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Magnetic Fields of Starspots: Transit Mapping Revelations

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Abstract. Starspots, regions of strong magnetic fields, serve as indicators of stellar activity and the dynamo mechanism at play in the interior of stars. The magnetic fields of main-sequence stars play a crucial role in driving stellar activity. We propose a new method for estimating the magnetic fields of starspots that employs modelling techniques of planetary transit mapping, which provides estimates of the size, intensity, and location of spots on the stellar photosphere. A starspot's maximum magnetic field was calculated using the linear relationship with the spot flux deficit, $\Delta F_{\rm spot}$, and the well-characterised relation for sunspots, $B_{\rm spot} = 1170 + 844 \log(\Delta F_{\rm spot})$ (G). Applying this relationship to previously mapped spots on the photospheres of 14 FGK and M stars yields spot maximum magnetic fields ranging from 2700 G to 4600 G, with an overall average of 3900 ± 400 G. We find weak anti-correlations between the spots' magnetic field and stellar age as well as rotation period. When compared with previous results of small-scale magnetic field measurements, the B values obtained here are basically constant and near the saturation limit found for rapid rotators. This implies that it is not the intensity of the magnetic field of starspots that decreases with age but rather the filling factor.

Resumo. Manchas estelares, regiões de campos magnéticos intensos, servem como indicadores de atividade estelar e do mecanismo de dínamo em operação no interior das estrelas. Os campos magnéticos de estrelas da sequência principal desempenham um papel crucial na condução da atividade estelar. Propomos um novo método para estimar os campos magnéticos de manchas estelares que emprega técnicas de modelagem de mapeamento de trânsito planetário, que fornece estimativas do tamanho, intensidade e localização de manchas na fotosfera estelar. O campo magnético máximo de uma mancha estelar foi calculado usando a relação linear com o déficit de fluxo da mancha, $\Delta F_{\rm spot}$, e a relação bem caracterizada para manchas solares, $B_{\rm spot} = 1170 + 844 \log(\Delta F_{\rm spot})$ (G). Aplicando essa relação a manchas previamente mapeadas nas fotoesferas de 14 estrelas FGK e M, obtemos campos magnéticos máximos variando de 2700 G a 4600 G, com uma média geral de 3900 ± 400 G. Encontramos anti-correlações fracas entre o campo magnético das manchas e a idade estelar, bem como o período de rotação. Quando comparados com resultados anteriores de medições de campos magnéticos em pequena escala, os valores de B obtidos aqui são basicamente constantes e próximos ao limite de saturação encontrado para rotadores rápidos. Isso implica que não é a intensidade do campo magnético das manchas estelares que diminui com a idade, mas sim o fator de preenchimento.

Keywords. Starspots – Stellar activity – Stellar magnetic fields – Transit photometry – Stellar ages

1. Introduction

Stellar magnetic activity is caused by the dynamo inside stars and appears in different ways, including starspots. These areas of strong magnetic fields are similar to sunspots and are an important way to comprehend how stellar dynamos work. Understanding the properties of starspots, especially their magnetic field strength, is key to getting a full picture of stellar activity and how it changes over time. A major question in this area is how stellar magnetic activity decreases as a star gets older. Does this happen because the magnetic fields in starspots get weaker, or because there are fewer and smaller starspots?

The study of stellar activity is a main topic in astrophysics. It has important effects on our understanding of how stars evolve, if exoplanets can support life, and the basic physics of how stars create magnetic fields. Signs of stellar activity, like Ca II H and K emission, X-ray brightness, and ultraviolet radiation, all clearly decrease as stars get older. This decrease is described by the activity-age relation, which has been tested using star clusters of known ages. However, we still do not fully understand the physical reasons for this decline.

This work is based on the results of two previous studies: Menezes et al. (2024) and Araujo et al. (2025). In Menezes et al. (2024), we introduced a new method to estimate the magnetic fields of starspots using planetary transit mapping. This method allows us to determine the size, intensity, and location of spots on a star's surface as a planet passes in front of it. By combining this mapping technique with a well-established relationship between magnetic field strength and brightness for sunspots, we can infer the magnetic properties of starspots on other stars. In Araujo et al. (2025), we applied this method to a larger sample of stars and investigated the relationship between starspot properties and stellar parameters.

The study of stellar magnetic fields is fundamental to understanding stellar evolution and the habitability of exoplanetary systems. Main-sequence stars like our Sun generate their magnetic fields through a dynamo mechanism operating in their convective zones. These magnetic fields manifest as starspots, which are cooler regions on the stellar surface where concentrated magnetic flux inhibits convection. By studying the properties of starspots across different stellar types and ages, we can gain insights into how the stellar dynamo operates and evolves over time.

Past studies of stellar magnetic fields mainly used spectroscopic methods like Zeeman-Doppler imaging (ZDI) or measurements of activity signs in the chromosphere. These methods give useful information, but they often only work for fast-rotating stars and might not show all the details of the magnetic field structures. The transit mapping method offers a different approach that can see the large-scale shape of magnetic fields and can be used for many more types of stars.

2. Methodology and Observations

Our method uses precise light curve observations from space missions like CoRoT and Kepler. When a planet passes in front of its host star, it might cross over starspots, causing small changes in the transit light curve. By modeling these changes, we can create a map of the star's surface that shows the location and physical characteristics of spots, such as size and intensity. This is called transit mapping. We use the ECLIPSE model (Silva-Valio 2003) to create a 2D limb darkened image of the star, assuming the planet is a dark circle. When a planet crosses a starspot, the drop in brightness is smaller than when it crosses a clean part of the star. This lets us find and describe the spots.

Our analysis is based on the relationship between a spot's magnetic field and its flux deficit, $\Delta F_{\rm spot}$. The flux deficit measures how dark and large a spot is. It is calculated by multiplying the spot's area by its intensity difference compared to the rest of the star's surface (contrast). From observations of more than 30,000 sunspots, a linear relationship was found:

$$B_{\rm spot} = 1170 + 844\log(\Delta F_{\rm spot}) \quad (1)$$

where $B_{\rm spot}$ is the maximum magnetic field strength in Gauss (G). This relationship was first presented in Menezes et al. (2024), based on a detailed study of 32,223 sunspots observed during Solar Cycle 23 (from May 1996 to April 2008). This linear fit provides a robust calibration that relates observable spot properties to their underlying magnetic field strength.

We used this relationship for a group of 14 FGK and M-type stars where starspots were already mapped using the transit method. The star properties, such as spectral type, age, and rotation period, were taken from other studies and are listed in Table 1. This allowed us to estimate the magnetic field strength of spots on many different types of stars with varying masses, ages, and rotation speeds.

Our work is based on very precise light curve data from the CoRoT and Kepler space missions. These missions provided new opportunities to study stellar activity by observing planetary transits. The CoRoT mission observed stars of magnitude range of 5.7 to 16 with a photometric precision of approximately 10 ppm (parts per million) for bright stars. The Kepler mission achieved similar or better precision for its target stars, with typical noise levels of 1-10 ppm depending on stellar brightness.

The identification of starspots in transit light curves relies on the fact that when a transiting planet crosses a starspot, the observed transit depth is reduced compared to the transit depth over an unspotted region of the star. This is because a spot is cooler and darker than the surrounding photosphere, so when the planet crosses it, less light is blocked. By analyzing the variations in transit depth as the planet crosses different parts of the star over multiple transits, we can construct a two-dimensional map of the stellar surface showing the locations and properties of spots.

The transit mapping method used here is the ECLIPSE model, which treats the star as a simple disk with round spots of the same brightness. This is a simpler version of reality, but it allows a good first look at the star's surface and provides numerical information about the spots. The model is applied to fit the transit light curves, allowing the retrieval of the starspot's projected location, size, and contrast relative to the stellar photosphere. Once the spot properties have been determined from the transit mapping analysis, we calculate the flux deficit, $\Delta F_{\rm spot}$,for each spot. This quantity is directly related to the magnetic field strength through the empirical relation derived from sunspot observations (Equation 2).

3. Results and Discussion

As reported in Menezes et al. (2024), the analysis of the 14 target stars yielded starspot magnetic field strengths ranging from approximately 2700 G to 4600 G (see Table 1). The average maximum magnetic field strength across all the spots in our sample was found to be 3900 ± 400 G. These values are significantly higher than the average magnetic field of the Sun, which exhibits spot fields typically in the range of 2000–4000 G. The distribution of magnetic field strengths is relatively narrow, with most values clustering between 3500 and 4200 G, indicating a remarkable consistency in the maximum magnetic field intensity across different stellar types and ages. The standard deviation of approximately 400 G represents about 10% of the mean value, indicating a relatively tight distribution of magnetic field strengths.

The 14 stars in our sample span a broad range of fundamental properties. Their ages range from 0.21 Gyr for the young star Kepler-63 to 3.0 Gyr for the older CoRoT-6. Rotation periods vary from 1.9 days for the rapidly rotating Kepler-210 to 23.0 days for the more slowly rotating CoRoT-7. This diversity enables an investigation of how starspot magnetic properties relate to the underlying stellar characteristics.

We then looked for connections between the starspot magnetic fields we measured and different star properties. We found no strong link between the spot's magnetic field and the star's temperature ($T_{\rm eff}$) or its differential shear ($\Delta\Omega$). However, we did see a weak inverse connection with the star's age and rotation period. This suggests that younger, faster-spinning stars tend to have spots with slightly stronger magnetic fields.

The weak inverse connection between magnetic field strength and age (correlation coefficient $\rho \approx -0.33$) shows that the magnetic field strength does not change significantly as stars get older. In the same way, the weak inverse connection with rotation period ($\rho \approx -0.42$) suggests that the fastest-spinning stars do not always have the strongest spot magnetic fields. These results match the idea of a saturation level, where the magnetic field created by the dynamo hits a maximum value that does not depend on the rotation for fast-spinning stars.

To further understand the relationship between magnetic field strength and stellar properties, we examined the data for different spectral types. The results presented in Table 1 reveal interesting patterns in the magnetic field strengths across different stellar types. F-type stars (CoRoT-4 and CoRoT-6) show magnetic fields in the range of 3520–3650 G, while G-type stars display a wider

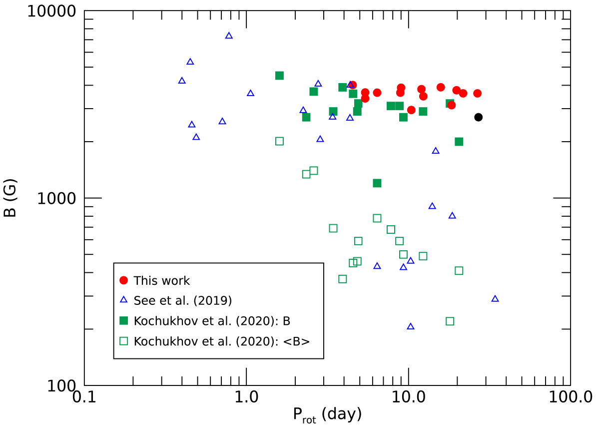

Figure 1. Comparison of starspot magnetic field strengths from this work (red circles) with previous measurements using Zeeman-Doppler imaging (See et al. 2019; Kochukhov et al. 2020) as a function of stellar rotation period. The black dot represents the Sun.

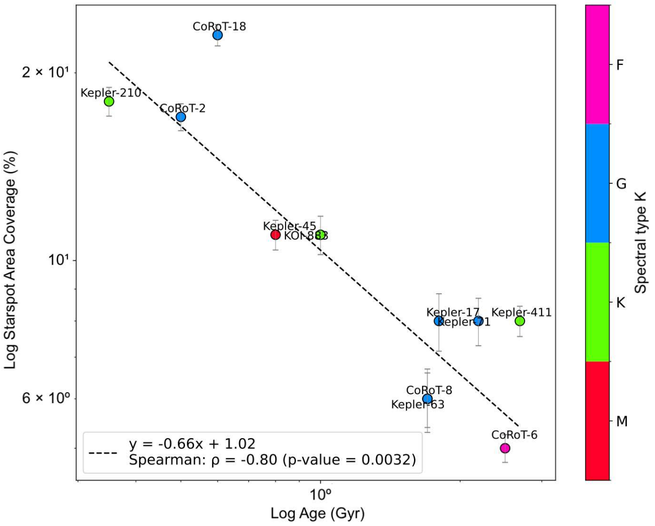

Figure 2. Starspot area coverage as a function of stellar age. The dashed line shows the best-fit power-law relation with Spearman correlation coefficient $\rho = -0.80$ (p-value = 0.0032). Colors indicate spectral type: red (M-type), green (K-type), blue (G-type), and magenta (F-type). This figure demonstrates that the filling factor of starspots decreases with stellar age.

range from 3620 to 4160 G. The M-type stars in our sample (Kepler-45 and Kepler-411c) exhibit magnetic fields of 3900 and 3330 G, respectively. The outlier in our sample is Kepler-210, a K2V star with an exceptionally strong magnetic field of 5490 G, which may be related to its very short rotation period of only 1.9 days. These variations are relatively small compared to the overall range, suggesting that spectral type (and thus stellar mass) does not strongly influence the maximum magnetic field strength of starspots.

The magnetic field strengths we found for starspots are always high, near the saturation level seen in fast-spinning stars (see Figure 1. This suggests that the dynamo in these stars is working very efficiently, creating magnetic fields with a nearly constant maximum strength. The saturation level for fast spinners is known for having magnetic field strengths that stay mostly the same even when the rotation speed changes, which matches our results.

Our key result concerns the implications for how stellar magnetic activity evolves with age. The weak inverse connection between spot magnetic field and age, along with the fact that the field strengths are near the saturation level (see Figure 1), suggests that it is not the strength of the magnetic field in starspots that decreases as a star gets older. Instead, as shown in Figure 2, it is more likely that the *filling factor* – the fraction of the star's surface covered by spots – decreases with age. In other words, older stars are less active not because their spots have weaker magnetic fields, but because they have fewer or smaller spots.

This interpretation is consistent with the findings of Araujo et al. (2025), who showed that younger stars exhibit significantly higher starspot coverage fractions than older stars. The filling factor, which represents the fraction of the stellar surface occupied by spots, has been shown to decrease from approximately 30% in young, rapidly rotating stars to just a few percent in older, slowly rotating stars. Our finding that the magnetic field intensity remains essentially constant across this range of ages and activity levels strongly supports the hypothesis that the decrease in activity is driven by a reduction in the number and size of spots, not by a fundamental change in the dynamo mechanism.

A comparison between our results and previous measurements of small-scale magnetic fields obtained through techniques such as Zeeman–Doppler imaging shows good overall agreement. The magnetic field values we obtain match the saturation values found for fast-spinning stars, which are usually between 2000 and 4000 G. This agreement supports the reliability of our method and indicates that transit mapping provides a valuable approach for characterizing stellar magnetic fields.

It is important to note that our results are based on a sample of stars with high-quality transit data and previously mapped starspots. This selection may introduce a bias toward systems that are easier to observe and exhibit strong spot activity. Nevertheless, the diversity of stellar types and ages in our sample lends robustness to our conclusions. Future studies incorporating larger and more heterogeneous samples will further refine the relationship between magnetic field strength and stellar properties.

4. Implications and Conclusions

The results of this work have important implications for our understanding of stellar dynamos. The finding that magnetic field strengths reach a maximum of approximately 3900 G across stars with different ages and rotation rates indicates that the dynamo operates in a saturated regime for rapid rotators, becoming largely independent of rotation speed. This behavior is consistent with theoretical dynamo models that predict a saturation threshold at high rotation rates.

The weak inverse correlation between magnetic field strength and stellar age, combined with the strong decline of spot coverage with age, offers a new perspective on the long-term evolution of stellar activity. Rather than indicating a progressive weakening

Table 1. Properties of the stars in the dataset, and the average magnetic fields of their respective starspots.

Star	Spectral type	Age (Gyr)	$P_{\rm rot}$ (day)	$B_{\rm spot}$ (G)	Ref.
CoRoT-2	G7V	$0.6^{+2.4}_{-2.2}$	4.522 ± 0.024	4010 ± 160	1,10
CoRoT-4	F8V	$1.0^{+1.0}_{-0.3}$	8.9 ± 1.1	3650 ± 130	2,11
CoRoT-5	F9V	6.9 ± 1.4	26.6 ± 0.5	3620 ± 260	2,11
CoRoT-6	F9	$2.5^{+2.1}_{-1.7}$	6.4 ± 0.5	3650 ± 210	2,11
CoRoT-8	K1	$1.7^{+2.3}_{-1.4}$	21.7 ± 0.5	3620 ± 210	2,12
CoRoT-18	G9	$0.6^{+0.0}_{-0.6}$	5.4 ± 0.4	3660 ± 310	2,11
Kepler-17	G2V	$1.8^{+0.0}_{-1.8}$	12.01 ± 0.16	3810 ± 170	3,11
Kepler-45	M1V	$0.8^{+0.7}_{-0.5}$	15.80 ± 0.20	3900 ± 260	4,11
Kepler-63	G	0.210 ± 0.045	5.401 ± 0.014	3400 ± 110	5,13
Kepler-71	G	$1.700^{+0.914}_{-0.490}$	19.773 ± 0.008	3760 ± 180	6,14
Kepler-210	K	$1.8^{+0.9}_{-0.5}$	12.338 ± 0.002	3490 ± 180	7,14
Kepler-411A	K2V	0.212 ± 0.031	10.40 ± 0.03	2950 ± 360	8,15
Kepler-1651A	M	–	18.43 ± 0.02	3130 ± 260	2
KOI-883	K2V	0.9 ± 3.8	8.994 ± 0.016	3880 ± 170	9

Notas. Notes. (1) Silva-Valio et al. (2010), (2) Valio et al. (2024), (3) Valio et al. (2017), (4) Zaleski et al. (2020), (5) Netto & Valio (2020), (6) Zaleski et al. (2019), (7) Valio & Araujo (2022), (8) Araujo & Valio (2021), (9) Zaleski et al. (2022), (10) Southworth (2011), (11) Bonomo et al. (2017), (12) Raetz et al. (2019), (13) Sanchis-Ojeda et al. (2013), (14) Morton et al. (2016), (15) Sun et al. (2019).

of the dynamo itself, the results suggest that the dynamo remains efficient but produces fewer and smaller spots as stars age. This behavior may be associated with age-dependent changes in stellar rotation or in the structure and efficiency of the convective zone.

Our results also suggest that the maximum magnetic field value may be a basic property of the stellar dynamo, set by the balance between creation and decay of the magnetic field. The fact that this maximum value is seen in many different stars suggests it might be a universal feature of dynamos in main-sequence stars.

Our findings also have implications for assessments of exoplanet habitability. Stellar magnetic activity—particularly flares, which are often associated with starspot regions—can substantially modify the radiation environment experienced by orbiting planets. The apparent constancy of starspot magnetic field strength with age suggests that field intensity itself is not the primary driver of long-term changes in high-energy stellar output. Instead, the decline in starspot coverage as stars age likely reduces the number of active magnetic regions capable of producing energetic flares. This decrease in flare occurrence would lead to a lower overall high-energy radiation environment, which could strongly influence the atmospheric evolution and surface conditions of exoplanets that might otherwise be capable of supporting life.

Also, our work shows that transit mapping is a powerful tool for describing stellar magnetic fields.Unlike spectroscopic methods that are effective only for fast-spinning stars, transit mapping can be used for stars with many different rotation periods, as long as they host transiting planets. This creates new ways to study the magnetic properties of stars and to understand how stellar magnetism changes with basic star properties.

We have shown a new way to measure the magnetic fields of starspots using planetary transit mapping. Our results, from a group of 14 FGK and M-type stars, show that starspot magnetic fields are strong, with an average maximum strength of about 3900 ± 400 G. We find that the magnetic field strength of spots does not decrease significantly as stars get older, and there is only a weak inverse correlation with rotation period. This leads us to conclude that the decline in stellar activity with age is driven primarily by a reduction in starspot filling factor, rather than by a weakening of the magnetic field within individual spots.

The implications of this work extend beyond the specific measurements presented here. By demonstrating that starspot magnetic field strengths remain near their maximum values across a wide range of stellar ages and rotation rates, we gain new insight into the operation of stellar dynamos. The near-constant field strength indicates that the dynamo remains robust and efficient at generating strong magnetic fields. It further suggests that the observed evolution of stellar activity is governed more by changes in the surface distribution of magnetic flux—such as variations in spot coverage—than by variations in the intrinsic strength of the dynamo itself.

This work creates new paths for studying stellar dynamos and the changes in magnetic activity. Future studies with more stars and better transit data will help us better understand the complex connections between magnetic fields, star properties, and age. The transit mapping method, as shown here, is a powerful addition to the usual spectroscopic methods and can be used for more types of stars and activity levels. With missions like TESS still running and by studying old data from Kepler and CoRoT, We expect that this method will substantially advance our understanding of stellar magnetism and its role in stellar evolution and exoplanet habitability.

The methodology presented in this paper can be extended to other stellar systems as new transit photometry data become available. The combination of high-precision photometry from space-based missions with sophisticated modeling techniques provides unprecedented opportunities to characterize stellar surface features and their magnetic properties. As our understanding of starspot magnetic fields improves, we will be better equipped to interpret the magnetic activity signatures observed in other stars and to understand the fundamental processes that govern stellar dynamos across the mass spectrum.

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