Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
Proceedings IAU Symposium No. 259, 2008
K.G. Strassmeier, A.G. Kosovichev & J.E. Beckman, eds.

doi:10.1017/S1743921309030968

On MHD rotational transport, instabilities and dynamo action in stellar radiation zones

Stéphane Mathis[1,2], A.-S. Brun[1,2], J.-P. Zahn[2]

[1] Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/SAp,
F-91191 Gif-sur-Yvette Cedex, France
email: stephane.mathis@cea.fr, allan-sacha.brun@cea.fr

[2] LUTH, Observatoire de Paris-CNRS-Université Paris Diderot,
5 Place Jules Janssen, F-92195 Meudon Cedex, France
email: jean-paul.zahn@obspm.fr

Abstract. Magnetic field and their related dynamical effects are thought to be important in stellar radiation zones. For instance, it has been suggested that a dynamo, sustained by a $m = 1$ MHD instability of toroidal magnetic fields (discovered by Tayler in 1973), could lead to a strong transport of angular momentum and of chemicals in such stable regions. We wish here to recall the different magnetic transport processes present in radiative zone and show how the dynamo can operate by recalling the conditions required to close the dynamo loop ($\mathrm{B_{Pol}} \rightarrow \mathrm{B_{Tor}} \rightarrow \mathrm{B_{Pol}}$). Helped by high-resolution 3D MHD simulations using the ASH code in the solar case, we confirm the existence of the $m = 1$ instability, study its non-linear saturation, but we do not detect, up to a magnetic Reylnods number of 10^5, any dynamo action.

Keywords. MHD – Sun: magnetic fields – Sun: interior – stars: magnetic fields – stars: interiors

---

1. MHD instabilities and possible dynamo in stellar radiation zones

Purely axisymmetric poloidal and toroidal fields are unstable (see Pitts & Tayler 1985 and references therein). Moreover, Spruit (2002) suggests that the instability of such toroidal field could sustain a dynamo in stellar radiation zones. This idea is quite interesting, but we argue that this dynamo cannot operate as he describes it. According to him, the non-axisymmetric instability-generated small-scale field, which has zero average, is wound up by the differential rotation "into a new contribution to the azimuthal field. This again is unstable, thus closing the dynamo loop." But this shear induced azimuthal field has the same azimuthal wavenumber as the instability-generated field, i.e. $m \neq 0$ and predominantly $m = 1$: it has no mean azimuthal component, and thus it cannot regenerate the mean toroidal field that is required to sustain the instability. For the same reason, the instability-generated field cannot regenerate the mean poloidal field, as was suggested by Braithwaite (2006). Therefore, the Pitts & Tayler instability cannot be the cause of a dynamo, as it was described by Spruit and Braithwaite. In fact, the dynamo loop can only be achieved through the azimuthal average of the fluctuation-fluctuation term of the induction equation $\langle \vec{\nabla} \times (\vec{v}' \times \vec{B}') \rangle_\varphi$ (cf. Zahn, Brun & Mathis 2007).

2. Numerical simulations

We perform 3D-numerical simulations of the problem using the global ASH code (Clune *et al.* 1999, Brun *et al.* 2004) to solve the relevant anelastic MHD equations in a spherical shell representing the upper part of the solar radiation zone ($0.35 \leqslant r/R_\odot \leqslant 0.70$) using a resolution of $N_r \times N_\theta \times N_\varphi = 193 \times 128 \times 256$. A detailed discussion of the set-up is given in Brun & Zahn (2006) and in Zahn, Brun & Mathis (2007). We study the case A

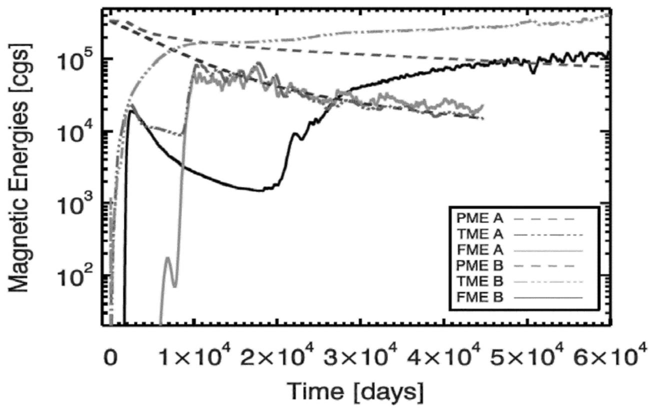

Figure 1. Time evolution of the energies of the mean poloidal (PME), mean toroidal (TME) and non-axisymmetric (FME) components of the magnetic field. Cases A and B refer respectively to higher and lower magnetic diffusivity. Note the steady decline of the poloidal field, which is not affected by the irruption of the $m = 1$ Pitts & Tayler instability (at t$\approx$ 8,000 days in case A and $\approx$ 20,000 days in case B). (Zahn, Brun & Mathis 2007, courtesy A&A)

discussed in Brun & Zahn (2006) and we performed an additional series of simulations with a lower Ohmic diffusivity (by a factor of 10, case B), in order to reach a higher magnetic Reynolds number in favor of a dynamo. In our simulations (cf. Fig. 1), the α-effect plays a negligible role since no regeneration of the mean poloidal field is found, at least up to the magnetic Reynolds number $Rm = R^2\Delta\Omega/\eta \sim 10^5$ for Prandtl number $P_m = \nu/\eta = 1$. On the other hand, the β-effect, i.e. the turbulence-enhanced diffusivity, is absent here. Hence, one should not expect much mixing of the stellar material and the magnetic transport of angular momentum is mainly due to the Lorentz torque that leads to Ferraro's law ($\vec{B}\cdot\vec{\nabla}\Omega = 0$) (cf. Brun & Zahn 2006). In fact, the smallest resolved scales do not act on the mean poloidal field as a turbulent diffusivity: they seem to behave rather as gravito-Alfvén waves. Finally, there is no sign either of a small-scale fluctuation dynamo. To check this point, we suppressed the mean poloidal field at the latest stage of our simulation. Then, the mean toroidal field decreases rapidly, because it is no longer produced by the Ω-effect, and the instability-generated field accompanies its decline. Thus the fluctuating field does not maintain itself. Therefore, we conclude that in our simulations the Pitts & Tayler instability is unable to sustain a large-scale mean field dynamo, in the parameter domain that we have explored (see also Gellert, Rüdiger & Elstner 2008).

References

Braithwaite, J. 2006, *A&A* 449, 451
Brun, A.-S. & Zahn, J.-P. 2006, *A&A* 457, 665
Brun, A.-S., Miesch, M. S. & Toomre, J. 2004, *ApJ* 614, 1073
Clune, T. L. *et al.* 1999, *Parallel Comput.* 25, 361
Gellert, M., Rüdiger, G., & Elstner, D. 2008, *A&A* 479, L33
Pitts, E. & Tayler, R. J. 1985, *MNRAS* 216, 139
Spruit, H. C. 2002, *A&A* 381, 923
Zahn, J.-P., Brun, A.-S., & Mathis, S. 2007, *A&A* 474, 145