprised of eight lectures on: (1) Cosmological Perturbations I : Newtonian perturbation theory; (2) Cosmological Perturbations II: Relativistic perturbation theory; (3) Statistics of Random Fields: Random fields in 3D Euclidean space; the Power Spectrum; two-point correlation functions; two-point statistics; Gaussian processes; Beyond the Power spectrum; Random fields on the sphere, Non-Gaussianity; non-Gaussianity tools; (4) Inflation I - Fundamentals of Inflation: Motivation of Inflation; Scalar Fields; Slow-roll inflation; Exact solutions; The end of inflation; (5) Inflation II - Fluctuations from Inflation: Scalar field fluctuations; Curvature perturbation; Equations of motion; Canonical quantisation; Heisenberg equations of motion; Mode expansion; Power Spectra; Predictions for Slow-roll inflation; Spectral index; Classicality and Gaussianity. Topological Defects - Cosmic Strings and structure formation; (6) The Cosmic Microwave Background I - The physics of the CMB: Temperature anisotropies; Polarization of the CMB; Anisotropy Power Spectrum; Mechanisms for primary fluctuations: Sachs Wolfe effect, Acoustics Peaks; Silk damping, damping of the CMB power spectrum; tensor perturbations - gravitational waves; (7) The Cosmic Microwave Background II -Cosmological Parameters in the CMB (with animations) An introduction to: CAMB, CMBFAST, COSMOMC, HEALpix, NGsims, CMB observations; (8) Large Scale Structure: Galaxy formation and clustering, non-linear gravitational clustering; The Zeldovich approximation; Press-Schechter theory; the clustering spectrum; biased galaxy formation; etc. Putting observations together.

My first degree in Theoretical Mathematics and my subsequent career in mathematical astrophysics provide me with a good basis for teaching General Relativity and other theoretical astrophysics courses. In addition my second degree in Physics/Applied Mathematics (Astronomy) provides me with a broad background knowledge for teaching a wide range of astrophysics courses.

### 3 Research experience

My research experience has been mostly dedicated to studying the Cosmic Microwave Background anisotropies, in particular CMB theory, data analysis and simulations with a view to cosmological parameter estimation. Recently I have begun new projects diversifying my research experience.

#### 3.1 Overview of the Cosmic Microwave Background.

The CMB is microwave radiation which fills our observable universe. It is thought to be radiation left over from a time only about 300,000 years after the Big Bang, when the expanding universe had cooled to temperatures of about 3,000 K. At the present cosmological epoch, this radiation has been redshifted to microwave wavelengths. It was first detected as an apparently uniform background of radiation in 1965, but it was only in 1992 that very low level fluctuations, departures from isotropy, were detected statistically by the COBE satellite. Those fluctuations are signatures of initial perturbations which subsequently grew under the influence of gravity to become the galaxies and structures that we see in the universe today. In the past years new experiments have made much more accurate measurements of the CMB anisotropies including the NASA satellite experiment WMAP and ESA is undergoing construction of the new Planck satellite experiment.

One of the key reasons for the interest in the CMB is that it provides extremely powerful constraints on the values of key cosmological parameters characterising the primordial fluctuations, the geometry of the universe and its matter content. Optimal methods have been developed to extract information about model parameters such as matter density of the universe, rate of expansion, baryonic content, cosmological constant content, dark energy content, spectrum of the initial fluctuations, whether the fluctuations are Gaussian, the history of re-ionisation and whether there is a tensor (gravitational radiation) contribution to the fluctuations.

Recent CMB experiments such as Boomerang, MAXIMA, DASI, CBI, VSA, ARCHEOPS, WMAP, QUAD, ACBAR, among others seem to validate, apart some intriguing discrepancies, the so-called concordance model of cosmology. This emerging standard model of cosmology is a flat- $\Lambda$  dominated universe with initial nearly scale

invariant adiabatic Gaussian fluctuations. In this model, the Universe is spatially flat and is dominated at late times by cold dark matter and a mysterious form of ‘dark’ energy that causes the observed accelerated expansion. Evolving on this background are density fluctuations, plausibly generated during an early period of inflation, which are very close to Gaussian and have a nearly scale-invariant power spectrum.

### 3.2 CMB data analysis.

My Ph.D. thesis, completed in 1997, was on testing the predictions of large scale structure models using the observations of the CMB anisotropies. My pursuit for such a standard model started at a time when the first detection of large angular scale primordial CMB anisotropy was reported using the COBE DMR experiment. This was followed by low frequency confirmation from the (ground-based switching experiment) Tenerife experiment. I was then given the task to interpret such detection and to confront the observations with the several existing models of structure formation. Bridging the gap between the theoretical realm of such models and the existing experimental set up. Therefore part of my PhD research work consisted of CMB data analysis, and in particular I became familiar with Bayesian techniques such as Likelihood analysis which I applied to the Tenerife [1] and, later on during my post-doctorate position at KSU, Python I-III experiments [2]. Meanwhile since the COBE detection, several other experiments had reported detections on intermediate angular scales whilst more sophisticated theoretical calculations of the temperature fluctuations of the CMB, arose with optimal codes for estimation of the angular power spectrum  $C_l$ . At this point in my PhD I proceeded with cosmological parameter estimation from the intercomparison of CMB experiments and models of structure formation [4, 5]. From this initial attempt to incorporate all the available CMB data sets in a single analysis emerged the first estimate of the angular position of the main Doppler peak which was used to place a direct limit on the curvature of the Universe. This work was later extended to include large scale structure observations [6]. This parameter cosmological estimation assumed that primordial fluctuations were adiabatic, that is the relative abundances of different particle species were unperturbed from their thermal equilibrium values. In the simplest inflationary models the perturbations are indeed adiabatic, Gaussian and with a nearly scale invariant spectrum. Nevertheless, if there are fields which were perturbed during inflation such that their excitations survived or decayed in a non-adiabatic way, then isocurvature fluctuations could be generated.

During my PhD I also produced Monte Carlo simulations of the temperature fluctuations for different observational strategies such as the COBE, Tenerife, SP, MAX and Saskatoon experiments [3]. I extended these simulations to incorporate non-Gaussian fluctuations for both full-sky and partial sky coverage [7]. More recently I have been generating realistic simulations for the future Planck satellite which encompasses generating Timelines and producing maps with inclusion of several possible instrumental systematics, [24, 25].

I am naturally concerned with the non-Gaussian imprints that are induced in the CMB temperature and polarization with the eventual aim of connecting the simulation activity with the sampling distributions for the primordial fluctuations. This will entail the linear propagation of specific realisations of the initial fluctuations through to the observable CMB fluctuations using standard Boltzmann-solvers.

One of the major problems related with CMB data analysis is the contamination of the true signal by emission from our own galaxy or from discrete radio sources, for instance. Multifrequency measurements are a means of determining the origin of the signal observed, given their different frequency dependence. In some experiments galactic foregrounds away from the galactic plane may be ignored, by suitably choosing the frequency channels. In some cases contaminations may be removed by subtracting off the correlated component, making use of templates. But this has to be complemented with some reconstruction technique of a map of the intrinsic CMB sky fluctuations. During my PhD I became familiar with techniques of reconstructing the underlying sky such as Maximum Entropy Methods MEM [8], and I have also investigated other tools such as wavelets, Wiener filtering etc. It has been shown that these are quite helpful in assessing the contamination of CMB data by foreground radio emission from our own Galaxy and from discrete radio sources, as well as in detecting and characterizing non-Gaussian structure in maps of the CMB. It might be of interest to apply families of wavelets to detect the presence of CMB anisotropies generated by gravitational lensing on small angular scales. This would allow an inter-comparison of their performance depending on the specificity of the problem to be solved. I am currently working on a new fast Bayesian discrete object detection algorithm, Powellsnakes, ([23] and 3 papers in preparation) jointly with Pedro Carvalho and Mike Hobson at Cavendish Astrophysics Group, University of Cambridge. During the last year I have also joined the Gibbs team at JPL, and I am currently familiar with Commander, a Gibbs based component separation algorithm and PowerSpectrum estimator (adequate for low- $l$  regime ie large angular scales). This method has shown to work very well for both Temperature and Polarization, it is adequate for low- $l$  regime, ie in the range

of large angular scales, providing a separation of the several sky components and a full posterior distribution of the CMB Power Spectrum. I am currently working with Jeff Jewell of JPL in extending the Gibbs method to extract Cosmological parameters from Markov chain Monte Carlo samples of CMB Temperature and Polarization Power Spectra [26].

Therefore characterization of the diffuse foregrounds like Free-Free, Synchrotron, possibly spinning dust, or thermal dust, is an important issue in itself not to speak of its relevance for CMB data analysis. I am currently a team member of the 'GEM Portugal' project which has been recently approved by the FCT (The Portuguese National Foundation for Science and Technology). This project aims at using an instrument the design of which will be based on the current 'Galactic Emission Mapping Project', GEM, located in Brasil, to characterize the emission from foregrounds such as our galaxy and the unresolved blend of external galaxies. The 'GEM Portugal' instrument will operate at 5GHz to survey the Northern Hemisphere sky, and the team will work closely with the GEM group. I have also joined the CBASS team, this experiment has similar goals to that of GEMP. I joined the BICEP collaboration meetings through the Caltech Observational Cosmology group. BICEP is the first experiment designed to search for the Cosmic gravitational-wave background predicted by Inflationary models. It aims at constraining Inflation with Degree-Scale Polarimetry from the South Pole. It has already a substantial amount of data which is currently being analysed. It is a very exciting moment to have been given the opportunity to collaborate with such project and interlink it with Planck. I concluded an exercise of constraining the PSM templates with the BICEP observations of the galaxy, work in collaboration with Andrew Lange at Caltech. I am currently contributing to the BICEP data analysis in particular regarding the study of the galaxy observation with this experiment, this work will result in a paper (in preparation). I am also assessing the viability of using BICEP data as a polarization calibrator for PLANCK.

### 3.3 CMB Non-Gaussianity.

The issue of whether the primordial fluctuations might have been non-Gaussian is an important question that I am also working on. Inflationary scenarios predict, in general, that CMB fluctuations are Gaussian, although it has been argued that for models with linear evolution, this only happens if one assumes that the wave function of the universe was in the ground state. Also primordial non-Gaussianity naturally arises in inflationary models if the potential energy function for the scalar (inflaton) field is sufficiently steep that the evolution of fluctuations in the scalar field cannot be linearised. Scalar fields with steep potentials arise frequently in four-dimensional effective theories that are obtained from higher-dimensional theories by 'integrating out' the additional degrees of freedom. Gaussian fluctuations in anisotropic models (such as universes with global rotation or shear, or with a compact topologies) may, in some sense, also mimic non-Gaussianity by introducing second-order correlations between the Fourier modes of the CMB sky. Models which include topological defects produce non-Gaussian fluctuations. On the other hand, the presence of contaminants such as discrete radio sources, Galactic backgrounds and systematic instrumental effects also leave a non-Gaussian signature on CMB maps. Thus non-Gaussianity tests are of fundamental importance for disentangling the signal from the generalized noise and as a probe of inflation. To date, most tests of Gaussianity have been conducted in a frequentist vein. Those Bayesian algorithms which have been used have assumed that the signal, noise, and even Galactic emission are Gaussian processes. If the assumption of the signal's Gaussianity is to be dropped then one must propose an alternative form for the likelihood. In the work [7], we set up a proper Bayesian framework with which to study the issue of non-Gaussianity. We proposed a new, rigorous, non-perturbative, Bayesian framework which enables one to test Gaussianity and to estimate the power spectrum of CMB anisotropies. The main achievement of this work was to convert the problem of testing Gaussianity into one of Bayesian estimation. An interesting feature of this formalism is that it can assist in generating realizations belonging to this most general ensemble of parameters. This technique has now been applied to the Very Small Array (VSA) interferometer data [18]. I have also investigated another Non-Gaussianity estimator, the Bispectrum, jointly with my PhD student. We have implemented this estimator to check for Gaussianity of the Very Small Array (VSA) interferometer data [19]. Finally I am concerned with the prospects for detecting realistic non-Gaussian features in CMB maps exploring both the frequentist approach e.g. hypothesis testing with statistics such as the cumulants of the distribution, the bispectrum, trispectrum, real-space correlation functions, statistics of maxima and minima in the CMB map, wavelets, Minkowski functionals and Phases of Fourier modes as well as from a Bayesian perspective as mentioned above. Ultimately, it would be of relevance to develop new Bayesian estimators as well as to simulate maps of temperature fluctuations drawn from these particular non-Gaussian distributions. In the work [21] we developed a simple method for simulating statistically-isotropic non-Gaussian CMB temperature fluctuations with a given power spectrum and analytically-calculable bispectrum and higher-order polyspectra, and  $n$ th order correlators of the pixel values The resulting (publicly available) package called

**NGsims** has been recently included in the version 2.10 of Healpix. I am currently calculating the phase correlations induced in these non-Gaussian simulations. I am also investigating the possibility of developing a rotationally invariant estimator of phase associations on a sphere, jointly with A. Challinor at the Cavendish Laboratory.

My work and experience on Non-Gaussianity techniques could be of assistance to the activities in the area of image processing and algorithm development. In particular techniques such as MEM, wavelets, MCMC, parallel processing, as well as tools I developed in the Fourier domain suitable for interferometer observations.

### 3.4 Non-Gaussianity: Galaxy Redshift Surveys and Surveys of Weak Lensing.

I would also like to extend my interest in non-Gaussian fields to other areas of observational astrophysics, such as the analysis of Galaxy Redshift Surveys and Surveys of Weak Lensing. The techniques I have been using to analyse CMB data, as well as the new methods I developed during my research, are not specific to CMB and can be used in other fields concerned with the estimation of the power spectrum or detection of non-Gaussianity, for example in weak lensing. As part of parameter estimation, I intend to adapt the Bayesian formalism described above to include nonlinear effects in galaxy redshift surveys. The majority of the analysis to date has been concerned with parameter estimation from large-scale, linear regime. Though important information on parameters arise from smaller scales, where nonlinear gravitational clustering has transformed the initial field. Additional nonlinearities might arise from the bias relationship between galaxies and matter. Existing and new large datasets that are becoming available make this an important topic. I recently started a collaboration with A. Challinor at University of Cambridge on lensing reconstruction with Planck.

### 3.5 CMB polarization.

The CMB radiation is expected to be polarised due to Thomson scattering of temperature anisotropies at the time CMB photons last scattered. One expects inclusion of polarization measurements to help to better constrain some of the cosmological parameters, by probing the ionization history of the universe and by allowing the detection of gravity waves. I confirmed this using a Fisher Matrix Analysis, FMA, for WMAP, Planck and a cosmic variance limited experiment [14]. The existence of a period when the intergalactic medium, IGM, was reionized as well as its driving mechanism are still to be understood. One possible way of studying this phase is, as mentioned above, via the CMB polarization anisotropy. The optical depth to electrons of the CMB photons enhances the polarization signal at large angles introducing a bump in the polarization spectrum at small multipoles,  $l$ . On the other hand reionization decreases the amplitude of the acoustic peaks on the temperature power spectrum at intermediate and small angular scales. This signal has now been detected by WMAP via the temperature polarization cross power-spectrum (TE). The natural follow-up is that of confirming such detection. My FMA analysis shows that Planck will be essentially cosmic variance limited for temperature but there will still be considerable room for improvement in polarization. This therefore argues for a post-Planck polarization experiment, not least because polarization is, in itself, better at determining cosmological parameters than temperature. The pattern of polarization on the sky is characterized in terms of the so-called E mode (scalar) and B mode (pseudo-scalar). It is also crucial to search for the so-called B mode of the polarized CMB radiation, since this is a direct signature of the presence of a background of gravitational waves. Weak lensing of the CMB can introduce B-modes which would therefore contaminate the signal. Weak lensing also introduces non-Gaussianity. In the work [22] we studied these issues and developed an appropriate likelihood function which can be applied to B-mode polarization data for use in parameter estimation. The polarization of foregrounds such as synchrotron and dust, is still to be fully understood. The polarized emission from these foregrounds could be prohibitive for CMB polarization observations in particular for detection of the B-mode, though this emission has not yet been fully characterised. With High-sensitivity polarimetry becoming more prominent, it seems to be particularly desirable to apply CMB or other techniques to investigate the polarization of diffuse galactic emission as well as to study Faraday screens in radio sources.

As mentioned above I am currently collaborating with the BICEP team at CalTech. This experiment is designed to detect primordial gravitational waves via detection of the B-mode of the polarized CMB. I have also joined the Primordial Polarization Program Definition Team, PPPDT, efforts in articulating the science case for CMBpol, in particular the Weak Lensing and Foregrounds working groups - we are currently drafting the report which will also result in a paper. To this effect I started a collaboration with Chris Hirata at Caltech on estimating the contamination of the lensing B-mode signal from extragalactic point sources as supposedly they are the largest foreground contribution.

I am very interested in pursuing the study of CMB polarization both in the theory and experimental aspects and would welcome any involvement with other CMB polarization experiments.

### 3.6 Gravitational waves.

Many models of inflation predict a significant gravity wave background. These tensor fluctuations generated during inflation have their largest effects on large angular scales and add in quadrature to the fluctuations generated by scalar modes. Whilst recent WMAP results placed limits on the amplitude of these tensor modes one still lacks an experimental evidence for the presence/absence of a stochastic background of gravitational waves. As mentioned above the detection of the pseudo-scalar field  $B$  would provide invaluable information about Inflation in that they reflect the presence of such background. Although CMB gravitational waves have limited direct link to gravitational waves at the present epoch, I am also interested in the direct observation of gravitational waves from sources such as black holes, supernovae and spinning neutron stars and would welcome collaborative work within international gravitational wave projects. My expertise in CMB data analysis provides useful expertise for Gravitational waves (GW) data analysis. The characteristic of GW signals is that they are non-stationary and possibly short-lived. The simplest models predict a "chirping signal" for which standard Fourier analysis does not provide good detectability. Other approaches currently adopted within this field are based around model-fitting using an expected signal. In fact these models are extremely uncertain, and in the case of merging black holes may even be truly chaotic and an alternative approach is to develop methods of mathematical analysis that can be optimised for non-stationary signals in a way that is not model dependent. One such method is the "non-commutative tomography" (NCT) mentioned above. The characterization of non-stationary signals requires joint time and frequency information. However, time and frequency being non-commutative variables there cannot be a joint probability density in the (time,frequency) plane. Alternatively, the NCT method obtains information on time-frequency by looking at the marginal distributions along rotated directions in the (time,frequency) plane.

### 3.7 Cosmic Strings revisited.

As previously mentioned there is a strong observational evidence that the early universe has gone through an inflationary epoch. In the brane world scenario, brane inflation is quite natural. A simple version of this brane inflation is that of a slow motion of a D3-brane towards an anti-D3-brane. Recently it has been shown that this D3-brane pair inflationary scenario can be achieved in superstring theory. The end of inflation occurs as the D3-brane pair annihilates. Towards the end of the inflationary epoch cosmic strings are produced. If they survive long enough these cosmic strings can leave signatures that should be detected by gravitational wave detectors such as LIGOII/Virgo or LISA. these cosmic strings will also produce B-mode polarization of the CMB which can be of the order or larger than the amplitude of the B-modes produced through gravitational weak lensing of the CMB polarization by large-scale structure. This amplitude depends upon the value of the tension of the string  $G\mu$ . On the other hand the presence of cosmic strings will also leave a Non-Gaussian signature which should be detectable at Planck resolutions. Therefore detection of the signatures of cosmic strings provides a good test of the brane inflationary scenario and opens up a window to the superstring theory. I recently got interested in investigating the detectability of such signatures both in the temperature and polarization of the CMB. To proceed with such study accurate calculations of the power spectrum for both the temperature and polarization of the CMB anisotropy due to cosmic strings, as well as a full cosmic strings network and generation of CMB maps at high resolution are needed. To this end while in Cambridge I started a reading group on this thematic which counted with the participation of George Efstathiou from IOA and Paul Shellard from DAMTP, among others. I also started looking into the issue of optimal estimators for detection of the Non-Gaussian signature left by the presence of cosmic strings.

### 3.8 Theories with varying fundamental constants.

There is an emerging concordance model, as mentioned above, but it is now the time to proceed to the next level of questioning and start asking what are the 'dark components' that constitute more than 96% of the energy content of the universe. Most of this is in a non-baryonic form, for which there is no direct experimental evidence or solid theoretical explanation. To understand the nature of these dark components one needs further developments in fundamental physics. Fortunately Cosmology and astrophysics provide a means of testing fundamental physics and

search for new paradigmas. Current unification theories predict the existence of additional space-time dimensions, which have observable consequences, including modifications in the gravitational laws on very large (or very small) scales and space-time variations of the fundamental constants of nature. The most promising case is that of the fine-structure constant  $\alpha$ , for which some evidence of time variation at redshifts  $z \sim 2 - 3$  already exists. Since one expects  $\alpha$  to be a non-decreasing function of time, it is desirable to try to constrain it at earlier epochs, where any variations relative to the present-day value should be larger. The cosmic microwave background (CMB) anisotropies provide such a probe, being mostly sensitive to the epoch of decoupling,  $z \sim 1100$ . Therefore another recent interest of mine has been the study of observational constraints on such theories with varying fundamental constants such as ‘varying speed of light theories’, theories with a varying fine structure constant,  $\alpha$ , etc. I have worked on this subject using CMB observations, in particular via the recent Boomerang, Maxima and DASI detections [9, 10, 11, 12]. We concluded that our results were consistent with no variation in  $\alpha$  from the epoch of recombination to the present day, and restrict any such variation to be less than about 4%. However we pointed out that there are some degeneracies in the problem which imply that strong statements about  $\alpha$  can not be made using this method until independent accurate determinations of  $\Omega_b h^2$  and  $H_0$  are available. We provided a analysis of these degeneracies and discussed ways to break these with both existing and/or forthcoming data. We then showed that WMAP and the forthcoming Planck experiments will be able to break most of the currently existing degeneracies between  $\alpha$  and other parameters, and measure  $\alpha$  to better than percent accuracy. Recently I extended this work to include information of both the Temperature and Polarization of the CMB [14]. In this work I proceed with a Fisher Matrix analysis, FMA, to investigate the precision with which cosmological parameters can be reconstructed using WMAP, Planck and a cosmic variance limited experiment, when both temperature and polarization measurements are jointly considered. We also analysed the recently released WMAP first-year data providing updated constraints on the value of  $\alpha$  at decoupling [13]. We point out that the existence of an early reionization epoch as suggested by the above measurements will, when more accurate cosmic microwave background polarization data is available, lead to considerably tighter constraints, which can be in principle as small as 0.1% using CMB data—tighter constraints will require further (non-CMB) priors.

I further carried out a study of the feasibility of making VLT observations to detect a variation in  $\alpha$  in high-redshift absorption-line systems by measuring, for example, a variation in the separation of fine-structure doublets in transitions such as Si IV (observable in the HDF-South quasar, J2233-606) or Al III (observable in the bright gravitationally-lensed quasar HE 1104-1805, which has  $z_{em} = 2.31$  and an Al III absorption system at  $z = 1.66$ ). Current observational capabilities are indeed close to being able to detect a variation at the level recently claimed by Webb et al. I also investigated the feasibility of detecting *spatial* variation in  $\alpha$  in the spectra of white dwarfs, a possibility suggested by Joao Magueijo, although the likely level of variation is in fact too small to be detected (being perhaps four orders of magnitude smaller than the gravitational redshift observed for white dwarfs).

Meanwhile I started a collaboration with C. Carilly at NRAO, to constrain variations in the fine structure constant. We analyzed some GBT data on a new HI 21cm absorption system, and new data on HI, OH, and other radio molecular absorption lines [15]. We also intend to find new systems to analyse as well as to search for other interesting lines to inter-compare.

### 3.9 Topology of the universe.

While general relativity specifies the local curvature of space-time, the global topology still remains undefined. Although a concordance model seems to emerge from the latest CMB observations there are some features that do not fully fit this scenario. For instance both COBE and WMAP seem to obtain a low quadrupole value, unexpected in such as the above mentioned standard model. This could be the first indication of discrepancy in the otherwise successful  $\Lambda$ CDM cosmology. If this low multipole measurements are not due to either systematics or foreground contamination or cosmic variance then a possibility to explore is that of a signature of a non-standard model such as a flat small universe with a compact topology. Such small universes have the effect of damping the power at low  $l$  ie at large angular scales. I have applied Spherical Mexican Hat wavelets to simulated CMB maps and real data from the COBE satellite to investigate the presence of a possible signature from compact, orientable topologies [16]. The new WMAP results encourage further investigation of the possibility of such non trivial topologies. This is done by creating simulations of non-trivial topologies. As mentioned above, I previously produced such simulations for the six flat compact orientable topologies with a COBE-like resolution wich only considered the Sachs-Wolfe effect. I am at the moment extending this work to include the Doppler peaks effects expected to become relevant at 1 deg resolution. These simulations will allow one to test the several possible detection methods vs the full sky maps of CMB anisotropies provided by WMAP and forthcoming Planck satellite. I have also investigated the possibility of

using phase correlations in CMB maps to constrain the topology of the Universe [17] I am interested in extending my study to encompass the effect of these six topologies on the polarization of the CMB. Another interesting possibility to explore is that of imprints left by a small universe with a compact topology on the gravitational waves signal.

### 3.10 CMB secondary anisotropies and Dark Energy

There is observational evidence that our Universe is accelerating. One possible explanation is that the energy content of the universe is dominated by dark energy, DE, with a negative equation of state. The cosmological constant,  $\Lambda$ , is the simplest DE candidate, although observations are also compatible with an evolving DE. I propose to investigate the problem concerning DE via surveys of galaxy clusters in particular via the Sunyaev-Zel'dovich effect (scattering of CMB photons by cluster gas), SZE. I would welcome involvement with SZE experiments. Surveys of galaxy clusters via the Sunyaev-Zel'dovich effect provide a sensitive measurement of the growth of structure and the parameters that control it. Furthermore it will help understanding the formation/evolution of clusters and their gas content in a cosmological context.

### 3.11 The first luminous objects and the epoch of Reionization

Simulations of first structure formation in the universe shows a complex morphological structure far from perfectly spherical. These regions are in size of the order of hundreds of parsecs at redshifts, say of order 15. Would be interesting to compute the required resolutions as well as S/N to try to assess the morphology of these regions. Recently it was developed a formalism similar to that describing the anisotropies of the CMB to quantify the variations in 21cm emission as a function of both frequency and angular scale. It was shown that inspecting its power spectrum one might be able to distinguish features arising from bubbles of ionized material from fluctuations produced by the density fluctuations. This same technique could also be implemented to search for features on these first star forming regions. Therefore I propose to apply CMB techniques to molecular clouds or HI clouds.

I have recently joined the group interested in the SKA (Square Kilometer Array) as well as in ALMA (Atacama Large Millimeter Array) at the Cavendish Astrophysics Group and I am currently one of the signatories to Cosmic Vision Themes: 'Early Universe and Fundamental Physics' and 'The Formation and History of Galaxies'.

### 3.12 Specific work for the Planck satellite

It would also be desirable to apply some of the methods referred above to experiments such as the Planck Surveyor satellite. As member of CPAC and of several Planck technical working groups I have been investigating the detection and removal of systematic effects in particular in time-ordered data. I am currently exploring a new idea based on a non-commutative time-frequency tomography which properly characterizes non-stationary signals [20], jointly with L. Miller at Oxford. I am as well investigating new ideas for detection of non-Gaussianities in future Planck data and generating examples of non-Gaussian maps of the CMB. In collaboration with George Efstathiou, I started investigating destriping residual error maps and residual maps for component separation to search for possible NG signatures. This exercise will help us to assess the performance of destriping and component separation techniques developed within CPAC. I also investigated the accuracy with which cosmological parameters could be estimated with the Planck satellite via a Fisher Matrix Analysis [14]. This analysis considers both the Temperature and Polarization of the CMB.

More recently as member of ADG at JPL I got involved with different stages of the data analysis pipeline, namely:

- Levels

I became familiar with the Levels codes and modules to produce time ordered data, TOD. I generated several set of simulations : ERCSC-single detector simulations, the FullFocalPlane I simulations jointly with Julian Borrill to study Point Sources and SZ cluster detection algorithms; Component Separation algorithms; the Trieste simulations (30GHz) to study different mapmaking algorithms [24]; simulations of all detectors at 100, 143, 217 GHz to investigate the amount of information that Planck will provide at low multipoles,  $l$ , ie at large angular scales, with a cut-sky [25], etc..

- Map-making

I am familiar with two main map-making algorithms: MapCumba (a optimal map-making method) and Springtide (a destriping fast and approximate map-making method). I ran both codes to produce maps from existing TODS with guidance from Eric Hivon and Mark Ashdown. These maps can subsequently be used to test the several existing discrete objects detection algorithms. They are also useful to proceed with optical studies. These maps are of major importance to proceed with the comparison of different map-making codes, to investigate the sub-pixel effects in the residual maps and to compare the different Power Spectrum estimators. Ultimately this step will help understanding how errors propagate to the Power Spectrum estimation and finally to Cosmological parameter estimation.

- Algorithms for discrete object detection

I am currently working on a new fast Bayesian discrete object detection algorithm: PowellSnakes, in collaboration with Pedro Carvalho and Mike Hobson [23]. This method speeds up the traditional Bayesian techniques by replacing the calculation of the Likelihood for the parameters characterizing the discrete objects by the calculation of a Likelihood Ratio. The speed up is achieved by 1) computing the likelihood ratio between the hypothesis one (presence of discrete sources embedded in the data) and the null hypothesis (no sources present), 2) using a multiple minimization code using the Powell's jointly with Brent's method, and a 'jump' procedure to avoid local minima. With this new approach we are able to speed up the performance of previous codes for Bayesian source detection by a factor of 'hundreds'. Maximizing this new objective function corresponds to maximizing the Likelihood function itself. Therefore the estimation of uncertainties on parameters and the validation technique follows previous procedures applied to maximum likelihood estimators. Furthermore our new method can be implemented in both the Real and Fourier space. In the latter case the speed up is achieved by taking advantage of the fact that the correlation matrix for the CMB is a circulant matrix. Finally the performance of our method is comparable to that of frequentist techniques such as applying optimal filters. This new algorithm has been tested against other already available techniques when applied to realistic Planck simulations within the Compact Source Investigation, CSI, collaboration I started in 2006. The CSI work will be published in a paper [27] (in preparation).

- Power-Spectrum estimation

I am familiar with existing methods of Power Spectrum estimation in particular with: MASTER (a Pseudo  $C_l$  estimator that requires Monte Carlo's); Hybrid estimator (a quadratic estimator at low  $l$ 's ie on large angular scales, and a pseudo  $C_l$  estimator at high multipoles, ie on small scales); Gibbs techniques; and I worked in the development of XFASTER, (a mixture of maximum likelihood estimator and pseudo  $C_l$  estimator that requires Monte Carlo's). This work involved coding to implement required changes in XFASTER algorithm and adapt it to PLANCK . This study has been conducted in collaboration with Carlo Contaldi at Imperial College, and will be published shortly [28] (in preparation). I am currently participating in the Planck CTP WG Power Spectrum estimation challenge with a view to compare and select one or more Power Spectrum algorithms. This work will result in a paper describing the collective CTP work currently being drafted into one of the CTP paper series, the Varenna paper [29]. I jointly with Carlo Contaldi completed the implementation of an approximate Likelihood for Planck , XFASTER Likelihood. I have put together the pipeline to go from from Maps to Cosmological Models Parameter Estimation via cosmomc. Compared the XFASTER Likelihood (an approximation for high- $l$  regime) with other approximations and with the full sky exact Likelihood. Ultimately I am interested in the study of propagation of errors along the data analysis pipeline to parameter estimation. To this effect I studied the impact of beam asymmetry. I am working with postdoc Loris Colombo on a parallel method to do parameter estimation with Xfaster Powerspectrum.

- Asymmetric beams

I have studied the impact of asymmetric beams in PowerSpectrum estimation - I realised that in computing the transfer function properly one can reduce the effect of this asymmetry but we still seem to require a deconvolution mapmaker. I am also working on the forward problem - I jointly with HK Eriksen and Kris Górski initiated the implementation of a pixel based convolution method to speed up convolution with the effective main beam. I am currently supervising Sanjit Mitra at JPL in developing this method further.

All the above work has been developed in close collaboration with Kris Gorski at JPL.

It is maybe worth noting that during all my research I coded in fortran and currently I code in fortran90. I am also familiar with IDL, Healpix, and other visualizing devices. More recently started studying C.

Moreover I am interested in developing methods to analyse large data sets, but my main goal is to reconstruct the fundamental physics with such analysis.

Finally I intend to continue working within the existing collaborations on CMB and related areas of research. I also embrace the possibility of working in a more theoretical research field.

## References

- [1] Hancock, S., Lasenby, A.N., Gutierrez, C.M., Davies, R.D., **Rocha, G.**, Watson, R.A., & Rebolo, R., MNRAS, 1997, vol **289**, pp 505-514.
- [2] **Graça Rocha**, Radoslaw Stompor, Ken Ganga, Bharat Ratra, Stephen R. Platt, Naoshi Sugiyama, and Krzysztof M. Górski, ApJ, **525**, 1R, 1999.
- [3] Bharat Ratra, Radoslaw Stompor, Ken Ganga, **Graça Rocha**, Naoshi Sugiyama, and Krzysztof M. Górski, ApJ, **517**, 549R, 1999.
- [4] Hancock, S., **Rocha, G.**, Lasenby, A.N. & Gutierrez, C.M., MNRAS, 1998, vol **294L**, pp 1.
- [5] J.C. Baker, K. Grainge, M.P. Hobson, M.E. Jones, R. Kneissl, A.N. Lasenby, C.M.M. O'Sullivan, G. Pooley, **G. Rocha**, R. Saunders, P.F. Scott, E.M. Waldram, MNRAS, **308**, 1173B, 1999.
- [6] Matthew Webster, S.L. Bridle, M.P. Hobson, A.N. Lasenby, Ofer Lahav and **Graca Rocha**, ApJ letters, **509L**, 65W, 1998.
- [7] **Graça Rocha**, João Magueijo, Mike Hobson & Anthony Lasenby, Phys. Rev. **D64**, 063512, 2001.
- [8] Jones, A.W., Hancock, S., Lasenby, A.N., Davies, R.D., Gutierrez, C.M., **Rocha, G.**, Watson, R.A., & Rebolo, R., MNRAS, 1998, vol **294**, pp 582.
- [9] P.P. Avelino, C.J.A.P. Martins & **G. Rocha**, Phys. Lett. B843, 210, 2000.
- [10] P.P. Avelino, C.J.A.P. Martins, **G. Rocha** & Pedro Viana, Phys. Rev. **D62**, 123508, 2000.
- [11] P.P. Avelino, S. Esposito, G. Mangano, C.J.A.P. Martins, A. Melchiorri, G. Miele, O. Pisanti, **G. Rocha** and P.T.P. Viana, Phys. Rev. **D64**, 103506, 2001.
- [12] C.J.A.P Martins, A. Melchiorri, R. Trotta, R. Bean, **G. Rocha**, P.P. Avelino, and P. Viana, Phys.Rev. **D66** 023505, 2002.
- [13] C.J.A.P Martins, A. Melchiorri, **G. Rocha**, R. Trotta, P.P. Avelino, and P. Viana, Phys. Lett. B **585**, 29, 2004.
- [14] **G. Rocha**, R. Trotta, C.J.A.P Martins, A. Melchiorri, P.P. Avelino, R. Bean and P.T.P. Viana, MNRAS, **352**, 20R, 2004.
- [15] Kanekar, N., Carilli, CL., Langston, G. I., **Rocha, G.**, Combes, F., Subrahmanyan, R., Stocke, J.T., Menten, K.M., Briggs, F.H., Wilklind, T., Phys. Rev. L 95, 1301K, 2005.
- [16] **G. Rocha**, L. Cayon, R. Bowen, A. Canavezes, J. Silk, A. Banday & K. Górski, MNRAS, **351**, 769R, 2004.
- [17] Patrick Dineen, **Graça Rocha**, & Peter Coles, MNRAS, **358**, 1285D, 2005.
- [18] Richard Savage et al., MNRAS, **349**, 973S, 2004.
- [19] Sarah Smith, **Graca Rocha**, Anthony Challinor & VSA team, MNRAS, **352**, 887, 2004.
- [20] **Graça Rocha** & Lance Miller, in preparation.
- [21] **Graça Rocha**, Mike Hobson, Pedro Ferreira, Sarah Smith & Anthony Challinor, MNRAS, **357**, 1R, 2005.
- [22] Sarah J. Smith, Anthony Challinor & **Graca Rocha**, Phys. Rev. D 73, 023517, 2006.
- [23] Pedro Carvalho, **Graca Rocha** & Mike Hobson, in preparation.

- [24] M.A.J. Ashdown et al, submitted to *Astronomy & Astrophysics*, astro-ph/08063167 (A paper from the CTP series: Trieste paper)
- [25] Krzysztof Górski, **Graça Rocha**, Kevin Huffenberger, et al, in preparation.
- [26] Jeff Jewell, **Graça Rocha**, Chad Fendt, Krzysztof Górski, Charles Lawrence, in preparation.
- [27] **Rocha, G., et al** in preparation
- [28] **Graça Rocha** & Carlo Contaldi, in preparation
- [29] CTP et al, in preparation, to be submitted to *Astronomy & Astrophysics* by September/October 2008. (A paper from the CTP series: Varenna paper)