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TURBULENT CONVECTION AND DYNAMO ACTION IN A- AND G-TYPE STARS

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Abstract.
We present recent 3–D magnetohydrodynamic (MHD) simulations of the convective region of A- and G-type stars in spherical geometry using the ASH code. We discuss the nonlinear interactions between turbulent convection, rotation and magnetic fields and the possibility for such flows and fields to lead to dynamo action. We find that both core and envelope turbulent convective zones are efficient at inducing strong mostly non-axisymmetric fields near equipartition but at the expense of damping the differential rotation present in the purely hydrodynamic progenitor solutions. We discuss our findings in the light of recent X-ray observations and in term of the classical α and ω-effect of mean field theory.

1 Scientific Context and Model Description

For the last three decades or so, the study of stellar magnetic activity has been a field of fast development, due in part to excellent theoretical work, more accurate observations and better resolved MHD numerical simulations. X-ray emissions have been used to detect stellar magnetic activity as a function of spectral type, since the Sun is known to strongly emit in this frequency band during its maximum of activity. Interestingly enough a gap exists in the curve showing the normalised X-ray luminosity to bolometric luminosity as a function of stellar spectral type around the late B, A and early F-type stars, the so-called “A-gap” (Schmitt 2003). In turns out that stellar structure and evolution models predict that all those stars possess a core convection zone except for shallow surface convection zones in late A and early F-type stars. On the contrary late F, G and K-type stars exhibit high level of X-ray emissions in agreement with them having rather deep surface convection zones. It is thus tempting to relate the existence of magnetic activity in late type stars with the presence of a convection zone at their surface. The source of this activity being due to magnetic dynamo action driven by turbulent convective motions. However a lot more work remains to be done in order to draw a fully consistent picture (Mestel 2001). In particular explaining the 22 yr solar cyle of magnetic activity and the magnetic fields observed in Ap stars has been unexpectedly challenging. It is currently believe that the solar global dynamo is organized in a shear layer called the tachocline at the base of the convection zone (Ossendrijver 2003, Brun et al. 2004), where for Ap stars, a fossil magnetic field is thought to be at the origin of the observed magnetism (Moss 2001). We have thus decided to compute, as a first step, 3-D MHD numerical simulations of the solar

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convection zone (Brun & Toomre 2002; Brun et al. 2004) and of the convective core of an A-type stars (Browning et al. 2004; Brun et al. 2005) using the anelastic spherical harmonic (ASH) code on massively parallel computers (Clune et al. 1999; Miesch et al. 2000; Brun et al. 2004). These simulations are part of a larger, long-term project that aims at understanding stellar dynamo and magnetic activity. We have chosen respectively the G and A-type stars as good proxy for envelope and core convection stars, thanks to the large quantity of observational constraints available, especially for the Sun.

Our models are intended to be simplified version of the convective region of a solar-type star (hereafter case G) and of an A-type star (case A).

- case G, possesses a solar luminosity, mass, radius, rotation rate and heat flux and a density contrast of 30; the computational domain extends from 0.7 to 0.97 $R_{\odot}$, with $R_{\odot}$ the solar radius. The following values for the Prandtl (Pr), magnetic Prandtl (Pm) and magnetic Reynolds (Rm) numbers have been respectively used, 0.125, 4 and 500.

- case A, possesses a luminosity ($L = 19\ L_{\odot}$), radius ($R = 45\ R_{\odot}$), mass ($M = 2\ M_{\odot}$) and heat flux typical of A-type star, rotates at the frame rate $\Omega_0 = \Omega_{\odot}$; the computational domain extends from 0.02 to 0.3 R, with the convective core edge located at $\sim 0.15\ R$; a heating source term is included in the energy equation to model the nuclear energy generated by the CNO cycle. The Pr, Pm and Rm numbers are respectively, 0.25, 5 and 800; the density contrast in the convective core is 2 and 20 over the entire domain.

Both models were started from mature purely hydrodynamic progenitor solutions, possessing strong differential rotations (Brun & Toomre 2002, Browning et al. 2004), in which we introduced a weak initial seed dipolar field. We then let the simulations evolve over several ohmic diffusion times.

2 Magnetic dynamo action

As the turbulent convective motions stretch, shear and fold the seed magnetic field (Moffatt 1978), dynamo action takes place, inducing a stronger magnetic field, whose energy rises by many orders of magnitude. Figure 1a and b show the temporal evolution (growth) of the magnetic energy (ME) densities for both cases.

We note that after a linear growth phase lasting 1200 days for case G and 2500 days for case A, ME saturates via the nonlinear feedback of the Lorentz forces on the convective flow. ME reaches about 7% of the total kinetic energy (KE) in case G and 40% in case A, but for the latter, large modulation on a longer time scale are observed as well (Brun et al. 2005). The fact that core convection can be as efficient as envelope convection (if not more) in generating strong fluctuating magnetic fields constitutes a very interesting result. Effectively, it indicates that massive stars certainly possess strong time dependent magnetic fields in their deep interior but that these fields are somewhat screened by the huge radiative envelope surrounding their convective core since such variability is not observed. Another interesting property of the dynamo simulations considered here is that most of the energy that channel to ME comes from the kinetic energy stored in the differential

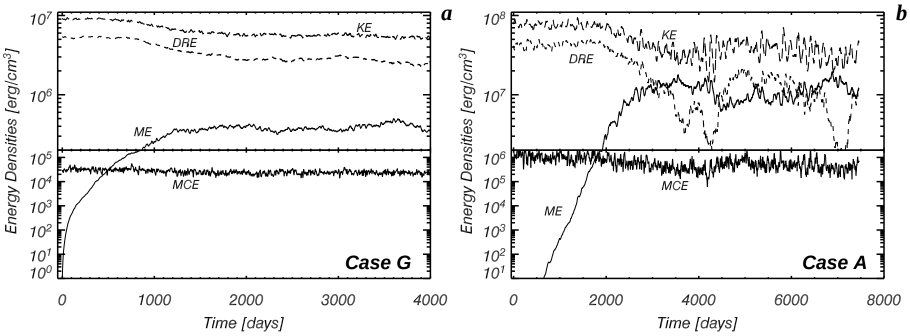

Fig. 1. Kinetic and magnetic energy densities as a function of time for a) case G and b) case A. Also shown are the kinetic energies contained in the differential rotation (DRE) and meridional circulation (MCE). Note the large reduction in amplitude of DRE.

rotation (DRE). In case A the interplay between differential rotation and magnetic field is so strong that each time ME becomes respectively greater (smaller) than 40% of KE, DRE drops (rises), resulting in highly time dependent angular velocity profile in the convective core. It seems that in convective rotating shells when ME is less than about 20% of KE, the kinetic energy is mainly store in differential motion whereas with ME above about 40% of KE the damping (or braking effect by Maxwell stresses) is so strong that the kinetic energy is mainly stored in non axisymmetric motions. Overall we find that the total energy ME+KE is smaller than KE in the progenitor hydrodynamic simulations.

3 Convective motions and magnetic fields

Figure 2 we represent the radial velocity, radial and longitudinal magnetic fields at midlayer depth in the convective zone for both cases. We clearly see that case A exhibits much larger spatial scales than case G, even though they have about the same level of turbulence. The convective motions in case A are slower and more symmetric between up and down motions due to a smaller density contrast. We see that Br tends to be concentrated in the downdrafts (after having been swept from the center of the convective eddies), whereas B_ϕ is more patchy and elongated due to the presence of a differential rotation or ω-effect (Moffatt 1978). The field strength is greater in case A than in case G, both because the energy content is larger and ME closer to equipartition. The mean axisymmetric magnetic fields are weak (less than 10% of ME). Some irregular reversals of the mean poloidal fields are seen but on too fast a time scale ($\sim 500-1000$ days) (Brun et al. 2004, 2005).

4 Conclusion

We have shown that dynamo action is realized in both type of convection zones (central or envelope) leading to field strength close to equipartition. The main

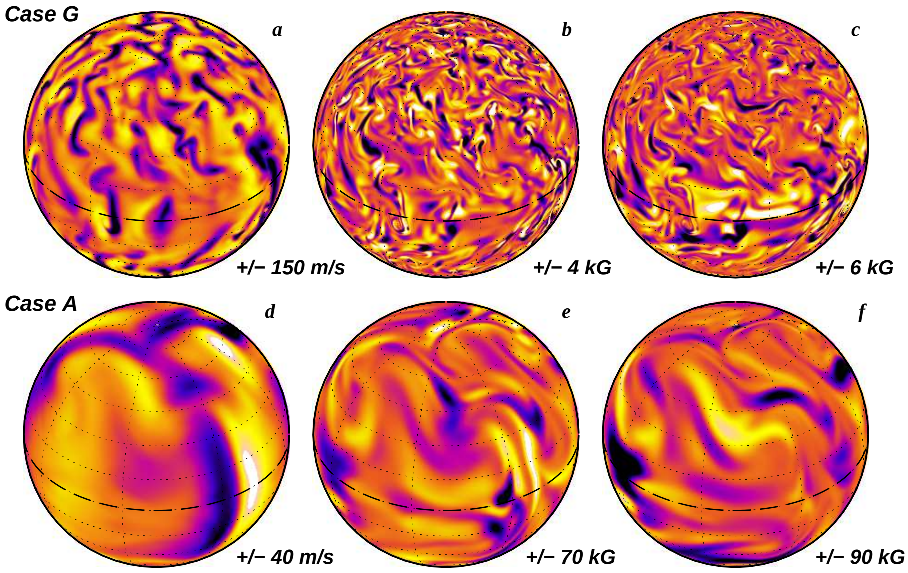

Fig. 2. Snapshot using an orthographic projection of the radial velocity (frame a and d), and radial (b and e) and longitudinal (c and f) magnetic fields for cases G and A. Downflows and negative polarities appears dark. The dashed line represents the equator.

effect of the Lorentz forces is to reduce the differential rotation contrast. In order to get the right timing for the solar cycle a stable shear layer (the tachocline) seems require, whereas in A-type stars whether or not the dynamo generated central fields are able to reach the surface remains a subject of debate.

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