Contributed papers

Dynamics of Solar and Stellar Convection Zones and Atmospheres
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A new generation of solar dynamo model and its application to explore the stellar magnetic cycle

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Abstract. In most of the Babcock–Leighton (BL) type solar dynamo models, the toroidal magnetic field is assumed to be generated in the tachocline. However, magnetic activity of fully convective stars and MHD simulations of global stellar convection have recently raised serious doubts about the importance of the tachocline in the generation of the toroidal field. We have developed a BL-type dynamo model operating in the bulk of the convection zone, and are extending this model to solar-type stars. In this study, we aim at exploring how the starspot properties affect the stellar magnetic cycle. Observations show that faster rotating stars tend to have stronger magnetic activity and shorter magnetic cycles. By considering the higher latitudes and larger tilt angles of starspots for faster rotators, our simulations reproduce observations that faster rotating stars have shorter magnetic cycle and stronger activity.

Keywords. Dynamo, Stars: activity, Stars: starspots

1. Introduction

Solar large-scale magnetic fields exhibit quasi-11-year cyclic variations, as evidenced by sunspots. Starspots and magnetic cycles are common among cool stars. The progress in solar magnetism is paving the way for understanding stellar activity. Observations of stellar magnetic activity indicate general relations of P_{rot}–P_{cyc} and P_{rot}–A_{cyc} (Wilson 1978). Specifically, younger and faster rotating stars tend to have longer magnetic cycle periods (P_{cyc}) and higher magnetic activity amplitudes (A_{cyc}).

Solar observations indicate that stronger solar cycles are associated with smaller tilt angles and sunspot emergence at higher latitudes (Jiang et al. 2011). Systematic studies have demonstrated the effect of tilt and emergence latitude variations on solar cycle (Jiang 2020). This raises an interesting question of how the starspots' emergence latitudes and tilt angles affect stellar magnetic cycles. Sunspots appear at latitudes lower than about 40°. While for starspots, the emergence latitudes could be distributed over the whole stellar disk (Strassmeier 2009). Observations also indicate that stars with faster rotation rates tend to have starspots located at higher latitudes, and even in polar regions (Vogt and Penrod 1983).

Zhang and Jiang (2022) have developed a new generation of the BL-type dynamo model that operates in the bulk of the convective zone rather than in the tachocline. The tachocline is not a necessary ingredient in their model, which is supported by stellar observations and MHD simulations that the dynamo process is more likely to operate in the bulk of the convection zone (Nelson et al. 2013; Wright and Drake 2016). This work aims at extending the solar dynamo model of Zhang and Jiang (2022) to stars with a solar mass $M_\odot$, ranging the rotation periods from 10 to 25 days, and explore the effect of starspots emergence properties on magnetic cycles.

2. Model

In this study, we adopt the kinematics dynamo model developed by Zhang and Jiang (2022). The flow fields and BL-type source term S_{BL} will be prescribed in the next subsection. The other ingredients are almost the same as Zhang and Jiang (2022). In this study, the computation domain is $0.72R_\odot \leq r \leq R_\odot, 0 \leq \theta \leq \pi$, which excludes the region of the tachocline.

2.1. *Differential rotation and meridional flow*

We will study the dynamo process of solar-mass stars with rotation periods ranging from 10 to 25 days. The flow fields will be obtained from a mean-field hydrodynamical model (Kitchatinov and Nepomnyashchikh 2017b).

We have calculated the latitudinal distribution of the latitudinal shear and the average return flow for various rotators. For stars with varied rotation periods, the strength of latitudinal shear all reaches their maxima at about 55 °, which means that the generation efficiency of the toroidal fields is the strongest there. This latitude dependence of the latitudinal shear also has a contribution to the butterfly diagram (Zhang et al. 2022). The strength of return flow decreases from 3.15 ms^{-1} to 2.4 ms^{-1} with the decreasing of rotation period.

2.2. *Babcock–Leighton source term*

The BL-type source term is defined as

$$S_{BL}(r,\theta,t) = \frac{\alpha_0 f(\theta)}{2}\left[1 + \mathrm{erf}\left(\frac{\mathrm{r} - 0.95\mathrm{R}_\odot}{0.01\mathrm{R}_\odot}\right)\right]\bar{B}(\theta,t). \tag{1}$$

Observations show that faster rotators tend to have starspots at higher latitudes. One explanation is the larger Coriolis force for faster rotators, which pushes the toroidal flux to higher latitudes (Schuessler et al. 1996). In this study, to explore the influence of appearing latitudes of starspots on the dynamo process, we consider

$$f(\theta) = \frac{\cos\theta \sin^n \theta}{Max[\cos\theta \sin^n \theta, \theta \in (0,\pi)]}, \tag{2}$$

in Eq. (1). A simple linear relation between rotation period and n that $n = 1 + (P_{rot} - 10) * 0.55$ is considered. With the increasing of rotation rate, n will decrease, allowing the faster-rotating stars to form starspots at higher latitudes.

A key parameter in the dynamo process is the dynamo number, $\alpha_0 \Delta\Omega R^3/\eta^2$. When α_0 is greater than or equal to its critical value α_c, a self-sustaining dynamo process occurs. Most previous dynamo models set α_0 arbitrarily. Kitchatinov and Nepomnyashchikh (2017a) (hereafter KN17) suggests that α_0 could be constrained on the basis of observations. Motivated by KN17, we give α_0 for a star with rotation period P_{rot} based on

$$\alpha_0 = (1 + m\frac{P_{max}}{P_{rot}})\alpha_c, \tag{3}$$

where m is a free parameter that constrains the amount of supercriticality. For the solar-mass stars we study, we take P_{max} to be 28 days. For the solar case, the saturated unsigned toroidal flux in the convection zone is about 10^{23} Mx. The flux puts a constraint on the value of m, which is taken to be $m = 0.2$.

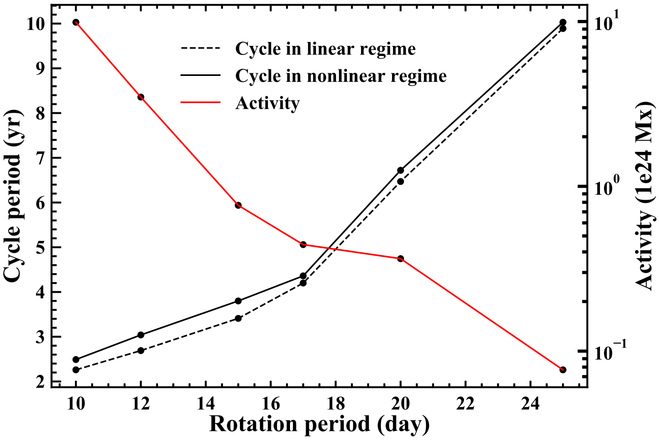

Figure 1. P_{rot}–P_{cyc} and P_{rot}–A_{cyc} relations. The solid (dashed) line represents the solution operating in the nonlinear regime (linear regime). Image reproduced with permission from Zhang et al. (2024).

3. Results

Figure 1 shows magnetic activity and cycle period versus rotation period. We explore the P_{rot}–P_{cyc} relation in both linear critical and nonlinear regime, and the cycle period of nonlinear solutions is slightly longer than that of linear marginal mode. The cycle period increases as rotation period, close to observations. When the meridional flow is faster, the magnetic cycle is longer. This indicates that our model is different from the flux transport dynamo (FTD) models. The strength of magnetic activity increases with rotation rate, as shown by observations. The reason for this P_{rot}–A_{cyc} relation is that larger tilt angles of faster rotators make dynamo operate in a stronger supercritical regime, leading to stronger saturated magnetic fields.

To further explore why faster rotators have a shorter magnetic cycle period, Figure 2 shows the time-latitude diagram of subsurface toroidal flux and surface radial fields of rotators of 10 and 25 d. Figure 2 (b) shows that faster rotators have starspots closer to ±55° latitudes, where the strongest latitudinal shear exists. The newly generated poloidal flux could be sheared efficiently then generating the toroidal field for the subsequent cycle quickly. High-latitude starspots emergence shorten the dynamo circle and hence the magnetic cycle. Slower rotators have starspots farther from the ±55° latitude (see Figure 2 (d)), so that additional time is required for the transport and winding of the poloidal flux, resulting in longer cycle periods. The emergence features of starspots in latitudes plays a crucial role in creating the observed relation between P_{rot} and P_{cyc}.

4. Conclusion

We have extended the BL mechanism to solar-mass stars and investigated the effect of starspot emergence properties on stellar magnetic cycles. The rotation-dependent emergence latitude and tilt angle of starspots are considered in a BL-type dynamo operating in the bulk of the convection zone developed by Zhang and Jiang (2022).

In our BL-type dynamo model, the emergence latitudes of starspots play a crucial role in reproducing the P_{rot}–P_{cyc} and P_{rot}–A_{cyc} relations. Faster rotators have poloidal flux appearing closer to about ±55° latitudes, where the toroidal field generation efficiency is the strongest. It takes a shorter time for faster rotators to transport the surface poloidal field from their emergence latitude to the ±55° latitudes of efficient latitudinal shear thus shortening magnetic cycles. The faster rotators operate in a more supercritical regime

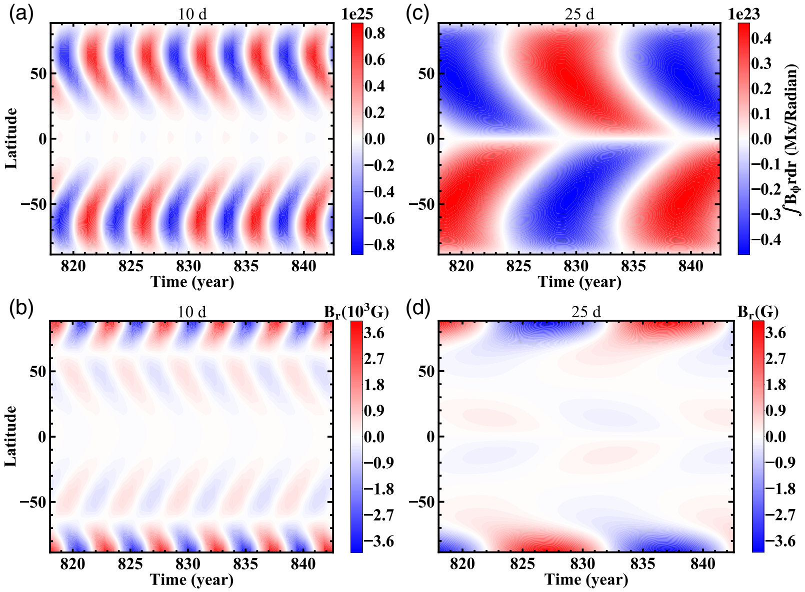

Figure 2. Time-latitude diagram of subsurface toroidal flux (top) and surface radial fields (bottom). Image reproduced with permission from Zhang et al. (2024).

due to a stronger BL α effect with respect to the tilt angles, leading to stronger saturated magnetic fields.

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