Beyond the Concordance Model - Research Plan

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1 Introduction

The Cosmic Microwave Background, 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 , the Wilkinson Microwave Anisotropy Probe WMAP, and the new ESA satellite experiment, Planck, to be launched in 2009.

Recent CMB experiments such as Boomerang, MAXIMA, DASI, CBI, VSA, ARCHEOPS, WMAP, QUAD, ACBAR among others seem to validate, apart from some intriguing discrepancies, the so-called concordance model of cosmology. This emerging standard model of cosmology is a flat-Λ (Cosmological Constant) 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.

Given the impressive agreement between the observations and this simple model, much effort is now being devoted to try and reproduce the key components of the concordance model within emerging ideas of fundamental physics. In this manner, cosmological and astrophysical observations can play an essential role in constraining fundamental physics.

2 Research Goals

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; are the primordial fluctuations indeed Gaussian; what can we learn with the polarization of the CMB; is there a stochastic background of gravitational waves; do the fundamental constants of nature vary; is the universe finite?, etc. I will now describe the specific aims and projects that I intend to pursue in helping to answer these questions.

2.1 CMB Non-Gaussianity

There is strong observational evidence that the early universe has gone through an inflationary epoch. However the detailed physics of inflation is still to be understood. The study of non-Gaussianity (NG) of CMB fluctuations is of major importance to probe this early physics and to understand the processes responsible for generating the primordial cosmological fluctuations as well as to isolate systematic effects. To show that this is indeed the case I describe in what follows the main sources of NG in the CMB:

- Single-field inflationary scenarios predict, in general, that CMB fluctuations are very nearly Gaussian, if one assumes that the quantum fluctuations start off in the ground state. However subsequent non-linear processing of the primordial fluctuations has been shown to amplify the tiny primordial NG to a level that may be detectable with future CMB surveys. Larger levels of NG can be produced in inflation models with multiple scalar fields, such as the curvaton and the inhomogeneous reheating scenarios.

- Models which include topological defects such as cosmic strings also produce significantly NG fluctuations; Gaussian fluctuations in anisotropic models (such as universes with global rotation or shear, or with a compact topology) may, in some sense, also mimic NG by introducing second-order correlations between the Fourier modes of the CMB sky.
- Second-order radiative transfer effects, such as gravitational lensing of the CMB, should produce a detectable level of NG in the CMB.
- It is also the case that inevitable contaminants such as discrete radio sources, Galactic emission and systematic instrumental effects leave NG signatures on CMB maps.

A number of present and future CMB experiments such as WMAP and Planck have sufficient resolution to constrain/detect NG of CMB fluctuations with high precision. Therefore I propose to extend my current work on the study of CMB non-Gaussianity, by:

- Investigating one's ability to detect and recover NG signals using NG simulations.

  (**a**) In a recent work, I developed a simple method for simulating statistically-isotropic non-Gaussian CMB temperature fluctuations [20]. Our full and flat sky simulation codes have been made publically available. The full-sky code is currently being packaged with HEALPix;

  (**b**) Studying phase associations in NG maps and in particular searching for a rotationally invariant estimator of phase associations on a sphere, suitable for full-sky NG analysis.

- Developing a rigorous set of NG tools for application in a number of upcoming experiments.

  (**a**) As a member of the Planck Core team and of the Algorithm Development Group, ADG at JPL and the LFI liaison at IPAC for the Early Release Compact Source Catalog, ERCSC, and of several Planck technical working groups, I intend to extend some of my statistical tools to the Planck surveyor satellite. One example is the Bayesian framework for NG estimation, I developed for the the Very Small Array (VSA) interferometer at the Cavendish Astrophysics Group. This new, rigorous, non-perturbative, Bayesian framework enables one to test Gaussianity and to estimate the power spectrum of CMB anisotropies at the same time [7, 17];

  (**b**) another, again for Planck, is the implementation of a non-commutative time-frequency tomography (NCT) which properly characterizes non-stationary signals [19] in time-ordered data; and for experiments aiming at direct detection of GW. Given that GW signals are non stationary and possibly short-lived, NCT might prove an invaluable tool for the direct search of GW signals as well.

  (**c**) Extending our pioneer implementation of NG estimators for interferometers, such as the bispectrum [18], to other interferometric experiments.

- Extending these studies to other areas of observational astrophysics, such as the analysis of galaxy redshift surveys and surveys of weak lensing. For instance by adapting the Bayesian formalism described above to include nonlinear effects in galaxy redshift surveys, with a view to parameter estimation. 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.

2.2 CMB polarization, Gravitational waves and Inflation

The CMB radiation is expected to be polarised due to Thomson scattering of quadrupole temperature anisotropies at the time CMB photons last scattered. The polarization signal depends on the conditions at the last scattering surface and thus contains a wealth of cosmological information, complementary to that encoded in the temperature fluctuations. In addition, the polarization at large angles is produced by re-scattering of photons as the universe reionizes, providing a unique glimpse of the ionization history at hight redshifts. So what else does CMB polarization tell us? It is common to characterize the pattern of polarization on the sky in terms of the so-called E/B mode decomposition. The importance of the B-modes stems from the fact that while they cannot be produced by linear, scalar (density) fluctuations, they can, however, be generated by:

- A cosmological background of gravitational waves (tensor modes): Many models of inflation predict a significant GW background, generated during inflation, which have their largest effects on large angular scales. Whilst recent WMAP and other experiments placed limits on the amplitude of these tensor modes one still lacks an experimental evidence for the presence/absence of a stochastic background of GW.

- The presence of cosmic strings: Although observations support the inflationary scenario, the origin of the inflaton field and its potential is still to be understood. In the recently suggested brane world scenario, brane inflation is quite natural and towards the end of the inflationary epoch, cosmic strings are produced. If they survive long enough these cosmic strings will produce B-mode polarization of the CMB and will leave a NG signature which should be detectable at Planck resolutions. Thus 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.

- Weak lensing of CMB photons by large-scale structure. Weak lensing also leaves a NG imprint on the CMB maps.

Furthermore the polarization of foregrounds such as synchroton and dust which could be prohibitive for detection of the B-mode, is still to be fully understood. It is therefore crucial to confirm WMAP results on the polarization of the CMB as well as to search for the B mode of the polarized CMB radiation. I intend to proceed with my current work on the study of CMB polarization, by:

- Developing statistical approaches to disentangle the several sources of B-modes using the NG signatures as a tool (jointly with other specific signatures) to help separate these diverse components and to estimate cosmological parameters.

- 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. I would welcome involvement with other CMB polarization experiments and in particular to extend my current plan of action to other experiments.

  I intend to contribute to CMB B-mode science by:
  (**a**) Separating NG contaminants that have same frequency spectra as CMB, e.g. weak lensing, unresolved defects, second-order effects from magnetic fields etc., using power spectra and NG tests;

  (**b**) Object identification: Intrinsically-low B-mode background makes it a promising place to look for known features, e.g. a (partially-resolved) string background: what does e.g. Kaiser-Stebbins look like in B modes? what would be the detection limits?

  I plan to contribute to the CMB B-mode data analysis via:
  (**c**) Cleaning of foreground contaminants: to consolidate current and near-future foreground data, to develop informed modelling of likely foregrounds in possible experiment survey areas and to develop appropriate cleaning algorithms based on spectral and/or spatial behaviour including non-Gaussianity. From the experience with VSA data analysis we know that NG is a powerful tool to probe the presence of foregrounds [17, 18];

  (**d**) Power spectrum (and error) and parameter extraction for NG likelihoods. The issue here would be estimating the B-mode signal in the presence of the NG signal, and estimating GW parameters and weak lensing parameters. [22]

- I am currently a team member of the 'GEM Portugal' project which has been 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.

2.3 Theories with varying fundamental constants.

One exciting area of theoretical development is higher-dimensional cosmology, inspired by ideas from string theory. Bold predictions emerge from such models, such as modifications to the laws of gravity on very large (or very small) scales, and spacetime variations of the fundamental ‘constants’ of nature. The most promising case is that of the fine-structure constant α, for which some controversial evidence of time variation at redshifts $z \sim 2-3$ already exists based on observations of optical quasar absorption spectra. Constraints on temporal variations at much higher redshift also exist from cosmological data, such as the fractions of light-elements produced during big-bang nucleosynthesis, and the anisotropy of the CMB. I have worked on this subject using CMB anisotropies [9, 10, 11, 12, 13, 14], which are mostly sensitive to the epoch of decoupling, $z \sim 1100$. In particular via the Boomerang, Maxima and DASI detections and via the recently released WMAP first-year data. We concluded that our results were consistent with no variation in α from the epoch of recombination to the present day, and restrict any such variation to be less than about 4%. We showed that WMAP and the forthcoming Planck experiments will be able to break most of the existing degeneracies between α and other parameters, and measure α to better than percent accuracy. I intend to update these results and attempt to constrain both temporal and spatial variations in the fundamental ‘constants’ over a variety of epochs using a number of astrophysical and cosmological probes. Possible avenues to explore include:

- Improve constraints on the value of the fine-structure constant at the time of recombination using new CMB temperature-anisotropy data from future WMAP, Planck satellite and upgraded VSA experiments. Current attempts to do this suffer from a number of near degeneracies noted above, that will be largely removed as more precise data becomes available. The situation should be further improved by including upcoming polarization data which will also allow constraints on alpha at the more-recent epoch of reionization.
- Investigate the impact of spatial variations of alpha on the Gaussianity of the CMB fluctuations, and on the polarization properties of the CMB.
- Constrain variations in alpha by analysing data on HI 21-cm absorption systems, and new data on OH and other radio molecular absorption lines, in collaboration with C. Carilli at NRAO. I am already involved in the observations for this purpose using the Greenbank telescope, GBT. To date, only optical lines have been studied but these have provided the controversial evidence for the variation in alpha noted above. The radio observations should provide a vital independent check on the work in the optical, with very different systematic effects, and should have the power to refute or confirm the optical results.
- Within the context of specific models (such as those that link variations in alpha to the local gravitational potential), study the feasibility of astrophysical probes, such as emission lines in extreme gravitational environments, to detect spatial variations in alpha.
- Attempt to constrain models with variations in other fundamental constants, such as in Brans-Dicke models where the effective gravitational constant varies due to the presence of a cosmological scalar field, with CMB and large-scale structure data.

2.4 Topology of the Universe

While general relativity specifies the local curvature of space-time, the global topology still remains undefined. Both COBE and WMAP seem to obtain a low quadrupole value, unexpected in the concordance model. If these measurements are not due to either systematics, foregrounds, or cosmic variance then a possibility to explore is that of a flat small universe with a compact topology such as the six flat compact orientable topologies. These topologies have the effect of damping the power at large angular scales. I have produced simulations for these topologies, and constrained these topologies using wavelets [15], and investigating phase associations in CMB maps [16]. I intend to continue this work by:

(**a**) extending the simulations to higher resolutions: to include the Doppler peaks effects expected to become relevant at 1° resolution. I intend to make these codes publicly available jointly with the Uzan et al. codes to simulate non-trivial toplogies.

(**b**) studying the effect of these six topologies on the polarization of the CMB and exploring the possibility of imprints left on the gravitational waves signal.

2.5 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. Initially as member of CPAC and of several Planck technical working groups and currently as Planck Core team member and as a member of the ADG team at JPL I have been investigating the detection and removal of systematics effects in particular in time-ordered data. I started exploring a new idea based on a non-commutative time-frequency tomography which properly characterizes non-stationary signals [19], 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 and currently in collaboration with Kris Górski, 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 Planck WGs. 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 jointly with Kris Górski and Charles Lawrence I got involved with different stages of the data analysis pipeline: Generation of timelines using LevelS pipeline [24]; Mapmaking using Springtide [24]; devising a algorithm for discrete object detection, PowellSnakes [23]; Power Spectrum estimation with Xfaster and Gibbs [28, 29, 26]; Study of asymmetry of the beam, Study of instrumental systematic effects; study of the effect of residual $1/f$ noise at low-l [25]; study the effect of residuals from component separation and in particular of the contamination from unresolved point sources, etc..

I intend to continue my involvement in Planck and in particular to continue:

- simulating Planck realistic data with inclusion of all sort of instrumental and systematic effects
- studying the effects of systematics and propagation of errors to parameter estimation
- taking into account of systematic effects by its inclusion in the Likelihood
- development/application of our new Bayesian method for detection os discrete objects, PowellSnakes
- development/application of the PowerSpectrum estimator, XFASTER and Likelihood with a view to parameter estimation
- development/application of Gibbs methods to estimate the Power Spectrum at low-l with a view to parameter estimation
- development/application of Commander for Foregrounds component separation and PowerSpectrum estimation
- implementation of my Bayesian method for detection of Non-Gaussianity as well as the bispectrum and other class of NG estimators
- using my NGsims to assess NG estimators and my topology simulator to constrain compact topologies
- contributing to the Planck Core areas and in particular to the PowerSpectrum and Likelihoods core area
- contributing to the Planck ERCSC
- assisting both LFI and HFI DPCS with my support concerning the codes I ported to the DPC pipelines
- etc.

In conclusion I intend to continue being very involved in the core science of Planck, with a view to connecting observations to theory.

2.6 Other

I have 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 Conclusions

To go beyond the concordance model is to question its foundations. Here I propose to investigate these through their effects on the CMB anisotropies, on the variation of the fundamental constants and on the topology of the Universe.

For that purpose I intend to continue being very involved in the core science of Planck, with a view to connecting observations to theory. I also intend to continue working within the existing collaborations on CMB and related areas of research. Furthermore I am very interested to use this experience in the context of other cosmology experiments (eg next generation satellite in CMB, lensing, BAO, or ground like LSST, as well as suborbital CMB B-mode experiments, etc..). I also embrace the possibility of working in a more theoretical research field.

Finally my major motivation is undoubtedly to try to unveil the fundamental physics which shaped the Universe we see today.

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