Sujet de thèse proposé

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The shaping of the interstellar web by turbulence and magnetic fields

The complex physics of the interstellar medium (ISM) stand at the crossroads of many key topics in modern astrophyics : star and planet formation, galaxy formation and evolution, astrochemistry and its offspring astrobiology, to name but a few.

The ISM is a partly ionised mixture of gas and dust, with densities varying from some 10^{-3} to 10^4 particles per cubic centimeter, illuminated by stellar radiation, interacting with cosmic rays, and threaded by a pervasive magnetic field. Stars are born out of the gravitational collapse of the densest clouds, and they in turn release energy and new elements into the medium, through winds and supernovae.

The structures observed in the atomic and molecular ISM span over four orders of magnitude in scale, and reveal the presence of widespread turbulent motions. At large scales (up to a few kiloparsecs), kinetic energy is injected into the medium via Galactic differential rotation and supernovae explosions, and cascades down to dissipation scales (below the milliparsec scale).

Observations of the ISM have seen much progress in recent years. First results from the Herschel Space Observatory have confirmed the complexity of the spatial and kinematic structures of the diffuse medium. At the same time, the Planck satellite has been mapping the thermal emission of Galactic dust, including its polarised component, which gives access to the interstellar magnetic field. High resolution interferometric observations of molecular lines have uncovered large velocity gradients at very small scales, with signatures indicative of intermittent turbulent dissipation.

All these observations reveal a network of filaments at various scales. There are massive self-gravitating filaments emitting in the submillimeter, observed by Planck and Herschel. There are much more diffuse, comb-like structures on the edges of these massive filaments. There are filaments appearing when considering the local coherence of polarised emission in Planck HFI data. There are filaments tracing regions of large velocity shears, and probably turbulent dissipation, in the maps of the rotational lines of CO at very small scales. These different types of filaments trace different physical properties : the first two types trace matter, the third one traces the magnetic field, and the last one traces the kinematic structure.

The aim of the proposed PhD is to understand the connection between these various networks of filaments. Are they really filaments or are they sheets that only appear when they are seen edge-on ? What are the respective roles of turbulence, gravity and magnetic fields in shaping this interstellar web ? How can these observations help us constrain models of the early stages of star formation ?

The proposed PhD work will build on the results of M. Berthet's M2 internship (2012). Using IRAS maps of thermal dust emission in the Polaris Flare, a large nearby region that sticks out of the Galactic plane, he extracted its filamentary structure using tools which were originally developed for the study of the cosmic web of large-scale structures and later adapted to the analysis of Herschel maps. He used polarisation measurements from background stars to probe the magnetic field's orientation on a number of lines of sight. As these do not necessarily go through a filament of matter, he resorted to comparing the starlight polarisation to the orientation of the most nearby filaments extracted by the algorithm. He found that, statistically speaking, the angle difference is not uniformly distributed, with a tendency for polarised starlight, and therefore magnetic fields, to be aligned with filaments of matter. Recent numerical simulations of magnetohydrodynamical (MHD) turbulence by P. Hennebelle seem to disagree with this finding, so the need for a clear answer is strong. This is all the more essential than the current paradigm of star formation is that gravitational instabilities develop in massive filaments of matter, leading to the formation of prestellar cores, and recent work by M. Joos has shown that the angle between the magnetic field in these cores and their angular momentum is a key factor in the formation of disks around the protostar. It is therefore of prime importance to understand the relation between the magnetic and kinematic structures in the ISM.

Specific tasks that the PhD student will undertake are the following :

- Improvement of the statistics : we have obtained supplementary polarisation data from background stars in the Polaris Flare, so a first step would be to improve the statistics of the angle difference between polarisation direction and filament orientation. This would allow the student to become familiar with the physical and mathematical concepts and tools involved.

- Refinement of the analysis tools : the current filament extraction method has some limitations, related to the mathematical description of the topology. It works well with bright, thick, isolated filaments, but low-contrast filaments are often overlooked. We will encourage the student to develop new tools to recognize and characterize the kind of filaments targeted in this work : low-brightness filaments close to the noise level with however a large coherence length, easily recognizable by the eye despite intersections with other filaments. This method will be applied to matter filaments, velocity filaments and polarized emission data.

- Analysis of Planck data : E. Falgarone and F. Levrier are both members of the Planck consortium, and as such have access to the data. The student would be allowed access as well, and perform filament extraction in both total intensity and polarised emission. This would do away with the shortcoming of the previous methodology that filament and magnetic field orientation were actually not measured at the same position. The analysis would be performed on other fields as well, to probe different physical conditions, in particular regarding the star formation activity (from diffuse, non-starforming clouds to massive clouds with significant star formation), and different orientations of the large-scale Galactic magnetic field.

- Analysis of CO data : extraction methods will be used on small-scale filaments disclosed as coherent structures in the two-point statistics of the velocity field, which is obtained via the rotational lines of CO. Comparing the orientation of these filaments to that of the magnetic field in the same direction would give essential clues towards understanding the interaction of the magnetic field with turbulence close to the dissipation scale.

- Analytical and numerical approaches : the student will explore the properties of polarised submillimeter emission from models of magnetised interstellar filaments, building on the works of Fiege and Pudritz (2000) and improving on those models by considering skewed filaments as they are observed in the ISM. He or she will also work on numerical simulations of polarised emission, in collaboration with P. Hennebelle (CEA) for the simulations of magnetised astrophysical fluid flows, and using tools developed by F. Levrier to build simulated polarised emission maps. In particular, the student will explore the projection effects from 3D simulation data to 2D observables.

This work is not only important to understand the processes at work in the shaping of the ISM and the pathways to star formation. It is also paramount to properly clean polarised emission seen by Planck from contamination by Galactic foregrounds, to obtain reliable information on the polarised Cosmic Microwave Background (CMB). The proposed PhD work is thus at the forefront of ISM research and will lead to several publications.

E. Falgarone is an expert on interstellar turbulence. She is Planck Scientist and a member of the Planck Editorial Board. F. Levrier is an expert on simulated observations of the ISM and a member of the Planck/HFI Core Team. LRA comprises experts in observations of the ISM (M. Gerin), state-of-the-art numerical simulations (P. Lesaffre, B. Commerçon), and has close connections with leading scientists at other regional institutes (P. Hennebelle at CEA Saclay, F. Boulanger at IAS Orsay), with whom the student will be encouraged to collaborate actively.

Proposed work plan

The proposed PhD subject fits well in the "Missions spatiales" axis put forward by DIM ACAV, as it implies analysis of the Planck mission data. The schedule drawn in the work plan detailed below should be taken as indicative, as phases 2, 3, and 4 may be undertaken simultaneously.

Phase 1 : Improvement of the analysis and tools
Period : September 2013 - January 2014

The first phase of the proposed work will see the student get acquainted with the physical concepts and mathematical tools involved. The sub-tasks that will be undertaken in this phase are the following :

- Exploration of the parameter space available in the filament extraction algorithm *Disperse* (Sousbie, 2011), devised in the cosmological context of large-scale structures and later adapted to maps of the ISM observed by Herschel (e.g. Arzoumanian et al. 2011).

- Confrontation of the algorithm's outputs to structures seen by eye, especially in the case of tenuous filaments as can be observed in fields such as the Polaris Flare.

- Improvement and development of filament extraction tools : It is known that *Disperse* has a flaw in the case of filaments whose brightness varies along the structure with variances above the noise level. In that case, they are artificially cut into two separate filaments. A fix to this will be devised, for instance based on the filament's mean brightness level. At the same time, the student will be encouraged to develop his or her own algorithms better suited to extract low-brightness filaments.

- Inclusion of new starlight polarization data in the analysis, obtained with the MIMIR instrument (Lowell Observatory) on the Polaris Flare field. This will improve the statistics of the angle difference between polarisation direction and filament orientation.

Phase 2 : Analysis of Planck polarization data
Period : January 2014 - December 2014

All-sky maps of thermal dust emission from Planck data in total intensity and in polarised emission will be made available to the student. He or she will use this data to better constrain the relative orientations of matter filaments and magnetic fields. The sub-tasks that will be undertaken in this phase are the following :

- Filament extraction in total intensity and statistical analysis of the relative orientation of filaments and polarization vectors on the same lines of sight. The significance of this comparison will make use of information entropy, as used in Levrier et al. (2006).

- Comparison of the results from the previous subtask on different fields in the nearby ISM. In particular, the student will look for a dependence on star formation activity. This will be done considering fields which may be in different directions on the sky, warranting taking into account the influence of the large-scale Galactic field.

Phase 3 : Analysis of CO data
Period : January 2015 - December 2015

Maps of the rotational lines of CO obtained with the IRAM Plateau de Bure interferometer are available in a small region of the Polaris Flare. They give access to the velocity structure at small scale in the molecular material, and reveal intense velocity shears in the form of filaments. The sub-tasks that will be undertaken in this phase are the following :

- Filament extraction and comparison of their orientation with that of the mean magnetic field : The student will indeed use Planck data to obtain that direction on a 5 arcmin scale which is larger than the field-of-view of the CO observations.

- New CO observations will be proposed, targeting lines of sight for which high signal-to-noise starlight polarization data is available. The student will be encouraged to participate in the observations and in the data reduction. This will give access to the potential connection between magnetic and kinetic structures at much higher angular resolution.

Phase 4 : Analytical and numerical modelling
Period : June 2015 - August 2016

The student will be encouraged to develop models to explain the observational findings obtained in the previous phases. The sub-tasks that will be undertaken in this phase are the following :

- Development of semi-analytical models of polarised submillimeter emission from magnetised interstellar filaments, taking into account rotation and geometrical effects such as skewness of the filaments. The student will build on work by Fiege & Pudritz (2000) and explore the effects of multiple filaments criss-crossing on the line of sight.

- Confrontation with numerical simulations : cutting edge simulations of magnetohydrodynamical (MHD) interstellar turbulence are easily accessible, e.g. via the STARFORMAT project (`http://starformat.obspm.fr` - P.I. : P. Hennebelle) and they may be post-processed to obtain simulated polarised emission maps in the submillimeter, using tools developed by F. Levrier for the preliminary analysis of Planck polarization data. The student will use these simulations and tools to explore the geometrical connection between three-dimensional density, velocity and magnetic filamentary structures, and their two-dimensional counterparts projected on the plane of the sky.