Simulations of fully convective M dwarf stars

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Hello there!

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THE MODEL

Star-in-a-box simulations of fully convective stars

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ABSTRACT

Context. Main-sequence late-type stars with masses less than $0.35M_\odot$ are fully convective.
Aims. The goal is to study convection, differential rotation, and dynamos as functions of rotation in fully convective stars.
Methods. Three-dimensional hydrodynamic and magnetohydrodynamic numerical simulations with a star-in-a-box model, where a spherical star is immersed inside of a Cartesian cube, are used. The model corresponds to a $0.2M_\odot$ main-sequence M5 dwarf. A range of rotation periods ($P_{\rm rot}$) between 4.3 and 430 days is explored.
Results. The slowly rotating model with $P_{\rm rot} = 430$ days produces anti-solar differential rotation with a slow equator and fast poles, along with predominantly axisymmetric quasi-steady large-scale magnetic fields. For intermediate rotation ($P_{\rm rot} = 144$ and 43 days) the differential rotation is solar-like (fast equator, slow poles), and the large-scale magnetic fields are mostly axisymmetric and either quasi-stationary or cyclic. The latter occurs in a similar parameter regime as in other numerical studies in spherical shells, and the cycle period is similar to observed cycles in fully convective stars with rotation periods of roughly 100 days. In the rapid rotation regime the differential rotation is weak and the large-scale magnetic fields are increasingly non-axisymmetric with a dominating $m = 1$ mode. This large-scale non-axisymmetric field also exhibits azimuthal dynamo waves.
Conclusions. The results of the star-in-a-box models agree with simulations of partially convective late-type stars in spherical shells in that the transitions in differential rotation and dynamo regimes occur at similar rotational regimes in terms of the Coriolis (inverse Rossby) number. This similarity between partially and fully convective stars suggests that the processes generating differential rotation and large-scale magnetism are insensitive to the geometry of the star.

Key words. Stars: magnetic field – Dynamo – Magnetohydrodynamics (MHD) – Convection – Turbulence

STAR-IN-A-BOX SETUP OF FULLY CONVECTIVE STARS

Käpylä (2020), Dobler et. al. (2006).

This model allows global dynamo simulations in spheres using a cartesian grid. The star is described as a spherical region of a radius R of a cubic box of a side half-legth of $H = 1.1R$. The usual equations of magneto-hydrodynamics (MHD) are solved with the Pencil Code.

$$\frac{\partial \boldsymbol{A}}{\partial \mathrm{t}} = \boldsymbol{u} \times \boldsymbol{B} - \eta \mu_0 \boldsymbol{J}$$

INDUCTION EQUATION

$$\frac{\mathrm{D} \ln \rho}{\mathrm{Dt}} = -\nabla \cdot \boldsymbol{u}$$

CONTINUITY EQUATION

$$\frac{\mathrm{D}\boldsymbol{u}}{\mathrm{Dt}} = -\nabla \Phi - \frac{1}{\rho}(\nabla \mathrm{p} - \nabla \cdot 2\nu\rho\boldsymbol{S} + \boldsymbol{J} \times \boldsymbol{B}) - 2\boldsymbol{\Omega} \times \boldsymbol{u} + \boldsymbol{f}_{\mathrm{d}}$$

EQUATION OF MOTION

$$\mathrm{T}\frac{\mathrm{Ds}}{\mathrm{Dt}} = -\frac{1}{\rho}[\nabla \cdot (\boldsymbol{F}_{\mathrm{rad}} + \boldsymbol{F}_{\mathrm{SGS}} + \mathscr{H} - \mathscr{C}] + 2\nu\boldsymbol{S}^2 + \mu_0 \eta \boldsymbol{J}^2$$

ENERGY EQUATION

Modules used by the model

PHYSICS MODULES

- HYDRO = hydro
- DENSITY = density
- ENTROPY = entropy
- MAGNETIC = magnetic / nonmagnetic
- RADIATION = noradiation
- PSCALAR = nopscalar
- EOS = eos_idealgas
- GRAVITY = gravity
- FORCING = noforcing
- SHEAR = noshear

TECHNICAL MODULES

- MPICOMM = mpicomm
- IO = io_dist
- FILE_IO = file_io_f2003
- REAL_PRECISION = double

M dwarfs

Why to study these stars?

- M dwarfs exhibit conspicuous and abundant evidence of surface activity (Villadsen and Hallinan 2019),
- 70-75% of all stars in the solar neighbourhood (Winters et al. 2019),
- M dwarfs have been recently established as favourable targets for searches of small exoplanets and in-depth studies of their atmospheres.

STELLAR PARAMETERS USED FOR AN M5 DWARF

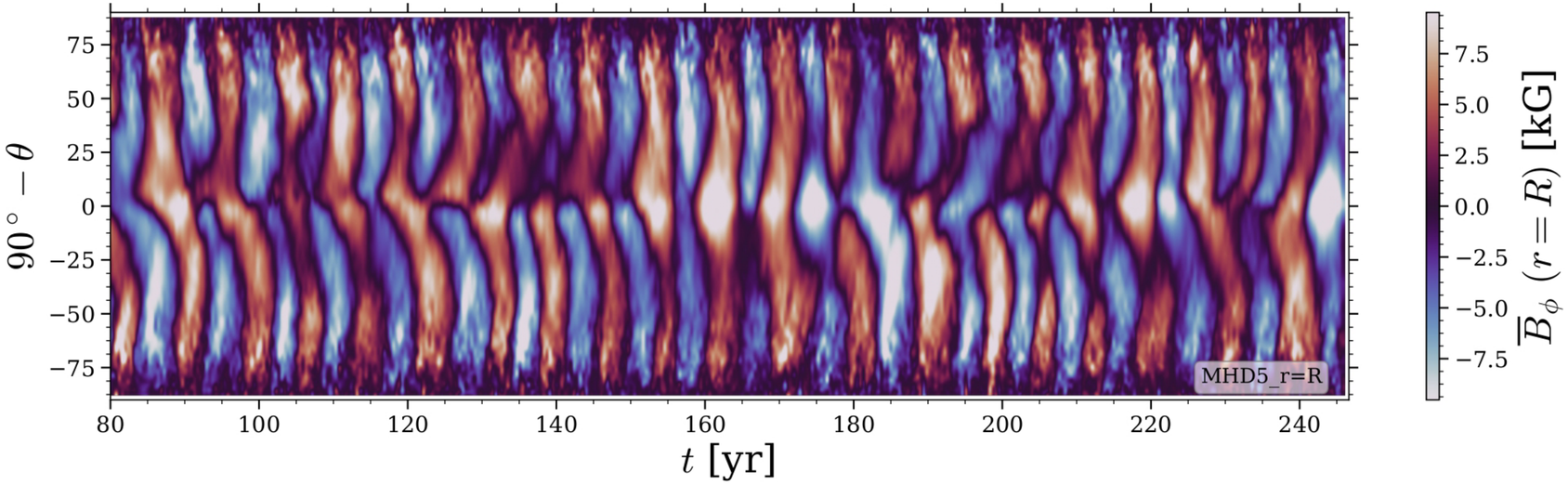
$$M = 0.21 M_\odot,\ R = 0.27 R_\odot,\ L = 0.008 L_\odot,\ T_{eff} = 4000\ K,\ \rho = 150\ g\,cm^{-3}$$

What do I want to learn?

The effect of kinetic viscosity and magnetic diffusivity on stellar dynamos and changes in the quadrupole moment.

Dynamo solution

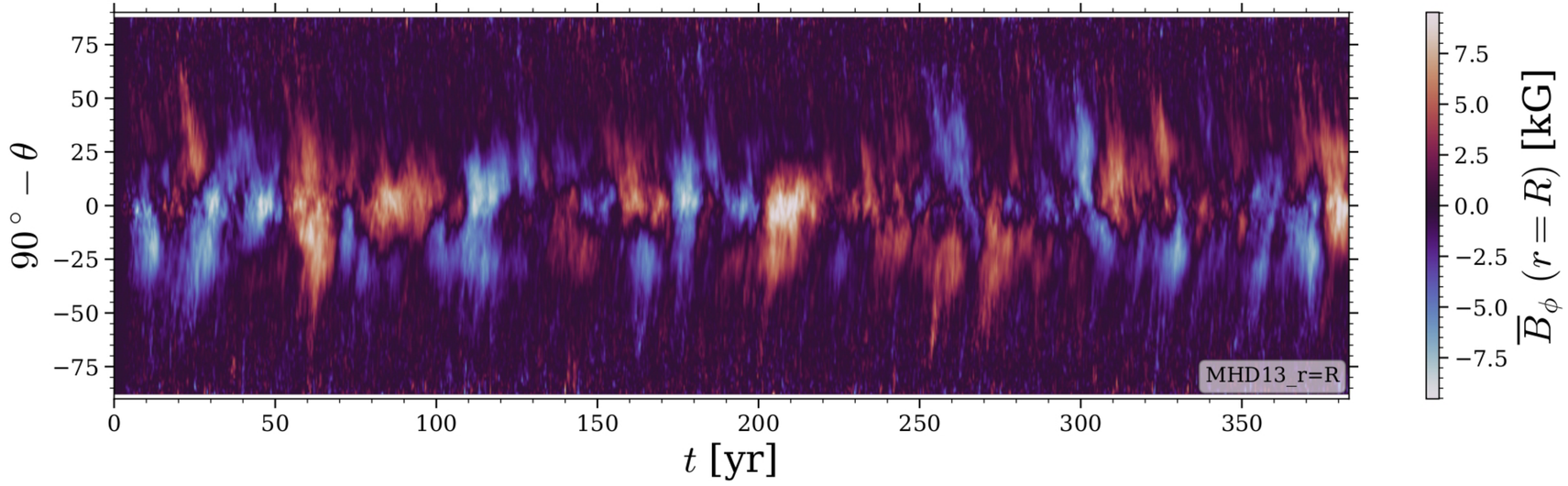
For simulations for stars with $\mathrm{P_{rot}} = 43$ days and magnetic Prandtl number $\mathrm{Pr_M}$ ranging from 0.1 to 1, the azimuthally averaged magnetic field is predominantly axisymmetric $\overline{B}_\phi(R, \theta, t)$ and shows cyclic dynamo solution with periods of $\sim 7 - 10$ years (cycle periods confirmed with FFT).



Azimuthally averaged toroidal magnetic field at $r = R$ as a function of time for a simulation with $\mathrm{Pr_M} = 0.9$, $\mathrm{Re_M} = 54$.

Dynamo solution

For simulations for stars with $\mathrm{P_{rot}} = 43$ days and magnetic Prandtl number $\mathrm{Pr_M} \geq 2$, the azimuthally averaged magnetic field $\overline{B}_\phi(R, \theta, t)$ is predominantly axisymmetric and the cycles start to disappear.



Azimuthally averaged toroidal magnetic field at $r = R$ as a function of time for a simulation with $\mathrm{Pr_M} = 10$, $\mathrm{Re_M} = 390$.

Post-Common-Envelope Binaries (PCEBs)

PCBEs are close binaries that usually contain a White dwarf and a main sequence star, most commonly an M dwarf.

90% of the PCEBs observed show eclipsing time variations (Zorotovic & Schreiber 2013). A possible explanation could be the presence of a third body orbiting the binary or it could be the magnetic activity of the secondary star that disturb its quadrupole moment Q.

Any of these options will leave a mark in the Observed-minus-calculated (O-C) diagram of the eclipsing times.

Quadrupole moment

Applegate Mechanism (Applegate 1989), (Applegate 1992), (Lanza 2020).

These mechanisms relate the period variations of binaries with the change in the shape and internal structure of the magnetically active star. This change is triggered by subsurface magnetic fields produced during a dynamo cycle and it is measured by the quadrupole moment Q:

$$Q_{ik} = I_{ik} - \frac{1}{3}\, Tr\, I$$

Where $Tr\, I$ is the trace of the inertia tensor. The inertia tensor is defined by

$$I_{ik} = \int x_i x_j \; dm = \int \rho(x)\, x_i x_j \; d^3x$$

Quadrupole moment

Applegate Mechanism (Applegate 1989), (Applegate 1992), (Lanza 2020).

- **Applegate 1992:** This model needs the presence of a subsurface magnetic field $\sim 10\,\mathrm{kG}$ which is responsible for redistributing the internal angular momentum of the star. Here the centrifugal force is a key ingredient and tidal locking is needed.

- **Lanza 2020:** The author assumed a permanent non-axisymmetric quadrupolar moment due to the presence of a non-axisymmetric magnetic field modeled as a flux tube. If the star is not tidally locked with the companion, the non-axisymmetric contribution of the quadrupole moment dominates the variation of the gravitational potential felt by the companion.

Quadrupole moment studies

- **Navarrete, et al. (2019):** They present 3D MHD simulations of the magnetic dynamo of solar mass star; a slow rotator and a rapid rotator. They found that the evolution of Q_{xx} is linked to the dynamo and angular momentum evolution. Q_{xx} is anticorrelated with the total and axisymmetric magnetic energies.
- **Navarrete, et al. (2021):** With the classical Applegate mechanism (tidal locking), the orbital period modulations between are one and two orders of magnitude smaller than observed in the target system V471 Tau.

If tidal locking is not considered, the results are compatible with the observed eclipsing time variations.

Summary

- The dynamo solution change with the diffusivities. Increasing $\mathrm{Pr_M}$ ($\mathrm{Re_M}$) leads to larger cycle periods of activity. At large enough $\mathrm{Re_M}$ the cycles start to disappear. This is consistent with in simulations in spherical wedges by Käpylä et al. (2017).

- Recent studies (for solar-like stars) show that the period variations of close binaries could be explained by the dynamo-induced influence of Q over the variations of the gravitational potential felt by the companion.

- The magnetic activity of the star could be indirectly studied with the the period variations of the binary system.

Thank you