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ON THE COUPLED INFLUENCE OF ROTATION AND MAGNETISM IN CONVECTIVE CORE OF A-TYPE STARS

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Abstract. We briefly report on an ongoing numerical project that aims at simulating, with the ASH code, the intricate magnetohydrodynamic processes present in the inner region of A-type stars. We mainly focus our attention, on the dynamics of the convective core, its associated differential rotation and meridional ciculation and the dynamo action than can occur in such tubulent MHD system. We indeed find that magnetic fields with amplitude greater than 10 kG are likely to be present in the core of A-type stars.

1 A Model for Core Convection

Our purpose is to model the inner region of a typical A-type stars. We believe that A-type stars are good proxies to understand the magnetism of massive stars possessing convective core. We use the anelastic spherical harmonics (ASH) code that solves the 3–D MHD anelastic equations of motion in a rotating spherical shell geometry using a pseudo-spectral/semi-implicit method (Clune et al. 1999, Miesch et al. 2000, Brun, Miesch & Toomre 2004). The model is a simplified description of an A-type star core convection zone: values for a two solar mass star are taken for the heat flux, nuclear energy generation (based on the CNO cycles), radius ($R_* \sim 2R_\odot$, where $R_\odot$ is the solar radius), and a perfect gas is assumed. The reference rotation rate Ω_0 is equal to or four times the solar rotational rate (i.e. the period $P \sim 28$ or 7 days). The computational domain extends from 0.02 to 0.3 R_*, thereby concentrating on the bulk of the convective core with penetration into the radiative envelope. The steep entropy gradient between the convection and radiation boundary ($r \sim 0.15R_*$) has been softened. The typical density difference across the shell in radius is about 30 (see Browning, Brun & Toomre 2004 and Brun, Browning & Toomre 2005 for more details).

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2 Dynamo Action in the convective Core

In Figure 1a we show the temporal trace of the magnetic energy (ME) along with the kinetic energy (KE) contained in the simulated domain. We clearly see that ME is growing by many orders of magnitude, reaching value close to equipartition, proof of the existence of a self excited dynamo. In Figure 1b, we have zoomed in and also display the energies contained in the non axisymmetric motions and in the differential rotation. We note the large fluctuations of these quantities along with ME and KE. This indicates how intimely linked all these quantities are and how convection, turbulence, rotation and magnetism continuously interact with one another.

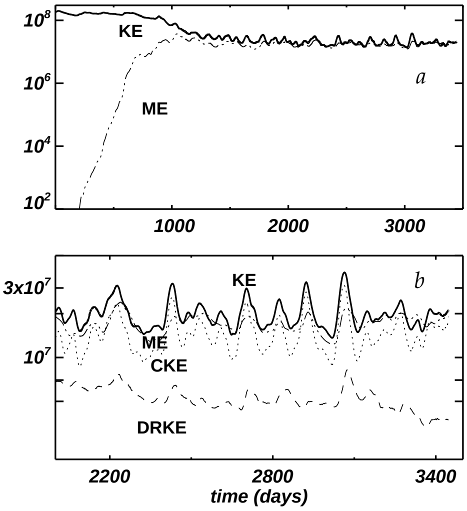

Fig. 1. Temporal evolution of the volume-averaged total kinetic energy density (KE) and the magnetic energy density (ME) in the case rotating at four times the solar rate. (*a*) The initial seed magnetic field is amplified by many orders of magnitude. After an initial phase in which ME grows exponentially, it equilibrates to a level in which it becomes comparable to KE, which has been lessened by the feedback of the magnetism upon the flows. (*b*) Detailed view of fluctuations of energy densities once equilibration is approached, showing also energy densities of the convection (CKE) and the differential rotation (DRKE).

3 Topology of Convection and Magnetic Fields

In Figure 2 we display 3–D renderings of the radial component of the velocity and magnetic field and of the longitudinal component of the magnetic field. Such a representation clearly exhibits the non-spherical shape (i.e. prolate) of the convective core. Outward motions overshoot further near the polar regions than near the equator.

Another feature is the relatively large physical scale of the convective patterns.

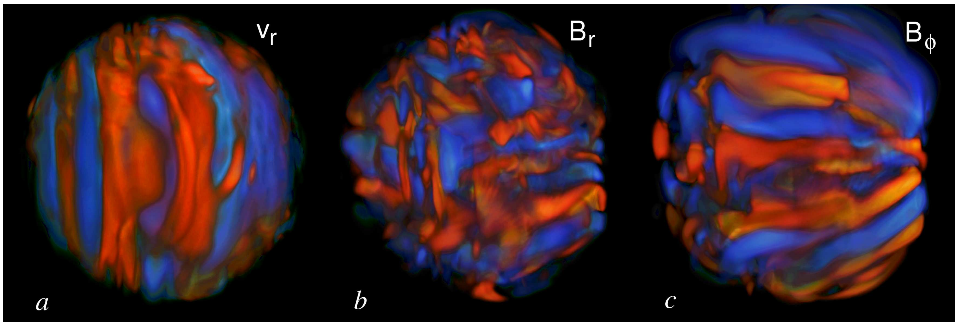

Fig. 2. Volume renderings of flow and magnetic structures at one instant for the case rotating at four times the solar rate near the outer boundary of the prolate convective core. (*a*) Radial velocity v_r exhibits columnar structures aligned with the rotation axis (here oriented vertically). Little asymmetry is apparent between upflows (darl) and downflows (light). (*b*) The radial magnetic field B_r is more tangled, with field polarity shown in contrasting tones. (*c*) The longitudinal magnetic field B_ϕ possesses a distinctive ribbon-like morphology, with coherent bands that extend around much of the core.

Effectively between our most laminar case and our most complex one, achieved by reducing the viscous and thermal diffusivities by more than a factor of 10, no small scales features have clearly emerged. In the latter the flow is more intricate and time dependent but the convective scales remain roughly the same. In addition, no obvious asymmetries between upflows and downflows are found. Both these results are at odds with our solar convection simulations (Brun & Toomre 2002) where strong downward vortical structures with a small filling factor (i.e. plumes) appear as the level of turbulence increases. One reason could be that in the convective core itself the radial density contrast is only of order 3 and that our runs are still too laminar. Nevertheless it seems that in a convective core large-scale motions are likely to be the dominant players. In the most central region the downflows and upflows are connected. As far as we can tell no spurious effects have been generated by the omission of the innermost core. Turning to the longitudinal magnetic field, we find that it extends quite far, about 0.05 stellar radius (if one considers the zone where B_{phi} is above 1/its core strength) beyond the adiabatic limit of the convective core and possesses a ribbon-like aspect. This is due to the strong shear layer present at the convective core edge, which could be seen as an "upside down tachocline" (see §3). In the core itself the longitudinal field possesses a spiral like structure. The radial field does not extend too far in the subadiabatic region and generally possesses a less organised structure. Of the 3 variables shown on Figure 2, the radial magnetic field possesses the smallest patterns and frequent reversal of the polarity. Contrary to the mean differential rotation, the mean axisymmetric magnetic field is found to be weak, representing only 10% of the overall magnetic energy. Most of the energy is contained in the fluctuating fields which are highly intermittent both in time and space and can reach several 10's of kG (see Brun et al. 2005).

4 Rotation Profile and Circulation Achieved by the Convection

Figure 3 display typical averaged rotation profiles as found in our magnetized core convection simulations for a case rotating at the solar rate and another case rotating four times faster, accompanied by latitudinal cuts of Ω of both the MHD case and its purely hydrodynamical (HD) progenitor. The most striking property is the significant slow down of the differential rotation in the MHD cases (in particular for the case rotating four times faster). This can be understood by considering the feed back of the Lorentz forces on the mean flow as studied in detail in Brun (2004) for the solar case. Another striking feature is the column of relatively slow rotation deep in the convective core leading to a significant angular velocity gradient both in radius and latitude. At the interface between the convective core and the radiative envelope, $\Delta\Omega/\Omega_0$ is very large, with the polar regions being slow and the equator fast relative to the reference rotating frame.

Associated with the differential rotation, we also find a weak meridional flow. A multi-cellular structure both in radius and latitude of this flow is observed in all the case we have computed. Typical velocities are of the order of 30 m/s. Circulations are also present in the radiative envelope but are many orders of magnitude weaker. These flows are time dependent, and with the Reynolds and Maxwell stresses play an important role in redistributing the angular momentum. With our choice of stress-free and potential magnetic field top and bottom boundary conditions, the total angular momentum is conserved in the simulations. A careful analysis of the angular momentum balance demonstrates that the prograde equatorial region is achieved due to an outward and equatorward transport of angular momentum by the Reynolds stresses that opposes the viscous, Maxwell and meridional circulation transports (see Brun et al. 2005). We also found that a positive viscous transport of angular momentum connects the two zones and as a consequence seems to speed up slightly the radiative envelope. Due to the geometry of the problem, the further a fluid element is from the rotational axis, the bigger is its angular momentum. It is a likely that the slow column at the center may be a direct consequence of such angular momentum conservation. We have also found that increasing the level of complexity of the flow increases the gradients of angular velocity. The case running with four times the solar rotation rate also exhibits similar rotation profiles (i.e. a deep slowly rotating column). Since most A-type stars are rotating significantly faster than the solar rate we expect the convective motions to be even more constrained by rotation and thus even more aligned with the rotation axis than our cases (Taylor columns). The consequence of such a rotation profile is, as we have seen in (§1), that strong magnetic fields can be generated by dynamo action, involving both the stretching of the poloidal magnetic field into toroidal

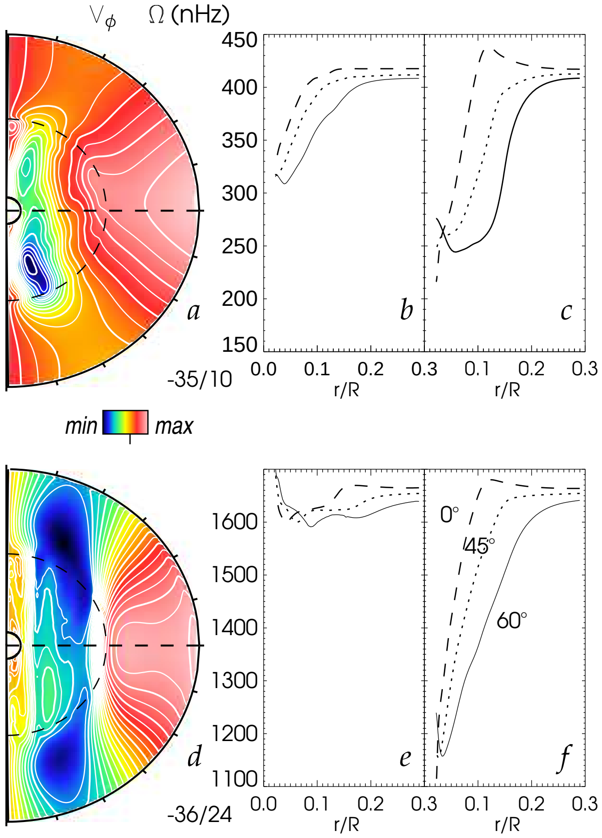

Fig. 3. Temporal and longitudinal averages of the angular velocity profile (left and middle panel) formed over an interval of 200 days for two MHD cases rotating at one (top row) and four times (bottom row) the solar rate along with their purely hydrodynamical progenitor (right). These cases exhibit a prograde equatorial rotation as well as a central region of particularly slow rotation. The circular dashed line delimits the convective core. A strong contrast $\Delta\Omega$ from equator to pole and in radius is clearly seen in the HD case (right panel) showing latitudinal cuts of Ω as a function of radius. By contrast the angular velocity contrast is significantly reduced in the MHD cases (middle and left panels) due to the feed back of the Lorentz forces, which become more and more dominant as the rotation rate is increased.

structures (i.e. the ω-effect) and the regeneration of the mean poloidal field by turbulent convective motions (helicity could potentially play an important role in generating large scale mean fields). The slowly rotating A stars have certainly undergone a strong magnetic breaking and could perhaps possess a much less pronounced columnar rotation profile and weaker field in their convective core. We refer to Brun et al. (2005) for a more detailed study of such effects.

A small overshoot of the convective meridional circulation is also observed that could mix material between the core and the radiative envelope. There is also a continous pummeling of the broad convective upflows into the stable layer, that generate gravity waves and could also potentially lead to some mixing. On average we find that for our stiffest and more complex case, that the overshooting extent is: $d_{ov} \leq 0.012 \pm 0.003\ R_*$ or $d_{ov} \sim 1.8 \times 10^9$cm.

We consider this value as an upper limit because our simulated flows are not turbulent nor the stable region as stiff as in a real A-type star. We believe that overshooting in a convective core is rather small and that evolutionary tracks for such stars are certainly influenced by other processes such as rotation, magnetic field and mass lost (Maeder & Meynet 2005). We do not find that the presence of strong magnetic field modifies the extension of overshooting in the simulations.

5 Conclusions

These 3–D MHD models of an A-type star convective core surrounding by a radiative envelope have revealed interesting properties: 1) the convective core is differentially rotating and exhibits strong (in the HD case) or moderate (in the MHD case) gradients in angular velocity, 2) the overshooting is nonuniform, seeming to be more prominent near the poles and certainly does not extend as far as generally considered in 1–D stellar models, and 3) gravity waves and slow circulations are found in the radiative envelope that could mix chemical species. 4) Dynamo action is very efficiently excited in convective core 5) the feed back from Lorentz forces on the mean (axisymmetric) longitudinal velocity (i.e the differential rotation) is very strong and can lead to significant quenching and the almost desapearance of the differential rotation. The threshold for such a strong feed back seems to manifest itself when the volume integrated magnetic energy reaches about 40% of the kinetic energy. 6) the magnetic field in the convective core are mainly non axisymmetric (representing up to 90% of the total ME), highly intermittent both in space and time and can reach amplitude of several 10's of kG.

A-type stars thus certainly possess an intense magnetic field in their interior, whose interaction with a trapped fossil magnetic field in the radiative envelope need to be studied in the years to come. We refer to the paper by Browning et al. (2004) and Brun et al. (2005) for more details on the intricate and fascinating properties of these objects.

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