Origin of magnetism in radiative stars

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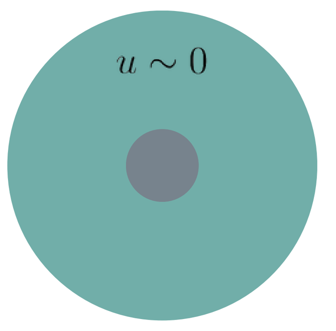
Background

Magnetic fields are ubiquitous in the universe. We believe that these fields are amplified and maintained via astrophysical dynamos, i.e. internal mechanisms that involves the motions of the plasma and its resistivity. The evolution of the magnetic field is given by the induction equation.

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{u} \times \vec{B}) + \eta \nabla^2 \vec{B}$$

Here, we can see the relevance of the flow velocity $\vec{u}$ is, because if the fluid is in a rest frame, this equation will reduce to a diffusion equation, removing the amplification term of the magnetic field. This is exactly why a dynamo is most likely to occur inside convection zones (see Brandenburg and Subramanian, 2005), where $u \neq 0$. This is the reason why fully convective M dwarfs and stars with convective envelopes (like the Sun) can generate a large-scale magnetic field.

✳ But, what happens with stars that are mostly radiative?



According to our understanding of stellar evolution, early-type stars (in this case, we will refer to O, B and A-type stars) are mostly radiative in their interiors, with convective cores due to a steep temperature gradient produced by the CNO cycle.

Let us focus on A-type stars (the most radiative ones). This population has a clear bimodality: bright Vega-like A-type stars with super weak sub-Gauss fields, and the Ap subclass with strong magnetic fields up to 34 kG (Babcock, 1960). The question here is, where do these magnetic fields come from?

Some possible explanations:

- Theoretically, if the star is partially convective the core should be able to drive a dynamo. Augustson et al. (2016) perfomed 3D simulations in spherical coordinates, modeling the inner 64% of a B-type star to explore this possibility. They concluded that the dynamo generated by the core is in fact able to build strong magnetic fields, with peak strengths exceeding a megagauss.
- The magnetic field of these stars is in fact a fossil field, remnants from an early evolutionary stage that have somehow survived in a stable configuration. Braithwaite and Nordlund (2006) found stable magnetic field configurations in a radiative interior starting with random field initial conditions, performing 3D MHD simulations with a grid of 96³ with a star in a box of side $l = 4.5R$.

Here, we will explore the partially convective case performing 3D simulations of the whole star, and the fully radiative case looking for stable configurations with a new model, higher resolution, and a different l/R ratio.

The Model

To explore the mentioned configurations we will perform 3D simulations of a massive early-type star of radius R inside a box with side $l = 2.2R$ using The Pencil Code (Pencil Code Collaboration et al., 2021), solving the non-ideal compressible MHD equations.

Advective derivative:
$D/Dt = \partial/\partial t + \vec{u} \cdot \vec{\nabla}$

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

with:
$$\vec{B} = \vec{\nabla} \times \vec{A}$$
$$\vec{J} = \vec{\nabla} \times \vec{B}/\mu_0$$

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

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

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

These equations describe the time evolution of the magnetic field (in terms of the vector potential $\vec{A}$), the mass conservation, the momentum equation including terms related to gravity (with a potential of an A0 type star), pressure, viscosity, Lorentz force, coriolis (where the rotation rate has its axis fixed on z), and a damping term that describes damping of flows exterior to the star. The energy conservation equation (in terms of the entropy) has a radiative energy transport term (assumed as a diffusion process), a subgrid scale entropy diffusion term, Joule heating, and finally some explicit heating and cooling terms, extracted from Käpylä (2021).

Preliminary results

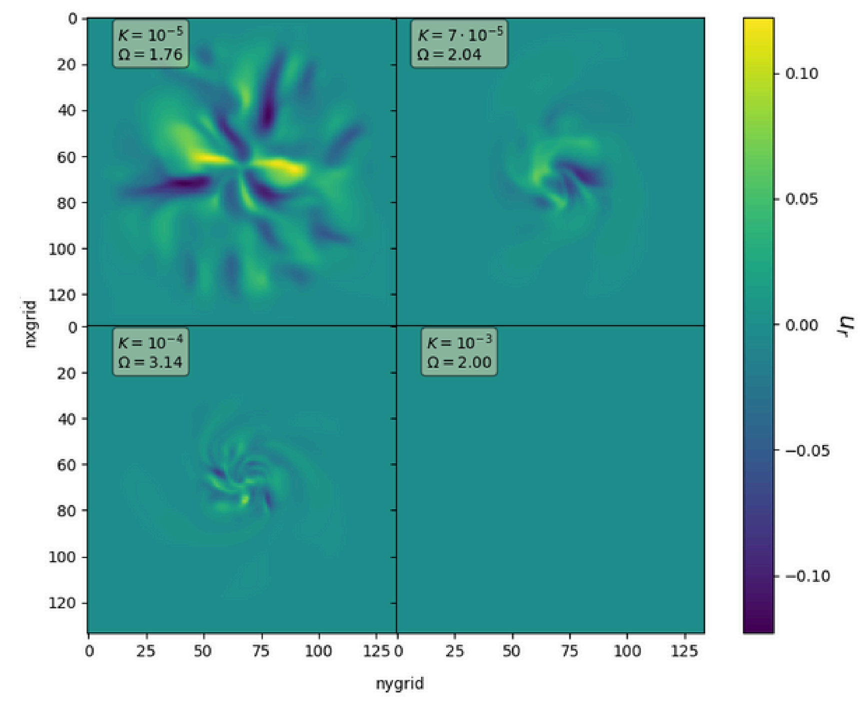


Fig 1. Snapshots of star-in-a-box simulations using a grid of 128³, viewing the *xy* plane in the middle of the *z* axis. The values of K are shown on each plot. The colorbar represents the radial component of the flow velocity.

✳ Initial conditions and units.

All simulations were performed with a resolution of 128³. The heat conductivity K related to the radiative energy transfer (which is inversely proportional to the opacity) is assumed to be constant on each run. Also, all runs had an initial magnetic field seed, given by a vector potential with a Gaussian profile of amplitude 10^{-9} . All the results here are expressed in *code units*, to make a relation to physical units, it is necessary to choose physical parameters of the star to be modeled.

✳ Changing the size of the radiative zone.

The size of zone where the radiative energy transport becomes more efficient depends directly on the radiative heat conductivity *K*, a quantity that is inversely proportional to the opacity κ of the star. In Figure 1 we can see how changing *K* modifies the size of such zone. Regions with $u_r \sim 0$ indicate a potential radiative zone.

✳ Summary of runs:

Run	K	ν	η	Ω	$B_{\max}$
Sim1 $\Delta r \sim 1R$	10^{-5}	10^{-3}	$5 \cdot 10^{-4}$	0	no dynamo
	10^{-5}	10^{-3}	$5 \cdot 10^{-4}$	0.352	0.01652
	10^{-5}	10^{-3}	$5 \cdot 10^{-4}$	0.704	-
	10^{-5}	10^{-3}	$5 \cdot 10^{-4}$	1.760	0.012778
Sim2 $\Delta r \sim 1R$	$4 \cdot 10^{-5}$	$5.7 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	0	no dynamo
	$4 \cdot 10^{-5}$	$5.7 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	0.245	0.012368
	$4 \cdot 10^{-5}$	$5.7 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	0.489	0.016551
	$4 \cdot 10^{-5}$	$5.7 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	1.224	-
Sim3 $\Delta r \sim 0.3R$	$7 \cdot 10^{-5}$	$2.5 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	0	no dynamo
	$7 \cdot 10^{-5}$	$2.5 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	2.044	no dynamo
	$7 \cdot 10^{-5}$	$2.5 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	4.087	no dynamo
	$7 \cdot 10^{-5}$	$2.5 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	10.218	no dynamo
	$7 \cdot 10^{-5}$	$2.5 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	20.435	no dynamo
Sim4 $\Delta r \sim 0.2R$	10^{-4}	$6.2 \cdot 10^{-5}$	$8.8 \cdot 10^{-5}$	0	no dynamo
	10^{-4}	$6.2 \cdot 10^{-5}$	$8.8 \cdot 10^{-5}$	3.140	0.0061353
	10^{-4}	$6.2 \cdot 10^{-5}$	$8.8 \cdot 10^{-5}$	6.280	0.0060869
	10^{-4}	$6.2 \cdot 10^{-5}$	$8.8 \cdot 10^{-5}$	15.700	0.0056404
	10^{-4}	$6.2 \cdot 10^{-5}$	$8.8 \cdot 10^{-5}$	31.401	no dynamo

The runs were divided into 4 main groups, depending on its value of *K* and hence, the size of its convection zone Δr , where R denotes the radius of the star. The dynamos in Sim1 and Sim2 are shown in Figure 2 as butterfly diagrams, and the time evolution of the root-mean-magnetic field in runs from Sim4 is shown in Figure 3.

Table 1. Summary of all the simulations, where K is the heat conductivity, ν is the kinematic viscosity, η the magnetic diffusivity, Ω the rotation rate, and $B_{\max}$ the maximun value of the root-mean-square magnetic field, "no dynamo" indicates that the maximun value is the seed field, and - means that the field has not stabilized yet.

The rotation rates Ω were chosen to get approximate values of 1, 2, 10 (and 30) for the Coriolis Number, and ν, η to get initial Reynolds Numbers (kinematic and magnetic) higher than ~20.

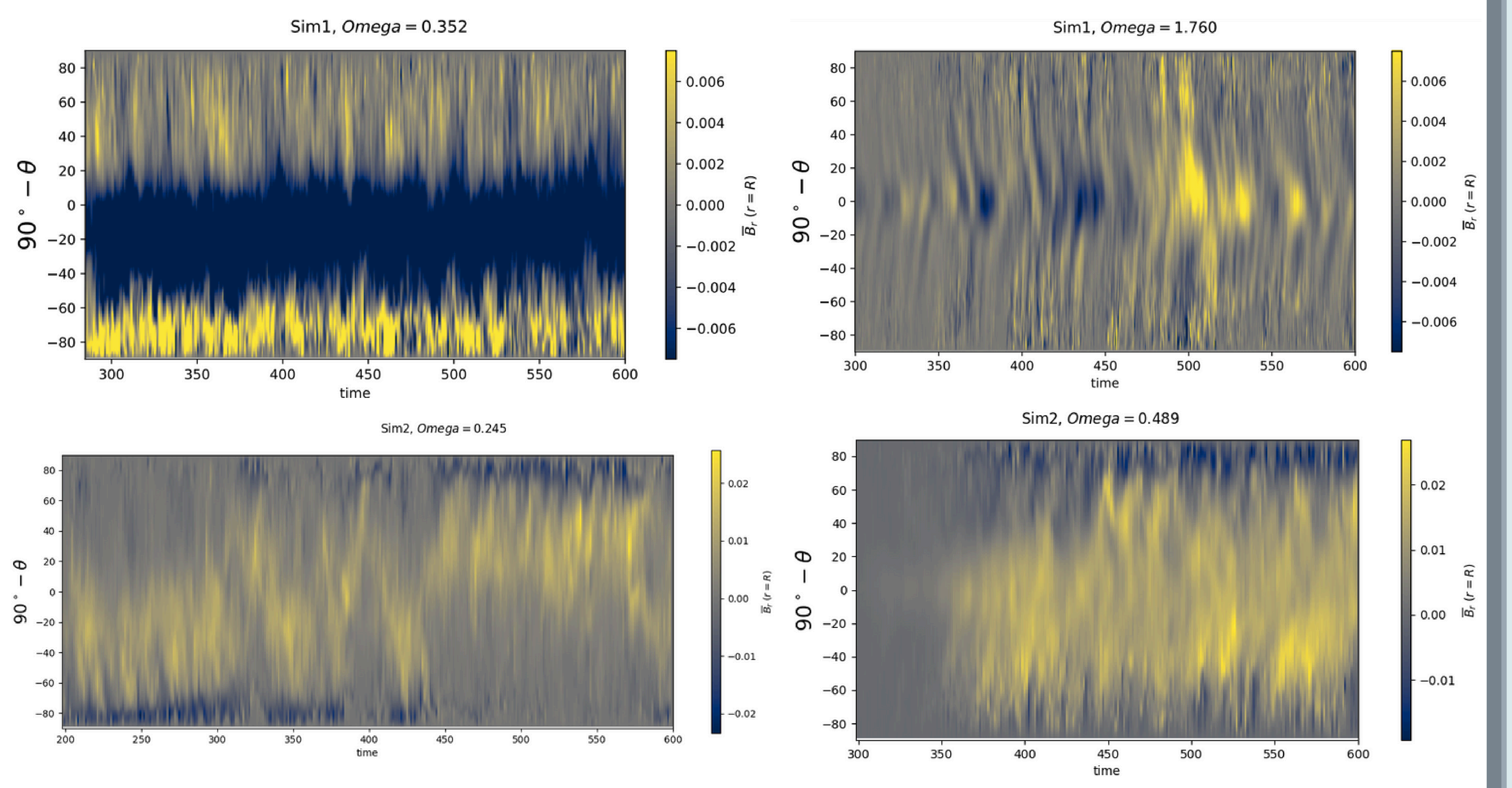


Fig 2. Time evolution of the surface averaged magnetic field (Butterfly diagram) of the runs that were able to generate a dynamo from Sim1 (upper panels) and from Sim2 (lower panels).

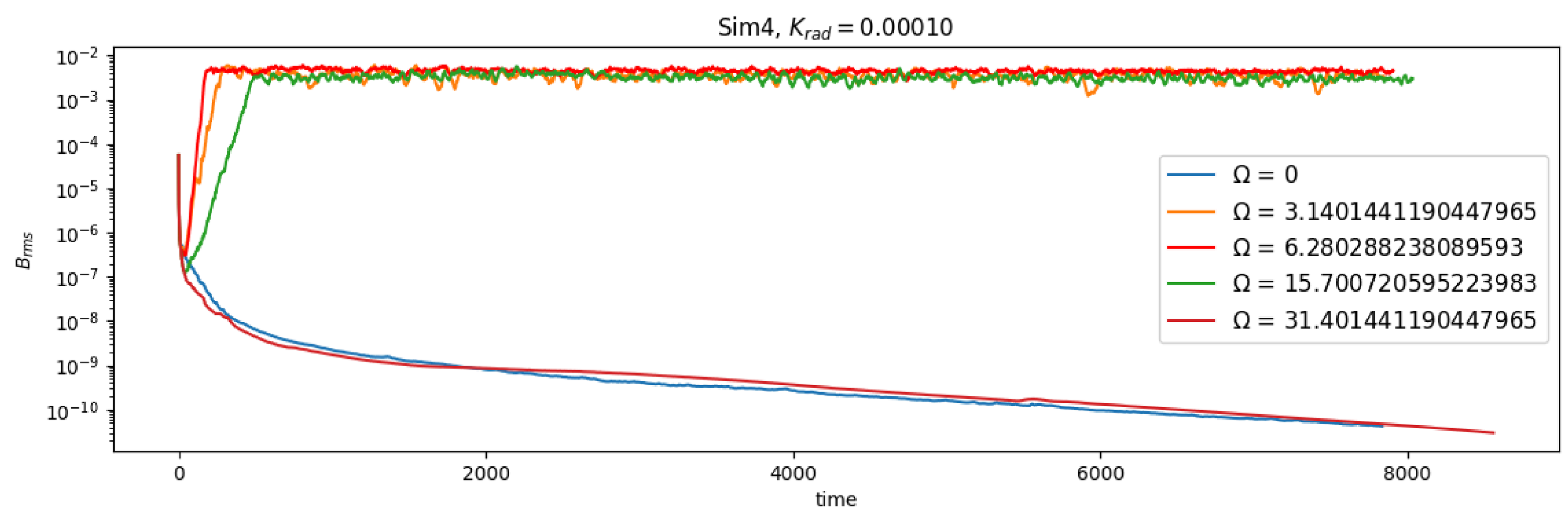


Fig 3. Time evolution of the root-mean-square magnetic fields of all the runs from Sim4, it is possible to see three stable dynamos corresponding to the three intermediate values chosen for the rotation rate Ω.

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