# Campagne 2022 - Contrats doctoraux de l'Initiative Physique des Infinis

February 21, 2022

**Description of the project:**
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 spectropolarimeters (NARVAL, ESPaDOnS, SPIRou), or space-borne missions (sattelites: 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…

Stellar magnetic fields can be classified into two broad categories. First, magnetic fields generated and maintained by motions in deep layers (dynamo effect). Second, magnetic fields in massive stars which harbor strong dipolar fields with a stable configuration that certainly result from the formation of their hosting star. For the latter case, we refer to them as "fossil fields". For the former, there are a large number of dynamos with different mechanisms giving rise either to stationnary fields, large-scale dipoles like those observed for rapidly rotating low-mass stars (of spectral type M), or to time dependent fields as the periodic solar field. For low-mass stars ($m \leq 1 m_S$, $m_S$: solar mass), the transfer of kinetic energy into magnetic energy (dynamo effect) certainly occurs in their thick convective zone where this dynamo effect is efficient as shown by many studies [Roberts and King, 2013, Petitdemange, 2018]. In contrast, understanding magnetism of more massive stars possessing a thick radiative envelope is a major challenge which is still poorly explored.

At different stages in the life of a star, radiative zones (i.e. stably stratified layers) may naturally harbor sheared flows at large scale. 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.

One of the complexities of magnetohydrodynamic (MHD) processes is its nonlinear nature. The magnetic field through the Lorentz force retroacts on the flow that initially amplified it. Differential rotation and magnetism thus appear as intimately linked phenomena. Differential rotation, by itself or by developing hydrodynamic instabilities, can generate dynamo-generated fields, and this magnetism can inhibit these instabilities or even greatly reduce the differential rotation by transporting AM. This last process could explain the rotation profile of stars [Deheuvels et al., 2012, 2014]. Recent seismic measurements confirm the low magnitude of the differential rotation in intermediate-mass stars [Christophe et al., 2018, Van Reeth et al., 2018], in contradiction with our current theoretical understanding modeled by 1D stellar codes including AM transport as prescribed by Zahn [1992].

Thanks to the improved sensitivity of a new generation of spectropolarimeters, the existence of a "magnetic desert" is now clear. Massive and intermediate mass stars have a thick radiative envelope. 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.

Turbulent motions in a radiative zone are known from analytical work to induce AM transport [Zahn, 1992]. Turbulent coefficients are frequently used in stellar evolution codes in order to analyze stellar observations and to predict the evolution of stars. However, such coefficients are not very well constrained by previous analytical works. Recent simulations can reach so turbulent regimes that direct comparisons between 3D models and theoretical studies are now possible.

We have already modeled with success MHD processes in radiative zones subject to differential rotation [Philidet et al., 2019] and a paper is under consideration in *Science* (accepted in minor revision). This model consists of a spherical Couette flow in which a conducting fluid is located between two concentric spheres rotating at different rates. A stable stratification is applied through a temperature difference between the inner shell and the outer one. 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. [2019], we prefer to use a more realistic spherical geometry. An important first step of our project has been achieved in Philidet et al. [2019] 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. Studying MHD turbulence and dynamo action resulting from 3D turbulent motions for higher Rossby numbers is the subject of our paper submitted to *Science*. 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 with the same parameters in order to better understand the development of turbulence and the magnetic field amplification. Magnetic effects will be highlited 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.

On this topic, we have recently obtained significant results that are under consideration for publication. An additional parameter study must be performeed in order to properly apply them to stars. Advances on hydrodynamic and MHD turlence 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 either 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 feasability 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 prescritpions 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. K.Belkacem's experience on 1D evolutionary code will enable us to deliver pratical 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 Plasapar) 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 prévisionel succint**

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

Nous avons obtenu un financment 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. Idéalement, nous souhaitons que le candidat ait suivi des enseignements soit en physique stellaire ou nonlinéiare soit en modélisation numérique.

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