Activity Report

Convection Dynamics in Celestial Bodies

by Prof. A.S. Brun in collaboration with Prof. Shin-ichi Takehiro et Prof and Director Michio Yamada at RIMS, Kyoto University.

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Abstract: Stars and planet share similar atmosphere dynamics involving the nonlinear turbulent coupling between convection, rotation and magnetism and curvature effects of spherical geometry. We have developed an innovative project based on a mathematical representation based on magnetohydrodynamics (MHD) fluid/plasma equations using numerical simulations of stellar convection to understand the state of rotation and convection of these objects. We also studied the impact of a stable layer and angular momentum transport by internal waves.

Introduction:

Stars can play the role of modern physics laboratory, because processes as diverse as turbulence, thermal convection, plasma eruption, and rotation induced large scale mean flows can be studied in details via direct surface observations (or indirectly via asteroseismology) allowing to characterize with an ever improving accuracy their complex dynamics. Of fundamental interest is turbulent convection, because it is both at the source of many of the most dynamical phenomena observed in stars and it impacts directly their short and long term evolution. Turbulent convection in stellar envelope helps transporting the heat generated deep inside their nuclear core. Depending on their mass M_{star}, high or low mass stars (with respect to the reference solar value (M_{sol}) have different internal structures and convection zones are not found at the same location. In massive stars (M_{star} > 2 M_{sol}), convection is mostly confined in the deep interior, in so-called core convection region, with little stratification. By contrast, solar-type stars and stars less massive than the Sun, have their convective zone located near their surface. This convective envelope deepens as the star becomes less and less massive, to occupy the whole star below 0.3 M_{sol}. This deepening of the convective envelope is accompanied by an increasingly stronger stratification. Hence convective process experiences in stars a large range of conditions and it needs to be studied in details to understand how it is modified under these changing situations.
Moreover, stars are rotating objects. Turbulent convection motions are thus influenced by the action of the Coriolis force and in the most extreme rotating situation, the star and all its internal layers (convective and radiative) are even deformed by the Centrifugal force, losing their spherical shape. So rotating convection zones not only transport heat and energy but also angular momentum yielding large scale mean flows such as differential rotation and meridional circulation Brun & Rempel (2009).
In the present study we aim at characterizing stellar convection and its associated large scale mean flows in solar-like stars by mean of 3-D numerical simulations of convection in a spherical shell for varying Ekman (Ek; a measure of the influence of rotation) or Rossby numbers (Ro; likewise a measure the influence of rotation on turbulence) and to make the connection with geophysical flows in planetary atmosphere. More specifically we wish to understand how the basic state of convection and the associated mean flows at the onset of the convective instability are behaving compared to their nonlinear counterpart such as the ones published in Brun et al. (2017). One key results of numerical simulation of rotating convection in a spherical shell has been to propose the possible existence of a retrograde state of differential rotation with slow equator and fast poles for slowly rotating stars with large Rossby number. This so called anti-solar rotation state, in reference to the Sun's prograde differential rotation that instead possesses fast equator and slow poles is very interesting because it can influence the evolution and dynamics of these stars via for instance a modification of their dynamo and magnetism and the associated stellar wind dynamics and the rotational braking it involves.

We illustrate an example of such retrograde and prograde states of differential rotation in Figure 1. In this study, we wish to understand if retrograde states of rotation as shown in left panel of Figure 1 are robust and naturally present in convective flow at the onset of the instability or instead the outcome of nonlinear processes.

To this aim we have systematically computed the critical state at the onset of the convection instability for the 15 simulations of rotating stellar convection published in Brun et al (2017) and assessed the 2nd order mean flows of each marginal states. Such approaches have already been done in the context of Boussinesq convection in planetary convection setup (see for instance Takehiro & Hayashi (1999)) and only recently extended to the anelastic approaches which is essential to take into account when considering solar-like stars with highly stratified outer convective envelope (Sasaki, Takehiro et al. 2018). Since Prof. Takehiro and Yamada have the tools to perform such study and I, Prof. Brun, have the data basis of numerical simulations, we have efficiently collaborated in Fall 2019 during my visit at Kyoto University (RIMS) to perform this analysis. The outcome is described in the next section and corresponds to a scientific article (Takehiro, Brun, Yamada) we submitted in December 2019 to the notorious Astrophysical Journal of the American Astronomical Society.

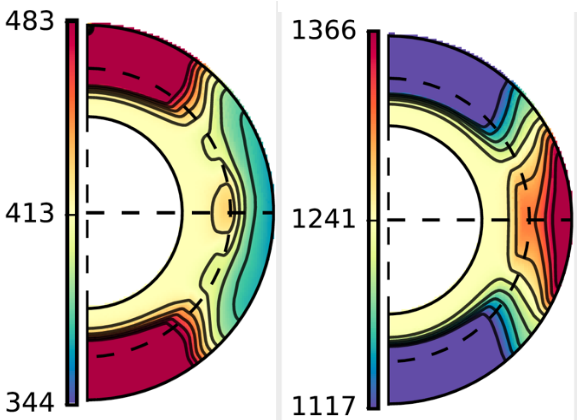

Figure 1: Differential rotation profiles in solar-like star: comparing anti-solar (left; slow equator – fast poles) to solar like (right; fast equator – slow poles) cases. Contour plots in meridional cuts of angular velocity with red tones indicating prograde flows (Brun et al. (2017)).

Results:

We have computed the marginal state of 15 solar-like star models ranging from 0.5 to 1.1. solar mass and rotation rates spanning 1/8 to 5 times the solar rotation rates. We have covered a range of Ekman number spanning 3 orders of magnitude. All models include both an upper convective envelope coupled to a stably stratified radiative interior. This coupling to a stable layer improves the realism of the simulations by providing a more realistic bottom boundary condition to the convective flows. In Figure 2, we represent the marginal state of convection for a 0.7 solar mass star for 4 rotation rates by displaying as contour plots the radial convective velocity in an equatorial plane. Each panel shows the most unstable convection mode and we clearly see that as the influence of rotation increases the pattern of convection becomes smaller both in longitudinal and radial extent. At high rotation rates, the patterns reach an azimuthal wave number greater than 40.

In Figure 3, we show the entropy fluctuations of the marginal state. Convection is a dynamical process driven by entropy perturbation and the associated buoyancy driving. In that case we have changed the aspect ratio and density stratification of the model fixing the Ek number (rotation). We note that convection is modified such that entropy fluctuations shrink both in longitudinal and radial extent as we go from left to right.

In Figure 4 we show how the various key critical parameters of convection, Rayleigh number, azimuthal wave number and frequency are influenced by rotation (Ekman number) and by the stellar mass (stratification and aspect ratio). We recover published results with scaling laws with respect to the Ekman number following the -4/3, -1/3 and -2/3 scaling (it becomes harder and harder to excite convection as rotational influence is increased and the critical mode is smaller and smaller). We also see that for the azimuthal wave number (Figure 4 panel b), stellar mass has a clear influence, this is less true for the 2 other quantities.

In Figure 5 we display the angular velocity associated to the marginal state for the 0.9 solar mass case (all stellar masses follow similar trends). We see that for small Ekman number (right panel), the flow is prograde (solar-like) and confined mostly to the equatorial region in the upper convective envelope. Uniform rotation is observed in the stable layer. By contrast, the slowly rotating (larger Ekman number) case (left panel) show a more distributed differential rotation, both in latitude and radius. The model retains a prograde rotation state in the upper equatorial region, with slower rotation at higher latitudes, hence retaining a solar like rotation profile. Contrary to the equivalent nonlinear supercritical state published in 2017, that exhibits an anti-solar rotation profile as shown in the left panel of Figure 1, we do not find this anti-solar state. This means that anti-solar rotation states are the outcome of nonlinear turbulent processes, likely to be present in real stars. This confirms the need to look in the sky for such anti-solar like rotating stars.

Further, the non-uniform rotation in the stable (non convective) layer came as a surprise and is an exciting finding. This implies angular momentum transport by a process different from convection in the stable layer. As we have seen in Figure 2 and 3, gravity waves are excited by the convective mode and are the mean of redistributing angular momentum in the stable layer. This is a very interesting results.

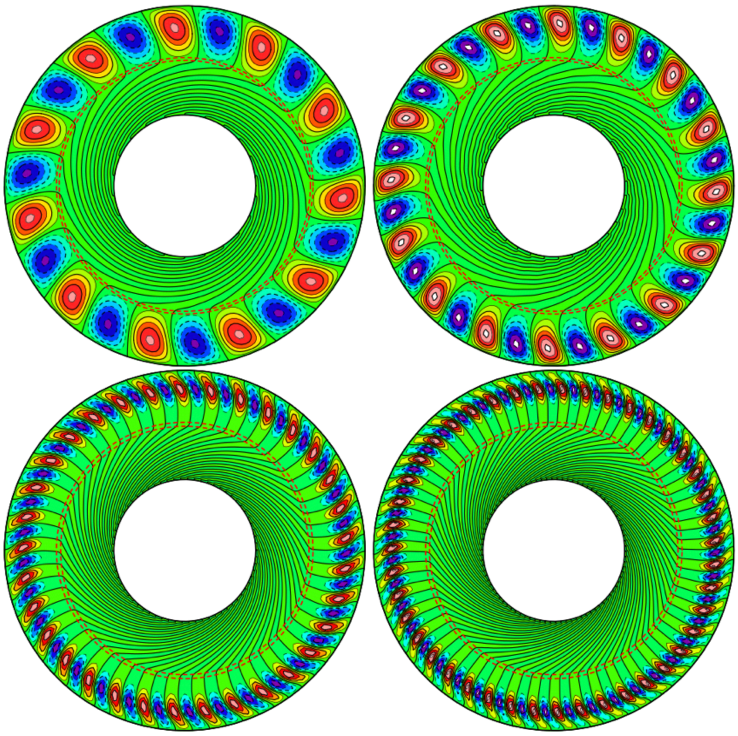

Figure 2: Contour plots in an equatorial cut of the radial convective velocity in 4 cases having the same stratification but a different rotation rate. The dash line represents the base of the convective envelope. In the inner stable layer we note the spiraling pattern of internal gravity waves.

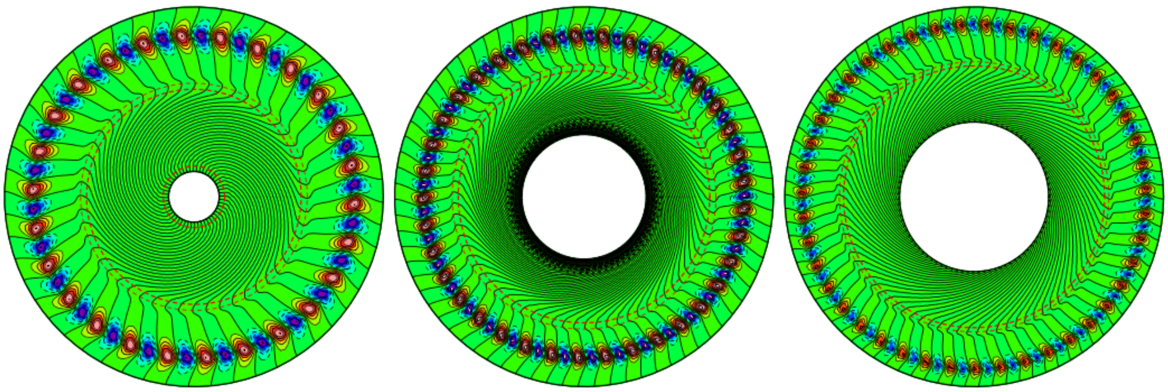

Figure 3: Contour plots in an equatorial cut of the entropy perturbations in 3 cases with varying aspect ratio and density stratification representative of the internal structure of a 0.5, 0.7 and 0.9 solar mass stars.

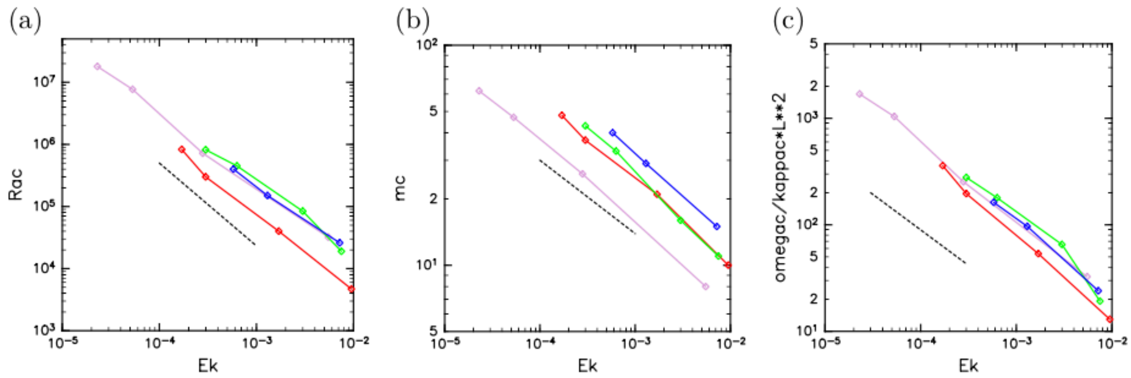

Figure 4: (a) The critical Rayleigh number as a function of the Ekman number. The dotted line is the slop with -4/3 power. (b) The critical azimuthal wave number as a function of the Ekman number.The dotted line is the slop with -1/3 power. (c) The non-dimensional critical frequency w_C as a function of the Ekman number. The dotted line is the slop with -2/3 power. Magenta, red, green and blue lines are for 0.5, 0.7, 0.9 and 1.1 solar mass star series, respectively.

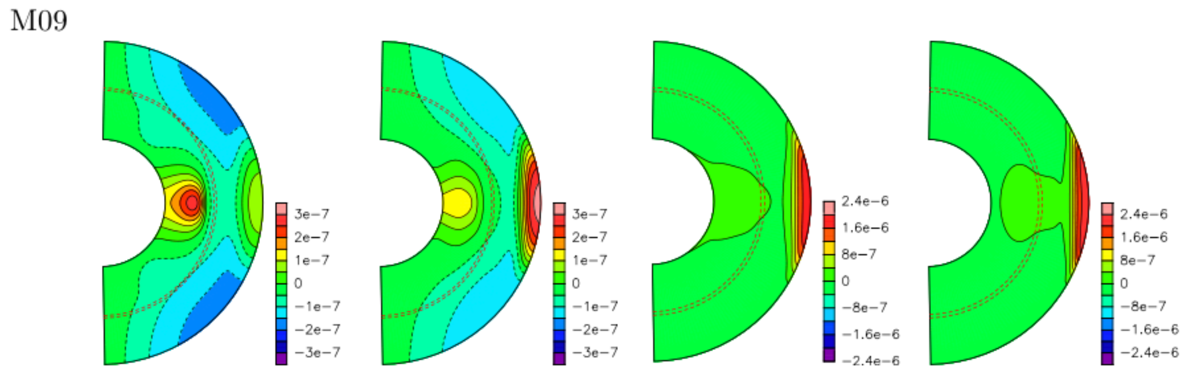

Figure 5: Contour plots in a meridional plane of the rotation state (angular velocity) associated to the marginal state of convection illustrated in Figure 2 and 3. Note how the rotation state goes from mostly confined in the equatorial convective region for fast rotation rates (right panel) to more distributed at all latitude and depth. Angular momentum transport by gravity waves is at the source of the non-uniform profile in the stable layer below the dashed line. We illustrate the rotation profile realize in the 0.9 solar mass star cases.

Conclusion: We have found that anti-solar rotation states of slowly rotating stellar convection models are likely to exist in real stars, because there are only found in supercritical state of convection in 3D numerical simulation. Since real stars have highly supercritical states it is encouraging that such states are not found at the marginal state of convection, there are less likely to be a spurious effect of large viscous effect or weak turbulence. We also showed that gravity waves excited by the critical mode of convection can transport efficiently angular momentum and break the uniform rotation of the inner stable layer. Overall this is a very fruitful collaboration and I wish to pursue it as we have new ideas for interesting applied mathematical problems.

Complementary Scientific Activities:

A.1) Organization of a scientific workshop:
During my stay at Kyoto University, we have also organized a workshop with many Japanese experts in fluid and plasma dynamics in stars and other systems. We indicate the program below:

Astrophysical and Solar MHD Workshop at RIMS on the 6th of December 2019
Convenors: Shin-Ichi Takehiro and Allan Sacha. Brun

Workshop starts at 10am in seminar room 110 in RIMS (to the right after entering the main entrance).
9:30 - 10:00 Welcome
10:00-10:30 K. Kusano "On the predictability of solar flares and CMEs"
10-30-11:00 A.S. Brun "On energy transfers and dynamo-wind coupling in stars"
Coffee Break 30mn

11:30 - 12:00 H. Hotta “Flux rising from deep convection zone and formation of sunspot“
12:00- 12:30 S. Toriumi “Flare-productive active regions and delta-spots simulations”
Lunch Break 1h30
14:00 - 14:30 T. Suzuki “MHD in a cylindrical shearing box”
14:30 - 15:00 T. Sakurai “Magnetic energy and helicity spectra of solar active regions”
15:00 - 15:20 T. Yokoyama “Magnetobuoyancy instability with effect of cosmic-ray pressure”
15:20 - 15:40 Y. Masada “Spherical-shell mean-field dynamo with turbulent α and η & solar differential rotation”
Coffee break 30 mn
16:10 - 16:40 M. Shoda “Alfvén-wave driven magnetic rotator wind: mass- and angular-momentum-loss rates”
16:40 - 17:10 N. Yokoi “Magnetoclinicity effect: Transport in strongly compressible MHD turbulence”
17:10 - 17:40 S. Takehiro “Critical states and generated mean zonal flows of stellar convection models”
17:40 - 17:55 Sakaue “Stellar atmosphere & wind model for cool main-sequence stars from the sun to M dwarfs”
17:55 –18:10 Kotoni “Anemone Jets in the Solar Photosphere and Their Effects on the Upper Atmosphere”

A.2) Participation on December 5th to a workshop organized at RIMS by visiting Prof. M. Farge:
French-Japanese Workshop on Wavelet and Large Eddy Representations to Study Turbulent Flows
10:30-10:50
Allan Sacha Brun, Département d'Astrophysique, Commissariat à l'Energie Atomique (CEA), Saclay (France)
Wavelet analysis of Large Eddy Simulations of stellar convection and magnetism
10:50-11:00 Open discussion

A.3) Collaboration with Prof. Shibata from Department of Astrophyics:

Co-Organisation of 2 seminars in Shibata-san’s MHD Group in room 328 of Graduate School of Science Bldg.4, one on October 28th and another in December 10th.

a) 2 topics seminar by Dr. R. Raynaud – Postdoc at DAp-AIM, CEA Paris Saclay, France, October 28th.
Title: Magnetar formation through convective dynamo in protoneutron stars
Abstract: Magnetars are isolated neutron stars characterized by a variable X-ray activity powered by the dissipation of strong magnetic fields. Their spin-inferred dipole field strengths range from 100 to 1000 times those of radio pulsars. For many decades now, understanding the origin of these objects has been a theoretical challenge. Thanks to the first 3D MHD direct numerical simulations of thermal convection that develops inside a nascent neutron star, we show that the in situ magnetic field amplification by dynamo action can explain magnetar formation. For sufficiently fast rotation rates, the instability saturates in the magnetostrophic regime with the magnetic energy exceeding the turbulent kinetic energy by a factor up to 10. Our results are compatible with the observational constraints derived from galactic magnetars and also provide strong theoretical support for millisecond protomagnetar models of gamma-ray bursts and superluminous supernovae central engines.

Title : Long-term modulation of the solar cycle
Abstract: We consider dynamo action driven by three-dimensional rotating anelastic convection in a spherical shell. Motivated by the behaviour of the solar dynamo, we examine the interaction of hydromagnetic modes with different symmetries and demonstrate how complicated interactions between convection, differential rotation and magnetic fields may lead to modulation of the basic cycle. For some parameters, Type 1 modulation occurs by the transfer of energy between modes of different symmetries with little change in the overall amplitude; for other parameters, the modulation is of Type 2, where the amplitude is significantly affected (leading to grand minima in activity) without significant changes in symmetry. Most importantly, we identify the presence of supermodulation in the solutions, where the activity switches chaotically between Type 1 and Type 2 modulation; this is believed to be an important process in solar activity.

b) 1 topic seminar by Dr. B. Perri – former PhD student of Dr. A.S. Brun, now postdoc at IAS, France. December 10th.

Title:The dynamo-wind feedback loop : Assessing their non-linear interplay

Abstract: Though generated deep inside the convection zone, the solar magnetic field has a direct impact on the Earth space environment via the Parker spiral. It strongly modulates the solar wind in the whole heliosphere, especially its longitudinal and latitudinal speed distributions over the years. However the wind also influences the topology of the coronal magnetic fi eld by opening the magnetic field lines in the coronal holes, which can affect the inner magnetic fi eld of the star by altering the dynamo boundary conditions. This coupling is especially difficult to model because it covers a large variety of spatio-temporal scales. Quasi-static studies have begun to help us unveil how the dynamo-generated magnetic field shapes the wind, but the full interplay between the solar dynamo and the solar wind still eludes our understanding.
We use the compressible magnetohydrodynamical (MHD) code PLUTO to compute simultaneously in 2.5D the generation and evolution of magnetic fi eld inside the star via an alpha dynamo process and the corresponding evolution of a polytropic coronal wind over several activity cycles for a young Sun. A multi-layered boundary condition at the surface of the star connects the inner and outer stellar layers, allowing both to adapt dynamically. Our continuously coupled dynamo-wind model allows us to characterize how the solar wind conditions change as a function of the cycle phase, and also to quantify the evolution of integrated quantities such as the Alfvén radius. We further assess the impact of the solar wind on the dynamo itself by comparing our results with and without wind feedback.