PhD subject proposal

Towards realistic models of polarized foregrounds for future CMB space missions

F. Levrier and F. Boulanger

LERMA, Observatoire de Paris, CNRS UMR 8112, ENS Paris, PSL, 24 Rue Lhomond, 75231, Paris cedex 05, France

francois.levrier@ens.fr *francois.boulanger@ens.fr*

The Planck all-sky dust polarization map was a spectacular highlight of the European Space Agency (ESA) mission, which revealed the imprint of the Galactic magnetic field on interstellar matter. With the Planck data, the study of interstellar magnetic fields became closely related to a paramount objective of observational cosmology: the quest for primordial B-mode polarization of the cosmic microwave background (CMB), which is expected to arise from gravitational waves produced during the inflation era in the very early Universe. The CMB and its anisotropies are one of the most dynamic areas of modern cosmology, whose study, building on successes of past experimental efforts, have driven the transformation of cosmology into the high-precision science it is today. The latest and potentially ultimate challenge that the field is facing is the detection and reliable characterization of these primordial B-modes. The pattern and amplitude of this signal on the largest scales reflect the conditions in the very early Universe, some 10^{-35} seconds after the Big Bang, and thus directly constrain the physics on energy scales twelve orders of magnitude higher than those reached at the Large Hadron Collider. This signal, however, is buried deep below the polarized foregrounds from our own Galaxy at similar frequencies. Any claim for a primordial B-mode CMB detection will face a critical assessment against alternative interpretations involving foregrounds (BICPE2/Keck & Planck Collaborations, 2015).

The structure of the polarized foregrounds (synchrotron and thermal dust emission) is closely related to the distribution of interstellar matter (electrons and dust grains) and to the topology of the interstellar magnetic field. As they corrupt the pristine cosmological signals in a way that depends on both the frequency of observation and its direction, the unbiased investigation of the physics of the early Universe must rely on multi-frequency measurements of the sky on the one hand, and high-precision modelling of the polarized foregrounds, on the other hand. The recovery of the cosmological signal rests on these two pillars, and is achieved through algorithms referred to as component separation methods.

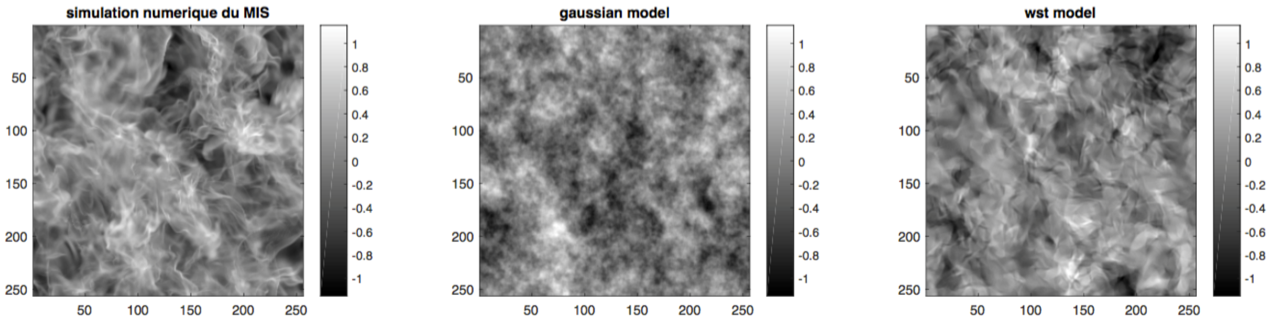
After Planck, and as the data sensitivity improves, the growing consensus in the CMB community is that uncertainties arising from foreground residuals and their potential interplay with data systematics have become dominant terms in the error budget of component separation algorithms. In the search for primordial B-modes, we need to accurately describe polarized foregrounds in a statistical manner, capturing the hierarchy of coherent, anisotropic structures of magnetized interstellar turbulence, and their interplay with dust and cosmic ray microphysics, across frequencies. We are thus faced with the problem of statistically characterizing complex sky images resulting from non-linear physics. The estimation of the probability measure of a statistical process given a realization observed over a finite domain is a generic problem of data science. In CMB analysis, this is routinely done using Gaussian random fields, but these models do not apply to describe random processes which include interactions across scales, as is inherent to non-linear physics. Indeed, when resorting to classical statistical tools, most of this complex information is lost.

The quest of non-parametric, low-dimensional, models providing accurate approximations of non-Gaussian phenomena is actually an active research field in mathematics, with applications in diverse fields of the natural and information sciences.

The goal of the proposed PhD thesis is to provide a description of polarized foregrounds using these novel statistical tools, to optimize and assess component separation methods in CMB data analysis, using data from Planck and the ACT ground-based and SPIDER balloon-borne experiments. This is the main purpose of the ANR project « BxB » (2017-2021, PI : F. Boulanger, http://bxb.lra.ens.fr). Within this project, we have started a collaboration with Stéphane Mallat (ENS), to apply his wavelet scattering transform

(WST) to analyze foreground polarization data. The WST represents complex processes by separating multiscale components with a first anisotropic wavelet transform, and capturing geometric interactions across scales through a second wavelet transform applied to the norm of the first wavelet transform coefficients. This algorithm outputs coefficients which can be interpreted as deep convolutional network coefficients computed with wavelet filters. Scattering moments are the expected values of these coefficients, and the distributions built from these moments efficiently capture the multiscale and geometric properties of the signal. They provide a non-parametric, low-dimensional, characterization of the input data (Bruna and Mallat 2013). These approaches have already been used to draw random realizations mimicking the features observed in complex phenomena (Bruna and Mallat 2012).

The ability of the WST to capture the essential statistical properties of complex processes is illustrated in the following figure, which shows the column density of gas (on a logarithmic scale) in a numerical simulation of an interstellar magnetized flow (left), a Gaussian random field with the same one- and two-point statistics (center), and a random realization having the same WST properties (right).



We expect the PhD student to contribute to the formal development of the method, through a direct collaboration with S. Mallat, focusing on the aspects particularly related to large astrophysical datasets, i.e. spherical geometry and projection effects. He/She will also contribute to the application of the method to the specific problem of polarized foregrounds to the CMB. He/She will work on the Planck sky survey in combination with ACT and SPIDER data, and will contribute to forecast performances of the anticipated CMB experiments operating from the ground, balloons and space, in particular the LiteBIRD project. Current CMB projects will achieve the sensitivity required to detect the B-mode signal predicted by the simplest models of inflation, but as Planck brilliantly demonstrated, only through the proper removal of much brighter Galactic foregrounds will any detection of this faint signal be reliable. The PhD student will thus work on a crucial aspect of the quest for primordial B-modes with current and future experiments. His/Her work will extend well beyond this quest, since the problem we face in CMB analysis is actually quite generic. Building probability models from experimental data (the observation of the sky, as far as astronomy is concerned) is indeed an issue in many research fields dealing with complex phenomena. It is formally explored in mathematics, with applications in diverse contexts, but not (yet) in cosmology. We thus expect the outcome of this thesis to be relevant for the statistical description of many types of data.

The successful PhD applicant will work at ENS Paris under the joint supervision of F. Levrier and F. Boulanger, who both have a strong expertise in the analysis of Planck polarization data and have initiated the inter-disciplinary collaboration with S. Mallat (ENS Department of Computer Science). The formal developments in the PhD work will be undertaken in close collaboration with S. Mallat.

Note that this subject has been preselected for 50% funding by the French space agency CNES. Complementary funding is being actively sought. The PhD student will also benefit from funding by the ANR project BxB for mission and equipment expenses.

<u>*Selected references*</u>

- **A Joint analysis of BICEP2/Keck Array and Planck Data**, BICEP2/Keck and Planck Collaborations, PRL, 114, 101301, 2015
- **Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes**, Planck Collaboration, Astronomy & Astrophysics, 586, 133, 2016
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- **Invariant Scattering Convolution Networks**, J. Bruna & S. Mallat, ArXiv:1203.1513, 2012
- **Intermittent process analysis with scattering moments**, J. Bruna, S. Mallat, E. Bacry, & J.-F. Muzy, ArXiv:1311.4104, 2013
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l'Observatoire de Paris LERMA ENS PSL RESEARCH UNIVERSITY PARIS

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique