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HOW WILL SOLAR MAGNETISM EVOLVE?

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Abstract. In solar-type stars, magnetic field is generated and sustained through an internal dynamo. This process is mainly determined by the combined action of turbulent convective motions and differential rotation profile. It can sometimes lead to cyclic magnetic reversals, like the 11 years cycle of the Sun, and ranging from a few years to a few tens of years in other solar-like stars. The understanding of what control these cycles is of major importance to decipher how the solar dynamo works and could evolve.

Recent 3D numerical simulations of solar-like stars show that different regimes of differential rotation can be characterized with the Rossby number. In particular, anti-solar differential rotation (fast poles, slow equator) may exist for high Rossby number (slow rotators). As the rotation of stars is slowing down during their main-sequence, we may wonder how the magnetic generation through dynamo process will be impacted if our Sun evolve toward this regime. In particular, can slowly rotating stars have magnetic cycles?

We present a numerical multi-D study with the STELEM and ASH codes to understand the magnetic field generation of solar-like stars under various differential rotation regimes, and focus on the existence of magnetic cycles.

We find that short cycles are favoured for small Rossby numbers (fast rotators), and long cycles for intermediate (solar-like) Rossby numbers. Slow rotators (high Rossby number) are found to produce only steady dynamo with no cyclic activity in most cases. Magnetic cycles can be produced with anti-solar differential rotation only if the alpha effect is fine tuned for this purpose.

Keywords: solar-like star, solar-type star, anti-solar, differential rotation, convection, solar dynamo

1 Introduction

Observations of the Sun show us two interesting and intertwined features. First, the magnetic activity of the Sun is characterised by a magnetic cycle of 22 years. It is usually shown in a magnetogram evolution *vs.* latitude illustration, so-called *butterfly diagram* (Hathaway 2015). Second, the helioseismic inversions show that the convective zone is differentially rotating, i.e. that not all latitudes rotate at the same speed. In particular, the Sun has a fast equator and slow poles, in a so-called solar differential rotation (DR) profile (Thompson et al. 2003). The latter is believed to be at the heart of large-scale dynamo action.
We know that the Sun has gone through different rotational phases during its lifetime. In particular, stars will start to slow down, losing angular momentum when they enter the main sequence (MS). This rotation influences the dynamo process that creates and sustains the stellar magnetic field. This field will then shape and magnetize the wind of the star, which is next responsible for the mass loss and magnetic breaking. Finally, this characterises the angular momentum loss, and this physical loop leads stars with similar masses to converge towards a similar rotational evolution, described by Skumanich's law (see Skumanich 1972; Vidotto 2021, and references therein). Further using ZDI techniques, the stellar magnetic field has been observed to decrease as a function of the Rossby number(See et al. 2019). This number is dimensionless and quantify the time-scale of convection over rotation. It allows us to characterise the structure and internal dynamics of stars. Indeed, recent 3D global and hydrodynamic simulations have shown that different DR regimes exist as a function of the fluid Rossby number $Ro_{\rm f} = \tilde{\omega}/2\Omega_*$, with $\tilde{\omega}$ the *rms.* vorticity (Brun et al. 2017, see also Gastine et al. 2014). For weak Rossby number, which are fast rotators, the DR profile will be highly constrained by its rotation. This is the Taylor-Proudman constraint making the angular velocity invariant along the rotation axis. For

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intermediate Rossby, we find the characteristic profile of the Sun with a fast equator and slow poles. Finally, it has been shown that so-called "anti-solar" rotation profiles (slow equator and fast poles) are possible for high Rossby numbers (slow rotators). As the rotation of stars decreases during their main-sequence, we may wonder if such a rotational regime could happen in the case of solar-type stars and more particularly for the Sun.How would the dynamo mechanism be affected? In general, can slowly rotating stars have magnetic cycles?

2 Anti-solar DR in kinematic mean-field dynamos

The dynamo mechanism is the ability of a plasma to create and maintain a magnetic field against its ohmic dissipation. A dynamo loop can be understood as illustrated in Figure 1. In a mean-field approach, one can start by considering the magnetic field in the meridional plane of the star, called the *poloidal field*. The latter will be sheared by the differential rotation into a horizontal magnetic field, called *toroidal field*. This process is called the Ω-effect. This toroidal component can then be transformed back into a poloidal field, for example by the α-effect. This effect characterizes the turbulent convection in a so-called $\alpha\Omega$ dynamo. To transform the toroidal field back into a poloidal one, another mechanism is possible, called Babcock-Leighton (BL) (Babcock 1961 and Leighton 1969). This latter characterises the influence of Coriolis force on the emerging toroidal structures. These structures are though to move up through the convective zone, and to be tilted at their surface emergence by this rotational effect. In such BL flux-transport dynamo models, meridional circulation (MC) can be used to link dynamically the two sources of the magnetic field (poloidal and toroidal). More generally and for all dynamo model, if the final poloidal polarity is opposite to the initial one, a cyclic activity can occur.
We first reproduce solar reference models, using the STELEM code in a 2D kinematic approach, prescribing a solar DR profile for $\alpha\Omega$ and BL models. After reproducing well the magnetic solar features observed in its cyclic activity, we then construct an anti-solar DR profile and apply it on both reference models. A cyclic magnetic activity emerges in the $\alpha\Omega$ dynamo model, which is not the case in the BL dynamo where the dynamo becomes stationary. It is therefore interesting to ask why this cyclic activity is lost. To do so, we move the location of the poloidal field generation in the solar and anti-solar DR $\alpha\Omega$ models, and analyse the impact on cyclic magnetic activity. We thus move the α-effect location up, from the tachocline into the convection zone (CZ). We finally reach the surface, where the poloidal generation term is located in the BL dynamo model.
All configurations illustrated in Figure 1 has been explored, and its conclusions has been confirmed. Indeed we note that the cyclic activity for anti-solar DR regime is lost as soon as the alpha effect is no longer spread enough on the tachocline, *i.e.* when the poloidal field generation moves in the CZ, appart from the radial shear of the DR. For the solar DR regime, the cyclic activity is preserved all along the convection zone. Furthermore, we note that the cycle period is longer for deeper locations and larger radial extensions of the α-effect. See more details and Figures in Noraz et al. (2022) submitted to A&A.

3 How stellar dynamos are characterised with the Rossby number?

In parallel, we used the ASH code (Brun et al. 2004) to conduct a systematic study in the 3D regime, using global MHD simulations of turbulent stellar dynamo, where convection and DR profiles are no longer prescribed and emerge self-consistently (Brun et al. 2022 submitted to ApJ). Based on a series of 15 simulations of solar-type stars, we cover 4 bins of rotation and mass, and thus different effective Rossby numbers.
First, we find rotational transitions as a function of the fluid Rossby number, similar to what was found in hydrodynamic cases of Brun et al. (2017). Indeed, solar-like DR profiles emerge for intermediate fluid Rossby numbers $Ro_{\rm f}$, while anti-solar-like profiles appear when the Rossby number exceeds 1. Moreover the Lorentz force feedback strongly constrains the rotation profiles for the lowest Rossby numbers, bringing some DR close to a solid rotation profile when the DR-quenching is maximum.
Second, we also observe magnetic transitions as a function of the fluid Rossby number, similar to what was found in the work of Strugarek et al. (2017), and illustrated in Figure 2. For low Rossby number, generally fast rotators, we note the emergence of short cycles with period ranging around a couple of years. These cycles result from a dynamo located near the equator and in the upper part of the convective zone (CZ), and which dynamics seem to follow well the *Parker-Yoshimura rule*. It is potentially this type of mechanism that could be at the origin of the quasi-biennial oscillation observed on the Sun Fletcher et al. (2010). For intermediate Rossby (typically around the solar value), we observe decadal magnetic cycles resembling the solar 11-years cycle. They result from a deeper-seated dynamo located at the base of the CZ, governed by a non-linear

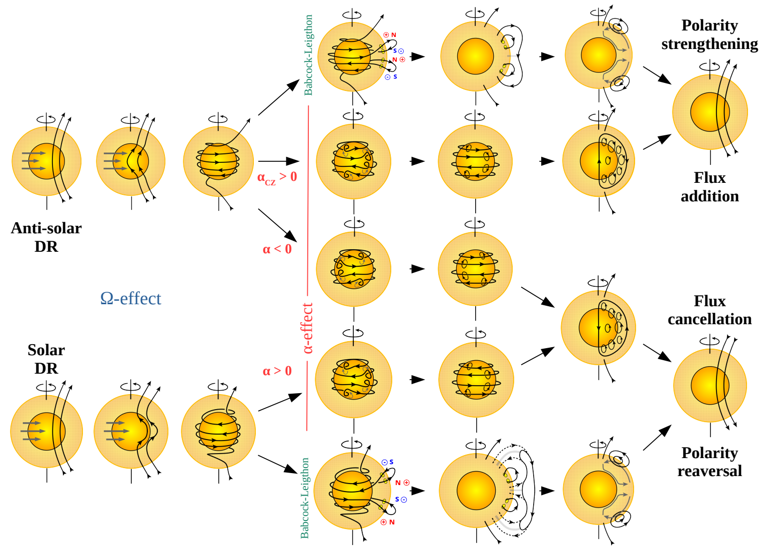

Fig. 1. The different steps for $\alpha\Omega$ and BL dynamo models in various geometrical configurations. They start on the left side with differential rotation (DR) performing the Ω-effect. It is represented on the first three columns, for anti-solar DR on the top, and the solar one on the bottom (see horizontal grey arrows). The next part (three next columns) illustrates the Babcock-Leighton mechanism on the first and last rows, while the three middle rows illustrate the α-effect For BL models, we represent the polarity of star-spots (red and blue), current sheet (light grey lines) and the meridional circulation (darker grey arrows), respectively on columns 4, 5 and 6. For the α-effect, column 4 illustrates orientation of cyclonic motions with grey arrows. Finally the last columns conclude the dynamo loop, with the presence of a cyclic activity when the final poloidal polarity is opposed to the initial one (bottom), or being stationary otherwise (top). The layout of this Figure is inspired from Sanchez et al. (2014), and soon published in Noraz et al. (2022, A&A).

feedback mechanism between the DR profile and the large-scale magnetic field. Indeed, we observe a cyclic energy exchange between the two energy reservoirs, resulting from a magnetic DR-quenching. Finally, when we transit towards high Rossby number (with $Ro_{\rm f} > 1$), models become anti-solar and all dynamos lose their cyclic activity, thus becoming stationary. We also note an increase in the toroidal magnetic field generation located at the bottom of the convective zone. These results are compatible with what we find in the mean field dynamo approach discussed in the previous section.
We then compare these simulations with observations by calculating the unsigned flux at the top of each model. We find flux from 10^{24} to 10^{25} Mx, which is in good agreement with the values observed on the Sun (Schrijver & Harvey 1994). Next, if time-averaged unsigned flux generally decreases as the Rossby increases, our models deviate drastically from this behaviour when Rossby becomes greater than one. This highlight a potential change of behaviour for this regime, possibly observed by Brandenburg & Giampapa (2018), that needs to be investigated further with additional high Rossby dynamo models. Finally, we perform a spectral decomposition of the magnetic field at the top of simulations, and observe no drastic drop in large-scale dynamo modes for the high Rossby regime (>1). As proposed by Metcalfe & van Saders (2017), such a drop could then have led to a less efficient wind braking (see how the Alfvén radius evolve in Finley & Matt 2017), which could have motivated and explained a *gyrochronology-break*. However, we do not find such collapses in the sample of simulations studied here. See more details and Figures in Brun et al. (2022).

4 Conclusions

In conclusion, we performed a numerical multi-D study through different DR regimes, focusing especially on their impact on the cyclic magnetic behaviour for stellar dynamos. This allows us to postulate the following scenario:
In its youth, the Sun had a relatively fast rotation in the first part of the main sequence. This resulted in a differential rotation profile strongly constrained by magnetic DR-quenching, and accompanied by a yearly-varying surface magnetic cycle. Subsequently, the decrease of its rotation rate brought the Sun into an intermediate Rossby range. This led its DR into its current regime, bringing out the emergence of the well known decadal

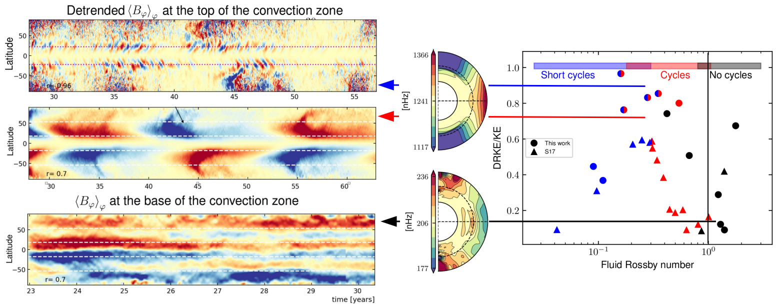

Fig. 2. Summary of the dynamo states found in our study. **Left:** Typical dynamo states on time-latitude representation of $\langle B_\phi \rangle$. The bottom panel represents a stationary dynamo found in anti-solar regimes. The middle one represents a deep decadal cyclic dynamo found around the solar regime. Both panels illustrate the toroidal magnetic component at the base of the CZ. The upper panel illustrates a surface and shorter dynamo in the same model, after filtering the longer cycle. **Middle:** Associated DR profiles achieved in the models. **Right:** Ratio between the differential rotation and total kinetic energies as a function of the Rossby number. Circles represent model of our study, while triangles represent the ones of Strugarek et al. (2017). Short cycles (blue) are found for low Rossby numbers, long decadal Sun-like cycles (red) appear for intermediate Rossby, and only stationary dynamo (dark) are found for high Rossby numbers (anti-solar DR).

cycle observed today. Finally, a quick calculation using the Skumanich's law show that the Sun's fluid Rossby number could possibly reach the value of 1 before the end of the MS. Then the Sun will be likely to change its DR regime toward an anti-solar DR (fast poles - slow equator), and finally to lose the cyclic character of its dynamo.

Indeed, most of the models of this study seem to show that stellar dynamos become stationary under this particular DR regime. However, we have found that a cyclic dynamo can still exist in anti-solar DR for particular alpha effect profiles (see also Karak et al. 2020). The detection of a cool main-sequence star in such a regime would therefore be a strong constraint to characterise the basis of the dynamo mechanism within our Sun. More generally, understanding stellar rotation and magnetism is of major importance for the data analysis of future missions, such as PLATO.

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