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A l'attention de l'Ecole Doctorale Astronomie & Astrophysique d'Ile de France

Report on the PhD thesis of Paul Barrère

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In this manuscript entitled "Modelling magnetar formation", Paul Barrère presents his PhD work prepared at the Département d'Astrophysique of CEA Saclay under the supervision of Jérôme Guilet and Raphaël Raynaud. Paul focused in particular on understanding the mechanisms behind the production of the very intense magnetic fields detected in these objects, and which are at the origin of various energetic events monitored in X-rays and γ-rays. One of the main questions that Paul addressed in his work was the possible formation of magnetars from stellar progenitors lacking both strong magnetic fields and rapid rotation. He thus focused on a particular mechanism which could amplify magnetic fields in the proto-neutron star a few seconds after the Supernova explosion, namely the Tayler-Spruit dynamo, whose basic ingredients are differential rotation and the current-driven Tayler instability. After introducing the subject and the method in the first part, Paul discusses his semi-analytical and then numerical results produced with the 3D magnetohydrodynamical code MagIC. He then presents two additional results about the interpretation of his numerical results with a reduced dynamo model and the use of his dynamo-generated fields as initial conditions for a study of the longer term evolution of a neutron star. He finally concludes and presents perspectives of his work at the end of the manuscript.

In the first chapter of the thesis, the observational constraints are presented and the definition of a magnetar is given. We understand here that magnetars are a class of neutron stars harboring extreme magnetic fields with typical dipoles as strong as 10^{15} G coexisting with almost equally strong non-dipolar fields. These extreme fields are at the origin of some of the most energetic events in the Universe like GRBs and giant flares and may play a central role in the production of hypernovae or superluminous supernovae explosions. The second chapter aims at presenting the various scenarii for magnetar formation, either before of after the core-collapse of a massive star. These 2 chapters are very nicely written, very clear and presumably quite exhaustive in the description of the various observations and theoretical explanations for the formation of these objects. The reader is then nicely guided towards the main question of Paul's PhD work which was dedicated to study a post-collapse formation scenario involving a slowly-rotating and « weakly » magnetized neutron star. Chapters 3 and 4 then present the MHD equations, a brief description of the general dynamo mechanism and a focus on the Tayler-Spruit mechanism before describing the numerical code in detail. I particularly appreciated the concise yet precise way to present the theoretical and modelling frameworks, as well as the state-of-the-art situation concerning the Tayler-Spruit dynamos for which very little numerical evidence existed before Paul's work.

The next part of the manuscript is dedicated to the results, mostly inspired by the first-authored articles either published (2 articles) or submitted for publication (1 article).

Chapter 5 presents a semi-analytical work aiming at studying the time-evolution of the magnetic field components, the shear rate and the rotation rate in a case where the stellar surface is spun-up by the accreted fallback mass from the supernova explosion. This dynamical system is simplified by postulating various assumptions about the creation and dissipation of each variable in the system. The prescription of the dissipation rates are inspired by a previous work by Fuller et al. 2019. This work is extended here by taking into account the temporal evolution of the fields. This original work results in an estimate of the minimum accreted mass necessary to produce the strong fields characteristic of magnetars, within the framework of the Tayler-Spruit dynamo mechanism. This is a first proof of concept that the TS dynamo is a potentially valid candidate to produce strong fields from a slowly-rotating progenitor.

Chapter 6 and 7 constitute for me the most impressive part of the thesis, with one of the first convincing evidence of an efficient Tayler-Spruit dynamo in full 3D MHD numerical simulations. Paul now considers the full set of equations and investigates the behaviour of a stellar radiative zone subject to differential rotation forced by the boundaries (a spherical Couette flow) in which a weak or strong initial toroidal field is introduced. The effects of varying the shear rate and the level of stable stratification are studied respectively in Chapters 6 and 7. The dynamical behaviour obtained in these simulations is very rich, with 3 distinct dynamo branches : one supercritical branch related to a kinematic dynamo associated with the hydrodynamical instability of the Stewartson layer located at the tangent cylinder and 2 subcritical branches with stronger magnetic fields, one hemispherical (found for the first time) and one dipolar. These last 2 branches are interpreted to be related to the Tayler instability acting close to the poles, favouring an $m = 1$ mode and showing a radial lengthscale strongly reduced by the stable stratification. This is for me the first time that the characteristics of the Tayler instability and the sustenance of a dynamo associated to it are found in numerical simulations. The work presented here is very thorough, the task of following the various branches being particularly difficult in the context of subcritical dynamos. The comparisons with theoretical predictions for the magnetic fields at saturation and the induced transport of angular momentum are also very interesting and useful for the whole stellar physics community (well beyond the magnetar experts), since reliable prescriptions coming from 3D simulations of the Tayler-Spruit dynamos will now be able to be introduced in 1D stellar evolution models, when only theoretical scalings were adopted before.

Chapter 8 focuses on the effect of stable stratification on the hemispherical dynamo branch and its interpretation in terms of non-linear interaction between dipolar and quadrupolar modes, inspired by previous work in the experimental dynamo community. This works shows that Paul is also able to step back from the full 3D simulations and to be inspired by the work of other communities to interpret physically his results, extracting the main physical ingredients at play in his complex simulations. This already well-advanced work is close to being ready for publication in a Physics journal. Finally, chapter 9 confirms the collaborative skills of Paul who proposed to use his dynamo-generated magnetic fields as initial conditions for a longer-term evolution study of a neutron star, with the goal of comparing with the various energetic emissions coming from observed magnetars.

Finally, the conclusions and perspectives are clear and well presented. They also show that Paul is aware of the various limitations of his work and already has ideas on how to overcome these limitations and improve the applicability of his results.

This manuscript was very pleasant to read and the amount of work produced during this PhD thesis is very impressive. The novelty of the results presented here are undeniable, it is indeed the first time that the very rich behaviour of the Tayler-Spruit dynamo mechanism is revealed numerically and that detailed comparisons with theoretical prescriptions are so successfully shown. Paul's work definitely opens new prospects for the study of magnetars and has strong implications for stellar physics in general.

Je suis favorable à la présentation des travaux de thèse de Paul Barrère lors d'une soutenance orale en Septembre 2024.

Best regards, Laurène Jouve