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Differential rotation of stars from spot transit mapping: dependence on rotation period and effective temperature

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Abstract. Just like the Sun, other stars also exhibit differential rotation. Currently, the rotation profile of a star that hosts a transiting planet can be estimated if during a transits, the planet occults a spot on the photosphere of the star, causing slight variations in its light curve. By detecting the same spot during a later transit, the stellar rotation period at that latitude is determined. Here, we present the results of differential rotation for 48 stars, 13 from the spot transit mapping method, while the remaining 35 stars from other techniques. The results show that the differential rotation is correlated with the stellar mean rotation period for fast rotating stars and strongly anti-correlated for slow rotators. The transition occuring at rotation period of 5 days. On the other hand, the differential shear increases with effective temperature for fast rotating stars, but the correlation is lost for the slow rotators.

Keywords. Starspot, Stellar rotation, Differential Rotation

1. Introduction

Stellar evolution studies rely on star rotation to understand age, angular momentum transfer, and magnetic fields. Differential rotation, similar to the Sun, is observed in other stars, accompanied by magnetic phenomena like spots, plages, loops, and flares (Reinhold et al. 2013). Detecting starspots at different latitudes helps track differential rotation. Understanding differential rotation and its correlations with other stellar parameters, such as rotation period and effective temperature, is important for the stellar dynamo (Küker and Rüdiger 2011), but conclusive results are lacking. Space missions provide data to study stellar rotation, flares, and starspots, enhancing our understanding of stellar activity.

2. Data and Starspot mapping

2.1. *Data*

This study explores correlations between the differential rotation shear with effective temperature and rotation period. Differential rotation using the transit mapping technique (Silva 2003) are presented for 13 stars. For comparison, we further analysed 35 stars which differential rotation measurements were available in the literature. The stars studied here and their differential rotation are listed in Table 1.

Table 1. Effective temperature, rotational period and differential rotation for all stars.

Star	T_{Teff} [K]	P_{rot} [d]	$\Delta\Omega$ [rad d^{-1}]	Ref	Star	T_{Teff} [K]	P_{rot} [d]	$\Delta\Omega$ [rad d^{-1}]	Ref
Kepler-17*	5781	12.4	$0.0409^{+0.0043}_{-0.0007}$	1	LQ Hya	5019	1.60	0.194 ± 0.002	17
Kepler-45*	3820	15.76	0.031 ± 0.014	2	LO Peg	4577	0.42	0.036 ± 0.007	18
Kepler-71*	5540	19.77	0.00098 ± 0.00010	3	HK Aqr	3697	0.43	0.00484 ± 0.0019	19
Kepler-210*	4559	12.35	$0.0436^{+0.011}_{-0.007}$	4	EY Dra	3489	0.45	0.00030 ± 0.003	20
Kepler-411*	4832	10.52	0.050 ± 0.0006	5	KIC 03541346	4194	0.908154	0.017	21
Kepler-1651*	3594	18.43	0.022 ± 0.004	6	KIC 04819564	4125	0.380794	0.0099	21
KOI-883*	4840	8.99	0.069 ± 0.011	7	KIC 04953358	3843	0.649015	0.0048	21
KapCeti	5677	8.77	$0.064 \pm {}^{0.006}_{-0.005}$	8	KIC 05791720	3533	0.765051	0.0098	21
EpsilonEri	5146	11.2	$0.062 \pm {}^{0.03}_{-0.004}$	9	KIC 06675318	4206	0.577727	0.0098	21
CoRoT-4*	6189	8.87	$0.03780.0261^{+0.0002}_{-0.0009}$	10	KIC 07592990	4004	0.442148	0.0071	21
CoRoT-5*	6100	26.63	$0.014^{+0.001}_{-0.011}$	10	KIC 08314902	4176	0.813534	0.0061	21
CoRoT-6*	6090	6.35	$0.105^{+0.011}_{-0.08}$	10	KIC 10515986	3668	0.746207	0.018	21
CoRoT-8*	5080	21.7	$0.014^{+0.003}_{-0.008}$	10	KIC 11087527	4303	0.41096	0.0076	21
CoRot-18*	5440	5.4	0.094 ± 0.003	10	KIC 10063343	3976	0.3326	0.0057	21
CoRoT-2*	5625	4.54	$0.042^{+0.005}_{-0.016}$	11	KIC 8429280	5055	1.20	0.26 ± 0.001	22
IL HYa	4500	12.73	0.035 ± 0.003	12	HD 35850	6138	1	0.256 ± 0.017	23
V889 Her	5750	1.34	0.042 ± 0.044	13	KIC 7985370	5815	2.856	0.194 ± 0.0002	24
R58	5880	0.56	0.08 ± 0.07	14	KIC 7765135	5835	2.485	0.18 ± 0.0002	24
HD 171488	5800	1.33	0.41 ± 0.16	14	HD 175726	6030	3.95	0.636	25
HD 106506	5900	1.39	0.24 ± 0.03	14	HD 181906	6360	2.71	0.25	25
HD 141943	5850	2.17	0.240 ± 0.03	14	HD 307938	5859	0.57	0.025 ± 0.015	26
LQ Lup	5750	0.31	0.12 ± 0.02	14	AF Lep	6100	0.97	0.259 ± 0.019	27
PZ Tel	5448	0.944	0.0113 ± 0.0018	15	HD 155555A	5400	1.67	0.078 ± 0.006	28
AB Dor	5386	0.51	0.046 ± 0.006	16	HD 155555B	5050	1.67	0.039 ± 0.006	28

(1) (Valio et al. 2017); (2) (Zaleski et al. 2022); (3) (Zaleski et al. 2019); (4) (Valio and Araújo 2022); (5) (Araújo and Valio 2021); (6) (Araújo et al. 2023); (7) (Zaleski et al. 2022); (8) (Walker et al. 2007); (9) (Croll et al. 2006); (10) (Valio 2013); (11) (Silva–Valio et al. 2010) (12) (Petit et al. 2013); (13) (Marsden et al. 2006); (14) (Marsden et al. 2011); (15) (Barnes et al. 2000); (16) (Cameron and Donati 2002); (17) (Donati et al. 2003); (18) (Karmakar et al. 2016); (19) (Barnes et al. 2004); (20) (Barnes et al. 2005); (21) (Vida et al. 2014); (22) (Frasca et al. 2011); (23) (Mengel 2005); (24) (Fröhlich et al. 2012); (25) (Mosser et al. 2009); (26) (Marsden et al. 2004); (27) (Järvinen et al. 2015); (28) (Dunstone et al. 2008).

2.2. *Starspot mapping*

The stellar rotation profile can be estimated if the star is eclipsed periodically by an orbiting planet. During one of these transits, the planet may occult a spot on the photosphere of the star. This occultation will cause a slight increase in the intensity of the transit light curve during a few minutes. The fit of the transit light curve by a model allows us to determine the physical characteristics of the spots. By monitoring the positions of these spots in subsequent transits, it is possible to estimate the rotation period of a star Silva–Valio (2008). The model used is described in Silva (2003), and its basic assumptions are:

- Star: synthesised 2D image of a star with limb darkening.
- Planet: completely dark disc of radius $\frac{R_{planet}}{R_{star}}$.
- Spot: round grey feature with a given size, intensity (or temperature), and location (longitude and latitude).

2.3. *Differential Rotation*

It is assumed that all stars exhibit differential rotation with latitude similar to that of the Sun:

$$\Omega = \Omega_{eq} - \Delta\Omega \sin^2(\alpha) \tag{1}$$

where the constants are: Ω_{eq} (rotation rate at the equator) and $\Delta\Omega$ (rotational shear). Two measurements of the rotation are considered: the mean angular rotation, $\bar{\Omega}$, and the angular rotation, Ω_1, at a certain latitude α_1, which are given by:

$$\bar{\Omega} = \Omega_{eq} - \frac{\Delta\Omega}{2} \quad \text{and} \quad \Omega_1 = \Omega_{eq} - \Delta\Omega \sin^2(\alpha_1) \tag{2}$$

Since, the rotation period is $P = 2\pi/\Omega$, $\bar{\Omega}$ is obtained from the mean rotation period, usually measured from a Lomb-Scargle periodogram of the entire light curve. From the spot transit mapping, one can obtain the rotation period at a certain latitude, and thus Ω_1 (Valio 2016).

3. Result and Discussion

3.1. *Differential rotation of slow and fast rotating stars*

Recently, Araújo and Valio (2023) have analysed the differential rotation of 13 stars obtained from the spot transit mapping. To compare our results on rotational shear with those of other stars, we expanded our sample to include stars with $\Delta\Omega$ values reported in the literature. The full sample, consisting of 48 stars, is listed in Table 1. Here, we investigate the dependence of stellar differential rotation for both slow and fast (≤ 5 days) rotating stars. We present the results of the differential rotation for all stars in Figure 1 as a function of the stellar rotational period and in Figure 2 as a function of the effective temperature of the stars.

Shown in Figure 1, the results reveal a strong anti-correlation (Pearson coefficient of approximately -0.80, middle panel) between $\Delta\Omega$ and the rotation period for stars with slow (black squares) rotation rates, similar to that found by Araújo and Valio (2023).

On the other hand, the fast rotating stars (blue squares) exhibit an opposite behavior, with the rotational shear increasing with the rotation period of the star (Pearson correlation coefficient of 0.70, shown in the right panel of Figure 1). As can be seen in the left panel of Figure 1, an abrupt change in behaviour occurs at stellar rotation periods around 5.0 days.

The relationship between $\Delta\Omega$ and effective temperature for all stars is shown in the left panel of Figure 2. Stars with fast rotation rates (right panel) tend to exhibit strong

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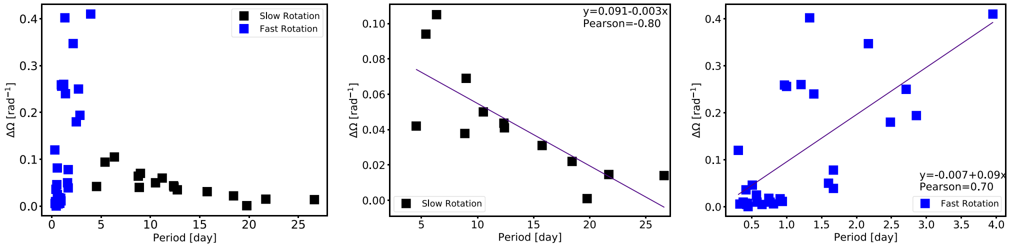

Figure 1. Differential rotation, $\Delta\Omega$, as a function of stellar average rotation period, for all stars (**Left**), for slowly rotating stars with average rotation periods $P_{\rm rot} \geq 4.5$ days, (**Middle**), and for rapidly rotating stars with average rotation periods of $P_{\rm rot} \leq 4.5$ (**Right**). Rapid rotators are shown as blue squares whereas the slow rotators are depicted as black squares.

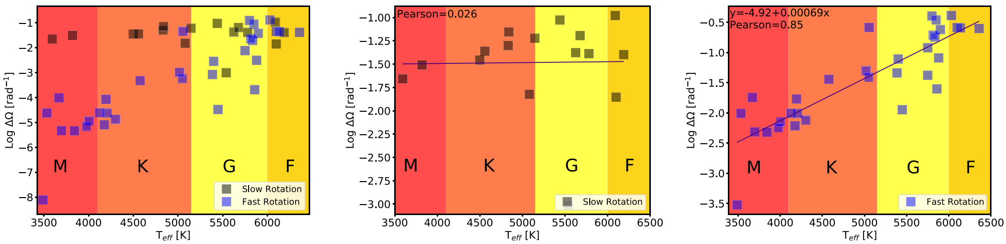

Figure 2. Relation between $\Delta\Omega$ and effective temperature, for all stars (**Left**), for slowly rotating stars with average rotation periods $P_{\rm rot} \geq 4.5$ days, (**Middle**), and for rapidly rotating stars with average rotation periods of $P_{\rm rot} \leq 4.5$ (**Right**). Rapid rotators are shown as blue squares whereas the slow rotators are depicted as black squares.

correlation (correlation index of 0.85) than their slow-rotating (middle panel) counterparts. In contrast, slowly rotating stars show significant dispersion, with no apparent correlation (Pearson correlation index of 0.026, middle panel of Figure 2). Thus, $\Delta\Omega$ tends to increase with temperature, but this trend is only evident in rapidly rotating stars. These results are consistent with the findings of Balona and Abedigamba (2016).

Studies have shown that there is a correlation between the magnetic activity of stars and their differential rotation, which is caused by the magnetic dynamo (Parker 1955). Young solar-type stars are known to have faster rotation periods and stronger magnetic activity compared to the Sun (Fröhlich et al. 2012). This relationship is evident in other phenomena associated with the stellar dynamo, including the presence of large stellar spots, such as those observed in Kepler-17 with mean radii of 49,000 ± 10,000 km (Valio et al. 2017), and the production of superflares and stellar spots with complex magnetic topology (Araújo and Valio 2023). Furthermore, our results suggest that there is an increasing difference in rotation rate, referred to as $\Delta\Omega$, between the equator and poles of stars, which increases with rotation periods up to ~5 days and then decreases as the rotation rates of stars decrease, or conversely the rotation period increases.

4. Conclusion

In this study, we compared the differential rotation behaviour of fast and slow rotating stars, for a total of 48 stars, ranging from spectral types M to F. The data included differential rotation of 13 stars from measurements of spot transit mapping method. Our aim was to explore how differential rotation relates to the stars' mean rotation period and effective temperature.

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We found that for young rotation stars ($P < 5$ days), the differential rotation increases with rotation period, and then decreases for stars with periods longer than 5 days, with a strong negative correlation between rotational shear and the average rotation period (coefficient = -0.80). As for the dependence of the differential shear with effective temperature (or stellar mass), our results showed that there is a strong correlation for the fast young rotating stars, but this correlation is lost altogether for the slowly rotators ($P > 5$ days).

A comprehensive understanding of the connection between rotational shear, effective temperature, and rotation rate is crucial to furthering our knowledge of stellar dynamos.

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