What happens inside Red Giant stars?

Convection and dynamos in evolved late-type stars

C. Ortiz-Rodríguez, P.J. Käpylä, F.H. Navarrete, D. R. G. Schleicher, J.P. Hidalgo, B. Toro-Velásquez, R. Banerjee, *Hamburger Sternwarte, Universität Hamburg*

In Short

- Motivation: The presence of magnetic fields has been detected in Red Giant stars. Theoretical and observational works indicate that dynamos operate in them.
- Goals. Our idea is to study magnetic fields and convection in these stars as a function of rotation, and how they are connected in terms of the convective turnover time and Rossby number.
- Methods. We will use 3-dimensional magnetohydrodynamical simulations of a Red Giant star embedded in a box. These simulations for the first time include rotation, magnetic fields, and the bulk of the convection zone to produce self-consistent dynamo solutions.

Observations of numerous types of stars have made it clear that they exhibit magnetic activity. One of the best examples is the Sun. We can see the manifestations of its magnetic fields in the form of sunspots, even with very simple instruments, such as a Solar projector. Low-mass stars like the Sun have a central core in which nuclear reactions take place; a radiative layer, which is where the heat produced in the core is transported by radiation; and an outer layer where energy is transported by convection. This layer is known as the convection zone, where hot plasma rises, cools down, and then descends deeper into the convective region.

The Sun is currently at an evolutionary stage where we do not expect significant changes in its structure. During this stage, stars live most of their lives until they run out of nuclear fuel. Once they do, their exterior convective envelope will expand and their structure will change. This marks the transition to the next evolutionary phase, called the Red Giant Branch (RGB). During this stage, red giant stars can be several times larger than they were during the Main Sequence, increasing the size of their convective zone as the star evolves during the RGB.

Stars in this evolved evolutionary stage also show magnetic fields. This has been confirmed via the Zeeman effect [1], which is the splitting of the spectral lines due to the presence of magnetic fields. Even though we have evidence of the presence of magnetic fields in red giants, the exact mechanism by which is sustained is not well understood.

Some important parameters characterise the fluids of stellar interiors. One of them is the Rossby number (Ro), which measures the influence of rotation on the flow, and it is defined as the ratio of the rotation period (P_{rot}) and the convective turnover time $\tau_{\mathrm{c}} \approx \ell/u$. τ_{c} is typically approximated from estimated mixing lengths (ℓ) and velocity scales (u). Particularly, Ro is usually used to study magnetic activity in stars. In this sense, it has been found by [2] that the chromospheric emission, which is an indicator of magnetic activity in young and evolved late-type stars, scales similarly with the Rossby number despite the latter rotating significantly slower. This suggests that the dynamos responsible for magnetic activity in these stars operate similarly. The determination Ro depends on the rotation period P_{rot}, a well-known parameter for most of the observed stars. However, it also depends on the determination of τ_{c}, which cannot be measured directly but needs to be calculated from stellar evolution models or using empirical fits [3]. This provides a relevant limitation for the determination of the Rossby number itself and more reliable models to obtain the convective turnover time are needed [4].

Numerical simulations are essentially laboratories to study processes and phenomena that are not well understood. So far, numerical studies aimed at RGB stars have not been systematically performed. Some of them include hydrodynamical simulations of the convection of red giants, without considering rotation or magnetic fields [5]. [6] performed simulations including magnetic fields but not rotation. [7] presented hydrodynamical simulations, considering 50% of the inner part of the convective zone of an RGB star. Most of the simulations so far did not focus on the nature of the magnetic fields or the dynamo mechanism sustaining them. Furthermore, they did not capture the whole picture needed to achieve more realistic results, e.g., they did not consider stellar rotation or the full extent of the convection zone.

This project aims to study where the red giant dynamos stand in the framework of the theory of stellar magnetism. Furthermore, we want to establish whether the current estimates of convective turnover time and Rossby numbers are reliable by computing these directly from computational simulations. We will do this via 3-dimensional magnetohydrodynamical (MHD) simulations using the star-in-a-box setup. This setup has been used before to study other types

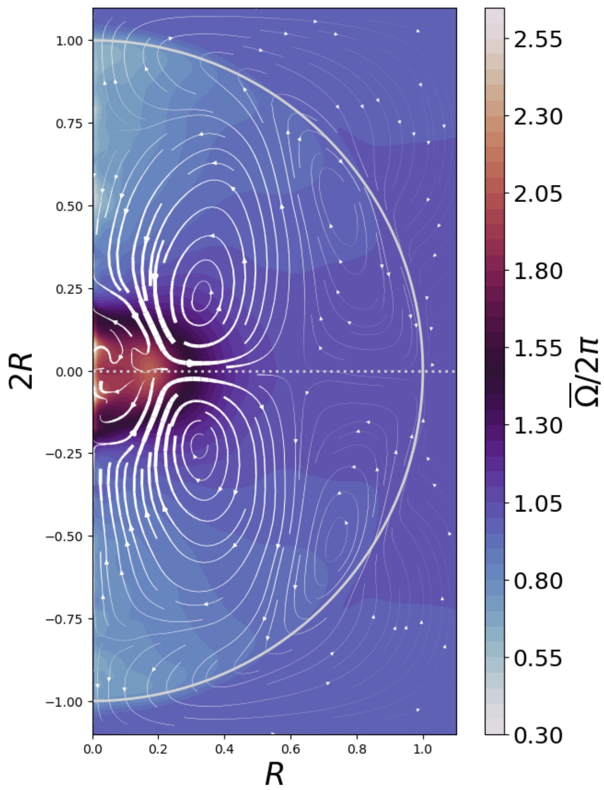

Figure 1: *Time averaged angular velocity of a Red Giant star run.*

of stars, such as fully convective stars [8][9], which are stars with masses below 0.35$M_\odot$, and partially convective stars like the Sun [10]. For this project, we have adapted the star-in-a-box setup to perform simulations of the red giant phase of a solar mass star. Figure 1 shows the rotational profile of a Red Giant star from our adapted setup. We can see that it rotates faster at the centre than at its exterior zone. This will be an important step into the theoretical understanding of magnetism in red giants. At the same time, the results of this project will be useful to observers as it can bring insights into the scaling laws of magnetism as a function of Rossby number.

WWW

https://www.physik.uni-hamburg.de/en/hs.html

More Information

[1] M. Aurière, R. Konstantinova-Antova, C. Charbonnel, et at., *Astronomy & Astrophysics* (2015) **574**, A90. doi:10.1051/0004-6361/201424579

[2] J. J. Lehtinen, F. Spada, M. J. Käpylä, N. Olspert, P. J. Käpylä. *Nature Astronomy* (2020) **4(7)**, 658-662. doi:0.1038/s41550-020-1039-x

[3] R. W. Noyes, L. W. Hartmann, S. L Baliunas, D. K. Duncan A. Vaughan. *Astrophysical Journal* (1984) **279**, 763–777. https://adsabs.harvard.edu/full/1984ApJ...279..763N

[4] W. C. Jao, A. A. Couperus, E. H. Vrijmoet, N. J. Wright, T. J. Henry. *The Astrophysical Journal* (2022) **940(2)**, 145. doi:10.3847/1538-4357/ac9cd8

[5] B. Freytag, M. Steffen, B. Dorch, *Astronomische Nachrichten* (2002) **323**, 213–219. doi:10.1002/1521-3994(200208)323:3/4<213::AID-ASNA213>3.0.CO;2-H

[6] B.F. Dorch. *Astronomy Astrophysics* (2004) **423**, 1101–1107. doi:10.1051/0004-6361:20040435

[7] A.S. Brun A. Palacios, The Astrophysical Journal (2009) **702**, 1078–1097. doi:10.1088/0004-637X/702/2/1078

[8] W. Dobler, M. Stix, and A. Brandenburg. *The Astrophysical Journal* (2006) **638**, 336–347. doi:10.1086/498634

[9] P.J. Käpylä. *Astronomy Astrophysics* (2021) **651**, A66. doi:10.1051/0004-6361/202040049

[10] P.J. Käpylä (2022). *The Astrophysical Journal Letters*, **931(2)**, L17. doi:10.3847/2041-8213/ac6e6b

Funding

DAAD/BECAS Chile, 2023 (57636841), DOCTORADO DAAD-BECAS CHILE/62220030.

DFG Subject Area

311-01