At the core of stellar magnetism

Convection and dynamos near the transition to full convection

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In Short

- The envelopes of late-type stars like the Sun are convective meaning that fluid motions transport the energy through these layers.
- Such convective motions are thought to be responsible for generating magnetic field of the Sun, manifested by sunspots and violent eruptions such as coronal mass ejections.
- Stars lighter than the Sun have progressively deeper convective envelopes such that stars with less than about a third of the solar mass are fully convective.
- Stars near the transition to full convection are ideal laboratories for testing theories of convection and stellar magnetism.
- In the current project we use a novel star-in-a-box model to address these questions using self-consistent three-dimensional simulations of stars in the vicinity of the transition to full convection.

The surface of the Sun reveals a dynamically evolving pattern with bright isolated patches surrounded by a dark network-like structure. This is characteristic of convection where warm (bright) material rises and cool (dark) material descends. The average size of the brighter convection cells is of the order of a few hundred kilometers at the surface of the Sun, which is thought to reflect also the vertical extent of the cells. However, helioseismology, a technique similar to seismology used on Earth, has revealed that the depth of the solar convection zone is about 200Mm or roughly 30% of the radius of the Sun.

The motions in the convection zone are highly turbulent. This means that the the flows have an enormous range of scales from centimeters to the depth of the convection zone all of which interact in complex and chaotic ways. However, such turbulent motions can collectively give rise to ordered large-scale phenomena. One such example is the surface differential rotation of the Sun: the rotation period of the equator of the Sun is around 25 days, whereas near the solar poles it is about 35 days. Furthermore, helioseismic results indicate that the convection zone rotates differentially throughout and that the radiative core below rotates essentially like a rigid body. A shallow layer at the interface of the radiative and convective zones, the tachocline, is where the rotation changes abruptly from rigid to differential. Another, perhaps more familiar example, are the large-scale magnetic fields which give rise to sunspots and the solar 22 year magnetic cycle. The magnetic field of the Sun is maintained by a dynamo within or just below the convection zone. Thus convection and its interaction with rotation is of crucial importance for understanding our nearest star.

In cooler stars that are less massive than the Sun, the convective envelopes become gradually deeper. Stars with a mass of roughly a third of the solar mass are fully convective. Such stars do not have a tachocline, and differential rotation is likely present throughout the star. This is important because some theories of the solar dynamo rely on a tachocline to produce the observed magnetism. Thus it is important to study the dynamos near the transition to full convection to ascertain the dominant dynamo processes. More specifically, are stellar magnetic fields generated predominantly within their convection zones or does the tachocline play an important role in stars such as the Sun?

In the current project we use a novel simulation technique where a spherical star is embedded into a cubic box. Figure [1] shows representative examples of the flows in simulations of a $0.2M$ solar mass star which is fully convective. This model enables simulations of convection and dynamos self-consistently without the need to impose solid walls immediately below or above the convection zone. Our models build on the work of [1] who were the first to consider this type of simulations in the context of fully convective stars. We have introduced several improvements into the model, such as a more realistic description of radiative diffusion that adapts to ambient thermodynamic state within the star [2].

Our results show that the dynamos of fully convective stars in the slow and intermediate rotators produce predominantly axisymmetric large-scale fields. Furthermore, the dynamo solutions change from quasi-stationary to cyclic as the rotation rate increases, see Figure [2]. For rapid rotation the magnetic field is no longer predominantly axisymmetric and a strong low-order non-axisymmetric contribution arises in such cases, see Figure [3]. These transitions occur around the same Rossby numbers as in partially convective stars which is hinting toward a common origin of stellar dynamos.

We use the Pencil Code [4] which is a free (licensed under GNU GPL v3) simulation framework for solving ordinary and partial differential equations

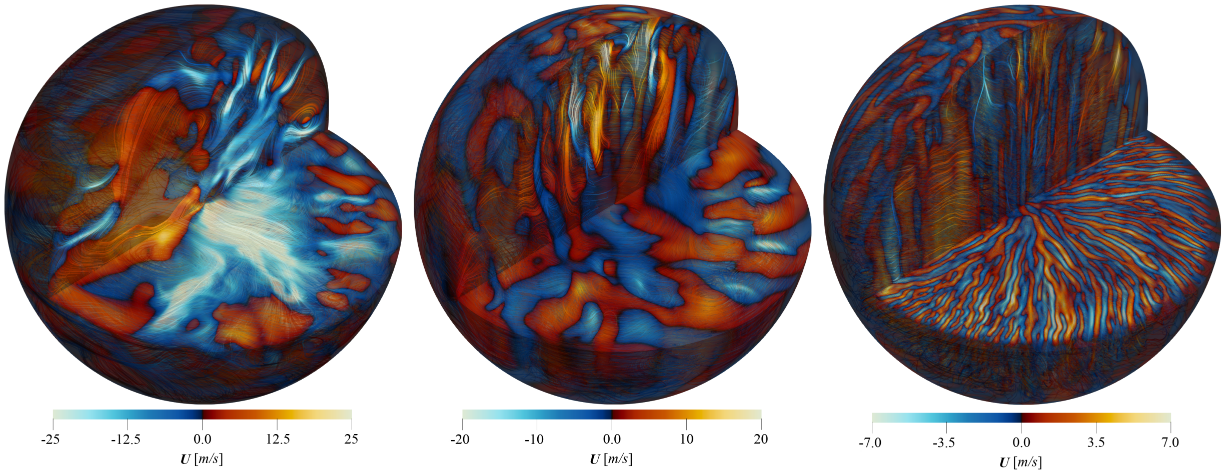

Figure 1: *Radial velocity U_r (colour contours) along with the streamlines of the flow colour-coded with U_r from simulations of a fully convective spectral class M5 star with $M = 0.2M_\odot$. A non-rotating run (left), and runs with $P_{rot} = 43$ days (middle), and $P_{rot} = 4.3$ days (right) are shown. Adapted from [2].*

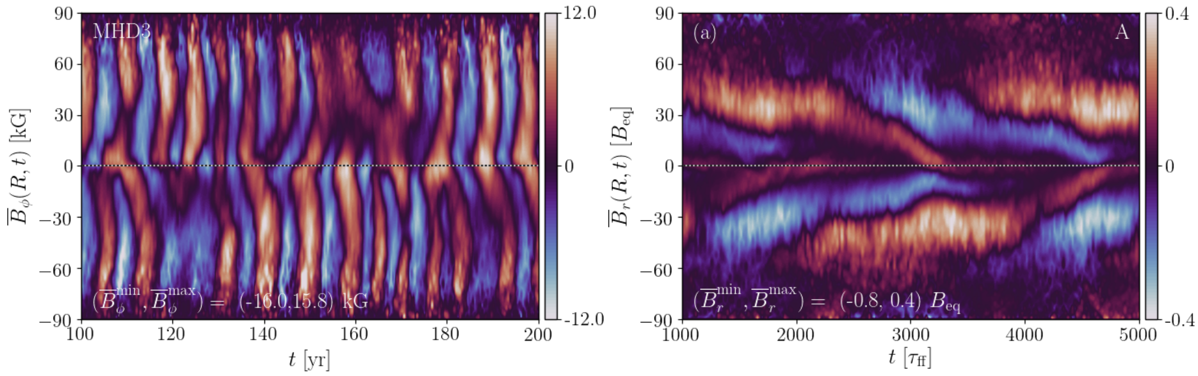

Figure 2: *Azimuthally averaged toroidal magnetic field $\overline{B}_\phi$ near the surface of the star as a function of time for an intermediate rotator with $P_{rot} = 43$ days (left). Adapted from [2]. Azimuthally averaged radial magnetic field $\overline{B}_\phi$ near the surface of the star as a function of time in a solar-like partially convective star (right). Adapted from [3]*

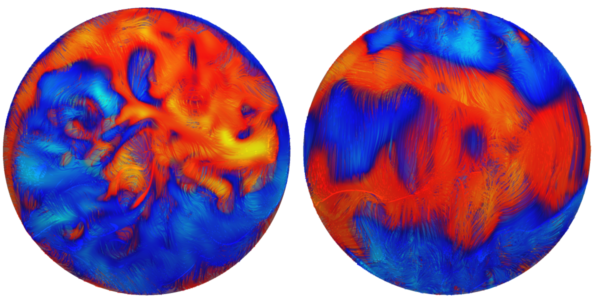

Figure 3: *Radial magnetic field B_r (colour contours) along with the magnetic field lines colour-coded with B_r near the surface of the star from a simulation of a rapidly rotating M5 star with $P_{rot} = 4.3$ days. Polar (left), and equatorial (right) views are shown. Adapted from [2].*

with a great variety of applications in physical problems ranging from gravitational waves, chemistry, planet formation to stellar magnetism.

WWW

https://www.uni-goettingen.de/en/203293.html

More Information

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[2] P. J. Käpylä, *Astron. Astrophys.* **651**, 66 (2021). doi:10.1051/0004-6361/202040049

[3] P. J. Käpylä, *Astrophys. J. Lett.* **931**, L17 (2022). doi:10.3847/2041-8213/ac6e6b

[4] Github: https://github.com/pencil-code

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