Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research xxx (2016) xxx–xxx
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Characterizing the feedback of magnetic field on the differential rotation of solar-like stars

J. Varela [a,*], A. Strugarek [a,b], A.S. Brun [a]

[a] AIM, CEA/CNRS/University of Paris 7, CEA-Saclay, 91191 Gif-sur-Yvette, France
[b] Département de Physique, Université de Montréal, C.P. 6128 Succ. Centre-Ville, Montréal, QC H3C-3J7, Canada

Received 11 January 2016; received in revised form 22 June 2016; accepted 24 June 2016

Abstract

The aim of this article is to study how the differential rotation of solar-like stars is influenced by rotation rate and mass in presence of magnetic fields generated by a convective dynamo. We use the ASH code to model the convective dynamo of solar-like stars at various rotation rates and masses, hence different effective Rossby numbers. We obtained models with either prograde (solar-like) or retrograde (anti-solar-like) differential rotation. The trends of differential rotation versus stellar rotation rate obtained for simulations including the effect of the magnetic field are weaker compared with hydro simulations ($\Delta\Omega \propto (\Omega/\Omega_\odot)^{0.44}$ in the MHD case and $\Delta\Omega \propto (\Omega/\Omega_\odot)^{0.89}$ in the hydro case), hence showing a better agreement with the observations. Analysis of angular momentum transport revealed that the simulations with retrograde and prograde differential rotation have opposite distribution of the viscous, turbulent Reynolds stresses and meridional circulation contributions. The thermal wind balance is achieved in the prograde cases. However, in retrograde cases Reynolds stresses are dominant for high latitudes and near the top of the convective layer. Baroclinic effects are stronger for faster rotating models.
© 2016 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Stellar magnetic fields; Solar-like stars; Convective dynamos; Star's differential rotation

1. Introduction

It is well known that there is a correlation between magnetic activity and rotation of stars (Durney, 1976; Noyes et al., 1984b; Pizzolato et al., 2003). Rapid rotators show a stronger and more intense magnetic activity (Saar and Brandenburg, 1999; García et al., 2010) than slower rotators such as the Sun for which the averaged magnetic field is weaker (Pallavicini et al., 1981), therefore a detailed analysis of the differential rotation (DR) is mandatory to understand the magnetic activity of the stars (Donahue et al., 1996).

Dopper imaging (Donati and Collier Cameron, 1997; Barnes et al., 2005), asteroseismology (Gizon and Solanki, 2004; Reinhold et al., 2013; García et al., 2014), classical spot models (Lanza et al., 2014) and short-term Fourier-transform (Vida et al., 2014) are methods to infer the differential rotation, while photometric and spectroscopic variability are good indicators of the magnetic activity along the star's activity cycle (Baliunas et al., 1995; Oláh et al., 2009). The combination of both sources of information helps to constrain the trends linking rotation with stellar differential rotation and magnetic activity, data available thanks to recent missions as CoRoT or *Kepler*. Recent analysis revealed weak dependency between DR and star's rotation ($\Delta\Omega \propto \Omega^{0.15}$) (Barnes et al., 2005; Reinhold et al., 2013), larger in case of star's temperature ($\Delta\Omega \propto T_{eff}^{8.92}$ (Barnes et al., 2005; Reinhold et al., 2013)) and $\Delta\Omega \propto T_{eff}^{8.6}$ (Collier Cameron, 2007). The differential rotation defined in these communications is $\Delta\Omega = \alpha\Omega_{eq}$

* Corresponding author.
E-mail address: Jacobo.Varela@cea.fr (J. Varela).

http://dx.doi.org/10.1016/j.asr.2016.06.032
0273-1177/© 2016 COSPAR. Published by Elsevier Ltd. All rights reserved.

Please cite this article in press as: Varela, J., et al. Characterizing the feedback of magnetic field on the differential rotation of solar-like stars. Adv. Space Res. (2016), http://dx.doi.org/10.1016/j.asr.2016.06.032

with Ω_{eq} the angular velocity at the equator and α the relative horizontal shear of the differential rotation between the equator and the pole. Ω_{eq} and α are deduced from the observations.

Several authors have performed global 3D magnetohydrodynamic (MHD) simulations to model differential rotation and stellar magnetism in the convection zone (Miesch et al., 2006; Ghizaru et al., 2010; Racine et al., 2011; Käpylä et al., 2011; Käpylä et al., 2014; Augustson et al., 2015; Karak et al., 2015), particularly for solar like stars (Brun et al., 2004, 2011; Brown et al., 2010, 2011). These studies pointed out the large magnetic temporal variability and the critical effect of stellar rotation and mass on magnetic field generation through dynamo mechanism, leading in some parameter regimes to configuration with cyclic activity (Gilman, 1983; Gilman and Miller, 1981; Nelson et al., 2013; Käpylä et al., 2013; Augustson et al., 2013, 2015; Guerrero et al., 2016). Several studies pointed out the effect of a stable region underneath the convection zone on the lengthening of the stellar dynamo cycle period (Guerrero et al., 2016; Lawson et al., 2015).

The present study is focused on solar-like stars, G and K stellar classes. Observations indicate that this group of stars show very different magnetic activity (Saar, 1990; Plachinda and Tarasova, 1999), with short Metcalfe et al. (2010) and long cycles (Baliunas et al., 1995), consequence of the range of masses, rotation, differential rotation, age, effective temperature or metallicity measured (Noyes et al., 1984a; Chaplin et al., 2010; Ballard et al., 2014; García et al., 2014; do Nascimento et al., 2014). We analyze the correlation between differential rotation and magnetism in solar-like stars using the anelastic spherical harmonic code (ASH) (Brun et al., 2004), performing several convective dynamo MHD simulations for star with different masses and rotation rates (Rossby numbers). One first achievement of the study was to simulate stars with prograde (solar-like) and retrograde (anti-solar-like, equator rotates slower than the poles) differential rotation (Matt et al., 2011; Bessolaz and Brun, 2011; Gastine et al., 2014; Karak et al., 2015). The aim of this study is to analyze the effect of a magnetic field on the star's differential rotation (Brun, 2004; Fang et al., 2014).We show that the trends of the differential rotation with the stellar mass and rotation for MHD simulations are in better agreement with the observational trends than equivalent hydro simulations (Donahue et al., 1996; Barnes et al., 2005; Reinhold et al., 2013).

The article structure is as follows: Section 2; we describe the ASH code, the boundary and initial conditions of the different models as well as the key parameters of each simulation. Section 3; we study the large scale flows for the different models analyzing the time averaged kinetic and magnetic energy of the system, differential rotation as well as the trends of differential rotation versus star's rotation rate and mass obtained for hydro and MHD cases. Section 4; we analyze the angular momentum balance in the models studying the mean radial and latitudinal fluxes transport. Section 5; we study the baroclinity and thermal wind balance for typical prograde and retrograde cases. Section 6; conclusion, discussion and perspectives of present study.

2. Numerical model

In this section we present the main features of the ASH code, describing the boundary and initial conditions of the numerical model and our choice of the global parameters.

We perform 3D simulations of convective dynamo action that consist in solving the Lantz–Braginski–Roberts (LBR) form of the anelastic MHD equations for a conductive plasma in a rotating sphere (Jones et al., 2011), a formulation that improves the energy conservation in stable stratified regions (Brown et al., 2012; Vasil et al., 2013). The code ASH performs a large-eddy simulation that uses a pseudo-spectral method with the spherical harmonics expansion in the horizontal direction for the entropy (S), magnetic field ($\mathbf{B}$), pressure (P) and mass flux. The density (ρ), entropy, pressure and temperature (T) are linearized about the spherically symmetric background values, denoted by the symbol ($^-$). The solenoidality of the mass flux and magnetic vector fields is maintained by a stream function formalism (Brun et al., 2004). The equations solved by ASH are (Alvan et al., 2014; Augustson et al., 2015):

$$\nabla \cdot \bar{\rho}\mathbf{v} = 0$$

$$\bar{\rho}\frac{\partial \mathbf{v}}{\partial t} = -\bar{\rho}\mathbf{v}\cdot\nabla\mathbf{v} - \nabla\bar{\varpi} + \frac{Sg}{c_p}\mathbf{r} + 2\bar{\rho}\mathbf{v}\wedge\Omega_0 + \frac{1}{4\pi}(\nabla\wedge\mathbf{B})\wedge\mathbf{B} + \nabla\cdot D$$

$$\bar{\rho}\bar{T}\frac{\partial S}{\partial t} = \bar{\rho}\bar{T}\mathbf{v}\cdot\nabla(\bar{S}+S) - \nabla\cdot\mathbf{q} + \Phi$$

$$\nabla\cdot\mathbf{B} = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\wedge[\mathbf{v}\wedge\mathbf{B} - \eta\nabla\wedge\mathbf{B}]$$

with the velocity field $\mathbf{v} = v_r\mathbf{r} + v_\theta\boldsymbol{\theta} + v_\varphi\boldsymbol{\varphi}$, the magnetic field $\mathbf{B} = B_r\mathbf{r} + B_\theta\boldsymbol{\theta} + B_\varphi\boldsymbol{\varphi}$, the angular velocity in the of the rotation frame $\Omega = \Omega_0\mathbf{z}$, $\mathbf{z}$ the direction along the rotation axis, g the magnitude of the gravitational acceleration and $\bar{\varpi} = P/\bar{\rho}$ is the reduced pressure in the LBR implementation. The motions not resolved by the numerical mesh are parametrized as effective eddy diffusivities ν, κ and η that account for the effect of the subgrid-scales transporting momentum, heat and magnetic field. The diffusion tensor D and the dissipative term Φ are defined as:

$$D_{ij} = 2\bar{\rho}\nu\left[e_{ij} - \frac{1}{3}\nabla\cdot\mathbf{v}\delta_{ij}\right]$$

$$\Phi = 2\bar{\rho}\nu\left[e_{ij}e_{ij} - \frac{1}{3}(\nabla\cdot\mathbf{v})^2\right] + \frac{4\pi\eta}{c^2}\mathbf{J}^2$$

Please cite this article in press as: Varela, J., et al. Characterizing the feedback of magnetic field on the differential rotation of solar-like stars. Adv. Space Res. (2016), http://dx.doi.org/10.1016/j.asr.2016.06.032

Download English Version:

https://daneshyari.com/en/article/5486585

Download Persian Version:

https://daneshyari.com/article/5486585

Daneshyari.com