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# Fossil fields in early stellar evolution

**Rainer Arlt**

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany
email: rarlt@aip.de

**Abstract.** Favoured explanations for the presence of magnetic fields on CP stars and the presence of the solar tachocline below the convection zone both imply fossil magnetic fields in the radiative zones. The initial, convective evolution of magnetic fields in a proto-star is studied by numerical, global simulations. The computations are to be extended by a change of the convection zone depth on an evolutionary time-scale.

**Keywords.** Sun: magnetic fields, stars: magnetic fields, turbulence, MHD

## 1. Introduction

While magnetic fields can often be attributed to a dynamo process, we are concerned with the possible long-term existence of magnetic fields in stellar radiation zones which are unlikely to host a dynamo. There are two indications for the presence of fossil magnetic fields in radiative zones. One of them is the presence of strong magnetic fields in chemically peculiar A and B stars (CP stars, *cf.* Arlt 2008 for a review). Since the convectively stable radiation zones covering the outer $\sim 80\%$ of the stellar radius do not provide a turbulent dynamo, the fields are often explained by fossil fields – left-overs from the contraction of the ambient magnetic field together with the proto-star. The second indication stems from the presence of the tachocline in the solar interior. The differential rotation of the convection zone (CZ), covering the outer 30% of the solar radius, turns into a nearly uniform rotation underneath the CZ on a length-scale of a few percent of the solar radius. A favoured explanation postulates the presence of a fossil magnetic field which maintains the uniform rotation in the solar interior, thus reducing the width of the tachocline to its small observed value (Rüdiger & Kitchatinov 1997; Gough & McIntyre 1998). The question arises to which extent magnetic fields can survive the early convective phase of star formation, *i.e.* which magnetic field strengths and geometries can be expected in the radiative zones of the Sun or a CP star after their proto-stellar phases.

## 2. Numerical simulations

Global, compressible simulations of stars are beyond the capabilities of computational facilities. When simplifying the problem to the Boussinesq approximation in which sound waves and the strong density contrast are eliminated, we may obtain results for reasonably long physical times. The computations thus employ the spectral spherical code by Hollerbach (2000) and integrate the velocity $\boldsymbol{u}$, the magnetic field $\boldsymbol{B}$, and the temperature fluctuations $\Theta$:

$$\frac{\partial \boldsymbol{u}}{\partial t} = \nu\nabla^2\boldsymbol{u} - (\boldsymbol{u}\cdot\nabla)\,\boldsymbol{u} - \nabla p - \alpha\Theta\boldsymbol{g} + \frac{1}{\mu_0\rho_0}(\nabla\times\boldsymbol{B})\times\boldsymbol{B}, \tag{2.1}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \eta\nabla^2\boldsymbol{B} + \nabla\times(\boldsymbol{u}\times\boldsymbol{B}), \tag{2.2}$$

$$\frac{\partial \Theta}{\partial t} = \kappa\nabla^2\Theta - \boldsymbol{u}\cdot\nabla\Theta - \boldsymbol{u}\cdot\nabla T, \tag{2.3}$$

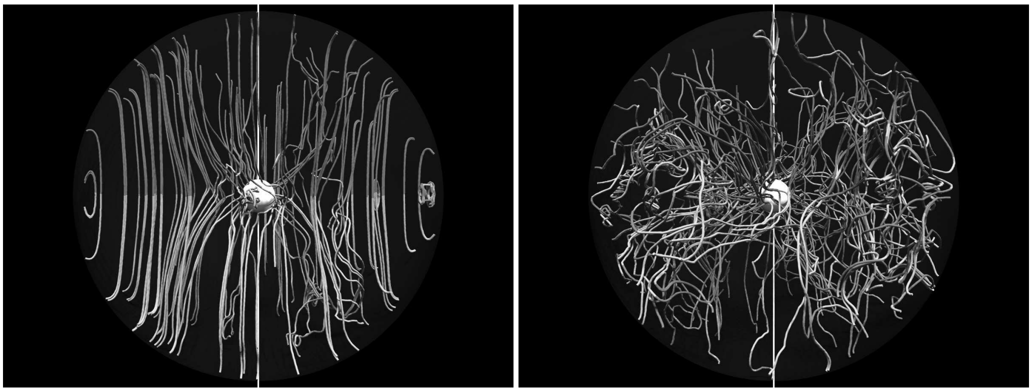

**Figure 1.** Magnetic field lines inside a convective sphere after roughly 1000 yr (left) and after about 2000 yr (right). The lines are rendered as tubes to enhance clarity in 3D; they do not represent flux-tubes. Dark parts of the lines denote $B_r > 0$, light parts denote $B_r < 0$.

where $p$ is the pressure. The the kinematic viscosity $\nu$, the magnetic and thermal diffusivities $\eta$ and $\kappa$, the thermal expansion coefficient $\alpha$, the magnetic permeability $\mu_0$, and the density $\rho_0$ are constants in this setup. $T$ is the non-convective background temperature profile. The runs are initialized by a uniform angular velocity $\Omega$ and a uniform magnetic field of strength $B_0$ parallel to the rotation axis, $\boldsymbol{B} = (B_0 \cos\theta, -B_0 \sin\theta, 0)$. When writing the equations in dimensionless form, the magnetic Reynolds number Rm, the magnetic Prandtl number Pm, the Lundquist number $S$, and a modified Rayleigh number $\tilde{\mathrm{Ra}}$ govern our system. The boundary conditions for the magnetic field are those of a perfect conductor at $r_\mathrm{i} = 0.1$ and those of a vacuum exterior at $r_\mathrm{o} = 1$.

Note that simulations of non-ideal MHD always bear the problem of not reaching the extremely large microscopic magnetic Reynolds numbers in stellar plasma. Although we are able to compute flows with $\mathrm{Rm} = 10^4$, the time-scales of rotation and microscopic diffusion are not as widely separated as in real stars.

Two snap-shots of the magnetic-field evolution inside a convective sphere are shown in figure 1. The left panel is an early distribution of random field lines, while the right panel shows a turbulent state in which the magnetic field is highly complex. The initial antisymmetry with respect to the equator is barely visible; the magnetic quadrupole and non-axisymmetric modes quickly gain more than 50% of the total magnetic energy.

## 3. Conclusions

We show that global, direct numerical simulations of the magnetic evolution of a protostar are doable in a simplified setup. The ongoing simulations of magneto-convection will include the opening up of a radiative core and the turbulent pumping of magnetic field into the core. The magnetic field strength and geometry will be determined after the proto-stellar phase of either a solar-mass star or an intermediate-mass star of say $2M_\odot$, and the incidence angle of the initial magnetic field can be varied.

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