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TURBULENT CONVECTION IN YOUNG SOLAR-LIKE STARS: INFLUENCE OF ROTATION

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Abstract. We have performed 3-D numerical simulations of turbulent convection of young solar-like stars using the anelastic spherical harmonic code. We aim at understanding the complex interactions between convection and fast rotation. In particular we have studied the redistribution of angular momentum and the resulting differential rotation profile. We find that as the rotation rate increases, the contrast of angular velocity slightly decreases and the convection becomes more intermittent both in space and time.

1 Introduction

Young stars are known to rotate faster than their main sequence brethren. They also exhibit peculiar X-ray emissions and magnetic activity properties, which in recent years have become the subject of intense research. Understanding the interaction between turbulent convection, fast rotation and magnetic fields is crucial to progress in our knowledge of such young stars. We here present the first attempt to model in three dimensions such complex and intricate physical processes by considering simulations of turbulent convection at a range of rotation rate Ω_0.

We use the anelastic spherical harmonic (ASH) code which has been previously validated in the solar context especially to analyze effects of turbulent motions, differential rotation driving or dynamo processes (cf. Brun & Toomre 2002; Brun, this volume). This code resolves the full set of (magneto)hydrodynamic equations for a compressible fluid within the anelastic approximation (Clune et al. 1999, Miesch et al. 2000, Brun et al. 2004).

Our numerical models consist of a simplified description of the stellar convection zone of a 10-Myr-old solar-like star (Ballot et al. in prep.). Stellar values are taken for the luminosity, mass, radius and heat flux and a perfect gas is assumed. The computational domain extends from about 0.54 and $0.95\,R_*$ (where R_* is the stellar radius), with such shells having a density contrast of about 60. Contact is made, for the internal structure, with an accurate 1-D model obtained with the stellar evolution code CESAM (Morel 1997). We have studied three series of models, each corresponding to a different level of turbulence, and possessing in turn a Prandtl number Pr=4, 1 or 1/4 ($\mathrm{Pr} = \nu/\kappa$, where ν is the effective viscosity and κ the effective thermal diffusivity). We have computed models with $\Omega_0 = 1,\ 2\ \&\ 5\,\Omega_\odot$ for each considered Prandtl number, for a total of nine models.

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2 Convective patterns and temporal evolution

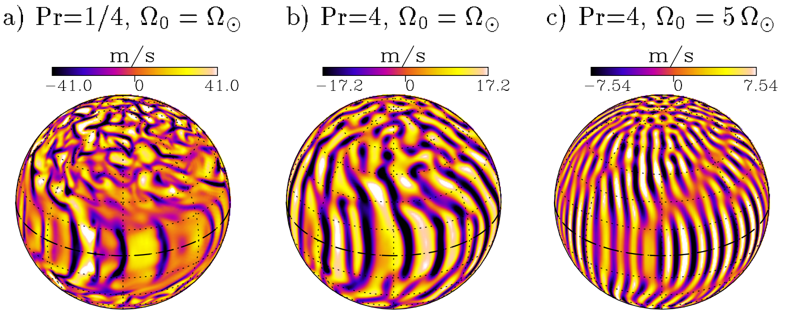


Fig. 1. Radial velocity near the top of the shell for three different models

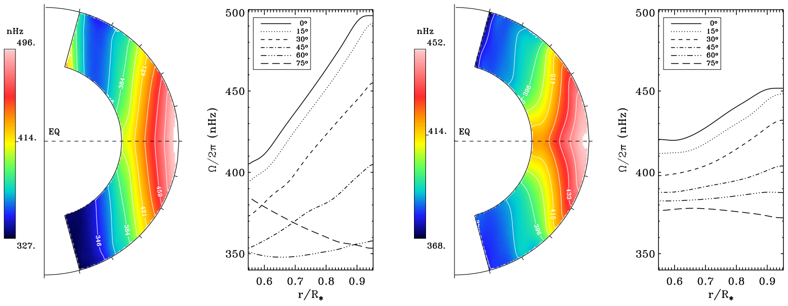
Figure 1 shows the radial conponent of the velocity for three models. In Figs. 1-a and -b, we show two cases rotating at the solar rate, the latter being more laminar (Pr = 4 instead of 1/4). As the turbulence increases, the convective patterns become more complex and time dependent. The banana cells, well defined in b), are less apparent in a). The asymmetry between downflows (faster and more collimated) and outflows is reinforced. The most turbulent models possess the strongest intermittency, both spatially and temporally.

In the cases shown in b) and c), the turbulent level is approximately the same, but Ω_0 is increased by a factor of 5. The convective patterns are smaller and narrower, since the most unstable convective mode has shifted to higher degree. Typically in the equatorial region, the most excited order m grows from 18 to 42. In Fig. 1-c, we can clearly see zones with weaker velocity contrasts. They are due to the stronger intermittency induced by the faster rotation. The case with Pr=1/4 (turbulent) and $\Omega = 5\,\Omega_\odot$ (not shown) is rather interesting for that respect. The model oscillates between a fully developed convective state and a quiet phase. This seems to be due to 1) the low Prandtl number, 2) the high rotation rate and 3) probably the shell thickness D. A similar behaviour has already been described by Grote & Busse (2001) in geodynamo Boussinesq simulations. This state of intermittent convection could be confined in our parameter space, being only a transitory state before a more chaotic and fully developed one appears.

3 Rotation rate, differential rotation and resulting scaling law

Figure 2 displays the differential rotation profiles for four cases, illustrating 1) the effect of turbulence level – comparing a) and b) – and 2) the effect of rotation rate –comparing b), c) and d). When the turbulence level increases, we notice that : 1) the profiles are organized around vertical cylinders, due to the lower viscosity resulting in a higher Taylor number ($\mathrm{Ta} = 4\Omega_0^2 D^4/\nu^2$), and thus a greater influence of rotation which tends to make the flow quasi 2–D (cf. Taylor-Proudman theorem) 2) the differential rotation contrast increases thanks to the enhance efficiency of

a) Pr=1/4, $\Omega_0 = \Omega_\odot$ b) Pr=1, $\Omega_0 = \Omega_\odot$



c) Pr=1, $\Omega_0 = 2\,\Omega_\odot$ d) Pr=1, $\Omega_0 = 5\,\Omega_\odot$

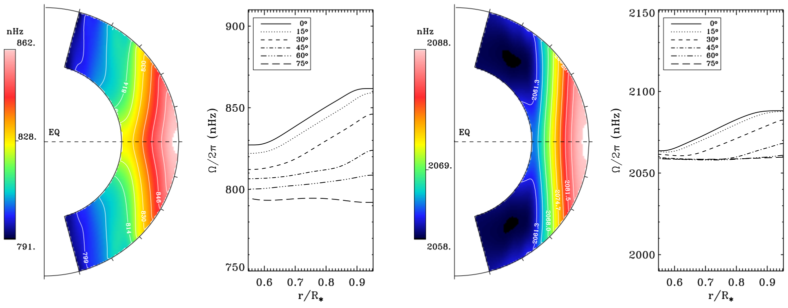


Fig. 2. Differential rotation rate for four models.

the Reynolds stresses in transporting equatorward the angular momentum. The increase of the rotation rate implies that: 1) the profile are more cylindric too (i.e higher Ta number); 2) the differential rotation contrast decreases due to the stabilizing effect of rotation.

Figure 3 summarizes the differential rotation contrast $\Delta\Omega$ obtained for the nine models. We have deduced a scaling law for each series of models (Pr=4, 1 or 1/4), by fitting a power law $\Delta\Omega \propto {\Omega_0}^{\alpha}$. The α exponent increases from -0.61 to -0.19 from the very laminar simulations to the more turbulent ones. The law obtained with the latter is likely to be more reliable due to the higher level of turbulence. The tendency is toward a decrease of $\Delta\Omega$ with an increase of Ω_0. However, we notice that the exponent α tends to zero, i.e. the law tends toward a constant angular velocity contrast $\Delta\Omega \approx$ constant. Such a result seems more consistent with the observations of young stars (Collier Cameron et al. 2001).

4 Conclusions and Perspectives

These preliminary results constitute a first step toward a better understanding of the complex interaction of turbulent convection and fast rotation in young solar-like stars. This set of models have shown the main effects of rotation on convection

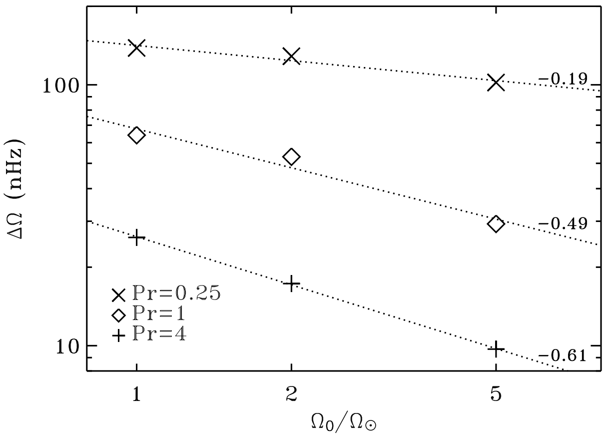


Fig. 3. Differential rotation contrast $\Delta\Omega$ versus rotation rate Ω_0. $\Delta\Omega$ is computed between the 0° and 60° latitudes. We have fitted scaling law $\Delta\Omega \propto {\Omega_0}^{\alpha}$ for each series of models (Pr=4, 1 or 1/4). The α exponent is indicated on the right.

(most unstable modes, intermittency...) and on differential rotation, enabling us to deduce some scaling laws. We must now constrain more strongly our results with observations. If the $\Delta\Omega$ vs Ω_0 observational trend becomes more accurate, we will be able to constrain more efficiently our models and thus become more confident in deducing other properties such as the meridional circulation profile and amplitude. A more detailed discussion can be found in Ballot (2004) and Ballot et al. (in prep.), but the important points have been exposed here. The next steps will consist in taking into account the magnetic field to study the dynamo processes in such shells, and comparing them with both what is observed and with their thin shells counterparts (cf. Brun et al. 2004).

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