

# Campagne 2023 - Contrats doctoraux de l'Initiative Physique des Infinis

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## *Magneto-Hydrodynamic instabilities in stellar radiative zones*

Understanding the physical conditions in stellar interiors induced by the combined effects of rotation, turbulence and magnetism is an active fundamental research topic in which important advances have been recently obtained and much more are expected. In particular, the observed diversity of stellar magnetic fields requires to question our theoretical basis on dynamo action. Stellar/plasma physics is at the same time pushed by new observations of ground-based instruments, the spectro-polarimeters (NARVAL, ESPaDOnS, SPIRou), or space-borne missions (CoRoT and *Kepler*, TESS, PLATO), and by the results of simulations that can now study the complex physics of stellar interiors taking into account many effects such as : rotation, magnetism, turbulence... In particular, stellar magnetism in stellar radiative interiors is a thorny and important issue in stellar physics. For example, during the subgiant phases, the core contracts and its angular velocity significantly increases from the simple principle of local angular momentum (AM) conservation. However, observations show that AM transport is very efficient in radiative zones. This important mechanism is still undetermined recent numerical simulations [Petitdemange et al., 2023] and observations [Li et al., 2022] support the idea that the angular momentum transport induced by magnetic fields in deep stellar radiative zones could explain the observed slow rotation rates of subgiant cores. Magnetic field, through magnetic instabilities and retroaction with differential rotation, could also explain the rotation profile of low-mass evolved stars [e.g. Deheuvels et al., 2014] and intermediate-mass stars [e.g. Christophe et al., 2018], in contradiction with our current theoretical understanding modeled by 1D stellar codes including AM transport. For massive stars, which have a thick radiative envelope, the main issue is slightly different. Thanks to the improved sensitivity of a new generation of spectro-polarimeters, the existence of a “magnetic desert” is now clear. A strong dichotomy is observed [Lignières et al., 2014] between strong fields (fossil fields) and fields of ultra-weak magnitude : 100 times lower. To understand these observations, we need to both determine how strong magnetic fields can be maintained on long time scales in their radiative zone, and at the same time we need to study dynamo action resulting from shear flows in a stably stratified environment. Such a configuration is known from analytical studies based on simple approximations to favor Tayler-Spruit dynamo mechanism [Spruit, 2002]. Recent global numerical simulations can now consider such a complex fundamental physics.

In this context, we have already modeled with success MHD processes in radiative zones subject to differential rotation [Philidet et al., 2020, Petitdemange et al., 2023]. This model consists of a spherical Couette flow in which a conducting fluid is located between two concentric spheres rotating at different rates. We consider the Boussinesq approximation, allowing us to neglect variations of the fluid density except in the buoyant term. A similar Boussinesq approach was also considered by two groups [Prat et al., 2016, Gagnier and Garaud, 2018] in order to test the validity of analytical prescriptions by running shear flows in a cartesian box. But, geometrical constraints have important effects in rotating flows as shown by Philidet et al. [2020], we prefer to use a more realistic spherical geometry. An important first step of our project has been achieved in Philidet et al. [2020] where we focused on a weak differential rotation (low Rossby numbers). Such a limit allows to consider axisymmetric simulations. In this case, no dynamo action can develop and we have highlighted the effects of magnetic dipoles, rotation and stratification by systematically varying their magnitudes. Petitdemange et al. [2023] have reported for the first time a numerical support for dynamo action resulting from 3D turbulent motions for higher Rossby numbers corresponding to the scenario proposed by Spruit [2002] (Tayler-Spruit dynamo). Using global numerical modeling, we have reported the existence of a subcritical transition to turbulence due to the generation of a dynamo magnetic field, which shares many characteristics with the (never observed) Tayler-Spruit model and significantly enhances transport in radiative zones. The resulting, deep toroidal fields are screened by the stellar outer layers, allowing for the existence of intense magnetism in radiative stars where no magnetic fields could be directly observed so far. These promising results require additional studies to link our numerical results to observations and better understand the existence of the magnetic desert and the impact of magnetism on stellar parameters. These particular points strongly motivate our proposal.

To do so, hydrodynamic and MHD 3D simulations will be performed to better understand the development of turbulence and the magnetic field amplification. Magnetic effects will be highlighted by comparing hydro- and MHD runs. Different initial conditions for the magnetic fields will be considered in order to study the existence of different dynamo branches and MHD instabilities. Depending on the initial conditions for the magnetic field (its topology and its strength), different MHD instabilities can be excited. Strong toroidal fields can give rise to unstable Tayler modes whereas strong dipolar fields combined with differential rotation can generate MagnetoRotational (MRI) modes. This particular confi-

guration corresponds to magnetic fields observed for massive stars. These MHD instabilities could explain the observed magnetic desert. Additional parameter studies must be performed in order to properly apply them to stars. Advances on hydrodynamic and MHD turbulence resulting from instabilities, are expected as well as results on dynamo action. Thanks to the expertise of Ludovic Petitdemange on this type of parameter study carried out on parallel architectures, we will be able to highlight the different dynamical regimes and the associated dynamos such as the Tayler-Spruit dynamo. Kévin Belkacem's expertise will allow us to link these numerical results to observations of stellar radiative zones. He is very involved on international space-borne missions as PLATO. We will do our best to determine new prescriptions from our 3D models in order to better take into account magnetic effects in 1D stellar evolutionary code. Such a task is crucial as these codes are used to interpret observations. This ambitious work is within reach of a thesis student, if the team works in close collaboration.

The PhD student will begin by becoming familiar with the code assisted by L.Petitdemange. Very quickly, massive simulations can be run since the code has already provided results that we will deepen. A more turbulent regime will be considered by increasing the resolution and by using the mesocentre MesoPSL as well as the national resources available to us. The integration time of simulations envisaged is approximately 3 months. During this time, a significant investment will be made to become familiar with the various tools for post-processing simulations in collaboration with the members of this project to clearly identify the relevant observables for our future simulations which will have to be recorded. Our first studies enable us to properly estimate the time integration of future simulations and demonstrate the feasibility of our project. A 3D turbulent flow influenced by rotation and stratification will be generated by gradually increasing the differential rotation (the Rossby number) from a steady solution. After three months of time integration, simulations will be analyzed by combining our expertise in order to provide new prescriptions for describing turbulent AM transport in 1D evolutionary codes. Then, the student will implement these new prescriptions in such a code. Magnetic effects can play at different evolutionary stages. By running 1D models with different stellar parameters, the student will show, for the first time, how magnetic fields affect the life of stars. We have already shown the existence of a subcritical dynamo solution developing in deep stellar interiors. This field could explain the observed efficient AM transport despite the lack of magnetic field at the stellar surface. However, the existence of the observed strong dipolar fields is still mysterious. Bifurcation diagrams of the dynamo instability will be obtained by increasing the Rossby number with a strong initial dipolar magnetic field in order to test its stability and subcritical behaviour. Then, simulations will be integrated during a period sufficiently long to reach a saturation of the magnetic energy and a statistically steady state. Magnetic effects will be directly highlighted by comparing MHD runs with their hydro counterparts. This project will be the focus of the second year. According to our experience on such MHD simulations, these runs will take between three and four months on MesoPSL. Dynamo action will be theoretically analyzed by the student and L.Petitdemange (given his expertise on this topic). In collaboration with K.Belkacem, we will interpret our results in the context of observations of stars. We will work together in order to provide simple prescriptions describing magnetic effects. By collaborating with Joao Pedro Marques (IAS) who develop a public version of the 1D model CESTAM, we will enable us to deliver practical results which will be of interest for the stellar community.

The development of turbulence and its ability to generate magnetic fields (dynamo action) are fundamental aspects in Physics and, in particular, in Plasma Physics. Researchers from the large Plasma community located at SU (Fédération de Recherche Plasaparc) will have the opportunity to join us and our results will provide advances which are also of interest for them. In this spirit, we have organized a workshop with 30 participants from Paris' region on "dynamo action : from the lab to the stars" at Jussieu in September 2019. Although important new advances are expected from our plan, it is obvious that our project will only represent the starting point of a new approach in stellar/plasma physics in which all skills used in fundamental Research are joined together to improve our knowledge on stars. The support of this project by IPI will allow to create a new group of different skills needed to analyze and understand past, recent (CoRoT, *Kepler*...) and future observations (SPIRou and PLATO). SU Laboratories are involved. This group will interact with the Plasma community at SU and Researchers from "Observatoire de Paris" by using the new program "Action Pluri-annuel de Physique stellaire" (AIPS) led by us. Our research topic is of interest as knowing the dynamics of stellar interiors and their links with observables is a major challenge to make the best use of future instruments such as SPIRou and PLATO, which will certainly considerably change our vision on the formation of planetary systems.

## Calendrier prévisionnel succinct

Le programme de travail anticipé pour le projet de thèse est décrit dans le tableau ci-dessous. En ce qui concerne le candidat, nous avons obtenu un financement auprès du programme AIPS (Action Incitative de Physique Stellaire) de l'Observatoire de Paris pour recruter un stagiaire de M2 jusqu'à fin juillet. Cela nous permettra de commencer à former cet étudiant sur notre thématique de Recherche et sur les outils

numériques. Nous sommes actuellement en train de finaliser la phase de sélection des candidats et venons de sélectionner un candidat sur le sujet.

Période	Tâches
6 mois	Prise en main du code 3D et de la thématique Analyse de stabilité linéaire pour différentes instabilités MHD (méthode WKB) Lancement des premiers runs
Du sixième au 9 <sup>ème</sup> mois	Analyse et implémentation de nouveaux observables pour des simulations complémentaires faiblement stratifiées en densité
Du 9 <sup>ème</sup> au 15 <sup>ème</sup> mois	Analyse des résultats 3D hydro et MHD, et publications
Du 15 <sup>ème</sup> au 21 <sup>ème</sup> mois	Étude sur l’effet de la stratification en densité dans le régime fortement magnétisé sur les résultats obtenus précédemment. Optimisation et simulations 3D anélastiques.
Du 21 <sup>ème</sup> au 24 <sup>ème</sup> mois	Analyse et publication des résultats
Du 24 <sup>ème</sup> au 27 <sup>ème</sup> mois	Détermination de nouvelles prescriptions pour le transport de moment angulaire (hydro et MHD) à l’aide des simulations 3D et d’arguments théoriques.
Du 27 <sup>ème</sup> au 30 <sup>ème</sup> mois	Implémentation de ces nouvelles prescriptions dans un code d’évolution stellaire 1D.
Du 30 <sup>ème</sup> au 33 <sup>ème</sup> mois	Étude de paramètres et publication des résultats.
Du 33 <sup>ème</sup> au 36 <sup>ème</sup> mois	Finalisation de la rédaction de thèse et soutenance

## Références

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