Differential Rotation of F G K M Main-Sequence Stars

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Abstract

Context: The Kepler mission spent 9 years discovering exoplanets; however, it also provided valuable information not only about these objects but also more than 200,000 light curves of active stars. From this data, we can measure stellar characteristics such as rotation period and differential rotation.//

Aims: Our main goal is to measure differential rotation (DR) using two methods. The first is the "Two-Peak Method," developed by Reinhold & Gizon (2015). Their research provided a formula that calculates the DR coefficient based on the difference between the periods of two peaks that are close to each other. The formula (Phigh-Plow)/ Phigh gives the DR parameter, where Phigh and Plow represent periods at higher and lower latitudes, respectively. A positive coefficient indicates solar-like differential rotation, while a negative coefficient indicates anti-solar differential rotation. The second method is the "Gaussian Distribution Function Method," which assumes that the full width at half maximum (FWHM) of the periodogram's Gaussian distribution can be an indicator of the star's differential rotation.

Method: We used the Kepler database (Q0-Q17 quarters) to derive differential rotation for 25,000 F G K M spectral-class stars using the two methods described above. We analysed their light curves using the Lomb-Scargle periodogram.

Results: In our research, we identified differential rotation in 500 stars using the "Two-Peak Method" and in 200 stars (with 10 solar-like effective temperature, radius, and rotation period stars) using the "Gaussian Distribution Function Method". From the first one, we found $\sim 10\%$ asymmetry between solar and anti-solar differential rotation. For these 500 stars, DR was measured for the first time in almost 300 stars. We also present the statistical characteristics (rotation period, temperature, radius, log g, and mass) of these stars in relation to the differential rotation coefficient.

1. Introduction-What is differential rotation?

Rotation is considered differential when different parts of an object rotate at dissimilar angular velocities, depending on factors such as depth, latitude, or distance from the centre. As we know, stars are non-rigid bodies, so it is possible for them to rotate not as a one, but differentially.

The best example of differential rotation is our Sun. This phenomenon was first described by Galileo Galilei in 1610, through his analysis of sunspots. It was observed that at the equator, the Sun completes a rotation in about 25 days, whereas at the poles it takes nearly 37 days. In general, the solar differential rotation formula is as follows:

$$\omega = A + Bsin(\phi)^2 + Csin(\phi)^4, \tag{1}$$

where A is the angular velocity at the equator and B and C are constants that control the decrease in velocity as the latitude increases.

Additionally, we should mention the differential rotation of two planets in our solar system: Saturn and Jupiter. Their rotation periods also differ between the equator and the poles. In our Galaxy, it has been confirmed that the Milky Way rotates differentially as well.

So why do we need to study this phenomenon? To understand the internal structure and dynamics of space objects (galaxies, stars, planets, etc.), to model and describe the evolution of stars, and to deepen our general understanding of fundamental physics.

2. Discussion

There are several methods for studying the differential rotation of stars. One of them is to obtain periodograms from the light curves. To create periodograms, we can use methods like wavelet analysis,

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Fourier transforms, autocorrelation, or the Lomb-Scargle. A star's rotation period can be influenced by the presence of star spots, transits of other stars, or differential rotation. It is challenging to separate DR from these other factors, but this is the focus of ongoing research.

In the article *"Starspot Signature on the Light Curve"*, researchers synthesized a light curve in which a star has two spots at different latitudes. They used the Lomb-Scargle method to test for differential rotation, applying a formula developed by Reinhold et al. (2013). It calculates DR coefficient based on the difference between the periods of two peaks that are close to each other. The formula is: $(P_{high} - P_{low}/P_{high}$, where P_{high} and P_{low} represent the periods at higher and lower latitudes, respectively. A positive coefficient indicates solar-like differential rotation, while a negative coefficient suggests anti-solar differential rotation.

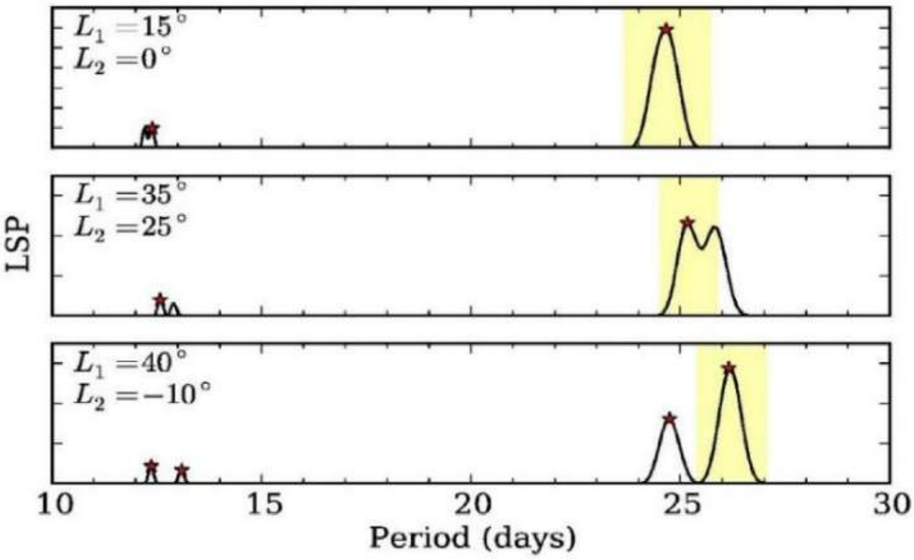

Figure 1. Lomb-Scargle periogram for three synthetic light curves from simulations with two spots at different latitudes, L1 and L2 (Santos et al., 2017).

Using this method, Reinhold and Arlt, in the article *"Rotation, Differential Rotation, and Gyrochronology of Active Kepler Stars"*, analysed data from 24,124 stars in the Kepler mission (Q1-Q14). They found the DR coefficient for 12,300 stars and calculated their gyrochronology ages. Their analysis revealed that the differential rotation coefficient increases in relation to the rotation period.

As we mentioned, DR can be revealed by analysing light curves, which are generated from databases provided by space missions.

3. Data

The Kepler mission, which launched in 2009, spent nine years discovering exoplanets. During this time, it identified almost 2,600 exoplanets and 2,368 candidate exoplanets. However, the mission also provided valuable information about not only these objects, but also about more than 200,000 light curves of active stars. We can obtain rotation periods from these light curves and observe Differential Rotation. For this purpose, we will refer to some catalogues.

McQuillan et al. (2014) derived the rotation periods for 34,030 stars of spectral classes F, G, K, and M. They used the autocorrelation method in their research. In addition, they calculated the gyrochronology ages for these stars.

Furthermore, we should mention Santos et al. (2019) and Santos et al. (2021) works which were derived star rotation periods using wavelet analysis and the Lomb-Scargle periodogram. Their catalogue includes 26,500 M and K (2019) and 24,200 F and G spectral class stars (2021). They reported that their research correlates 99% with MMcQuillan et al. (2014) catalogue.

Another important study is Reinhold & Gizon (2015), in which rotation periods for 67,000 stars were derived using a specific method (GPS). This method is particularly useful for stars of irregular types.

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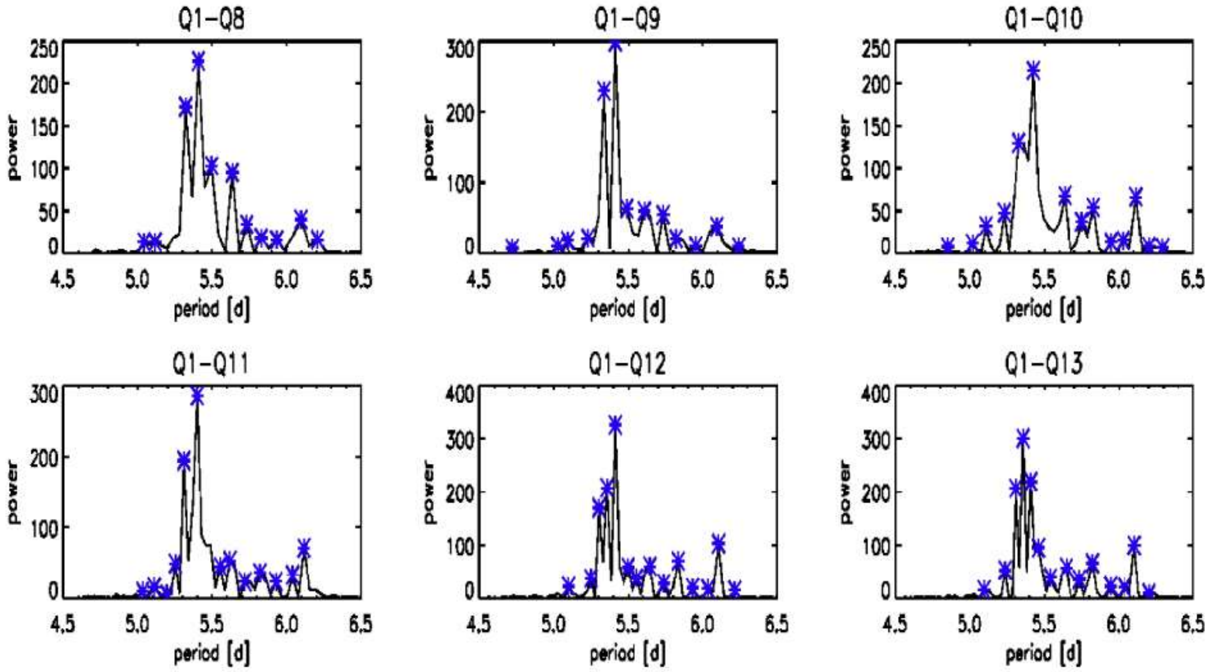

Figure 2. Periodograms of the segments of KIC 1163579 (Reinhold & Gizon, 2015).

4. Methodology

Our goal is to derive the differential rotation for F, G, K, and M spectral type stars. We aim to distinguish Sun-like stars, which share similar rotation periods, temperatures, masses, and radii. Additionally, we want to determine the difference in the number of stars with solar and anti-solar differential rotation.

First, we downloaded the Kepler database from the Mikulski Archive for Space Telescopes (MAST, https://archive.stsci.edu/missions-and-data/kepler). The complete dataset amounted to 2 TB; however, we created a smaller database containing only the data necessary for our research. The Kepler dataset includes some known issues, which are addressed and corrected by the Kepler team, with updates published incrementally. For our analysis, we used the same data release (RD25) that was utilized by Santos (Santos et al., 2019).

Each quarterly dataset is provided in FITS (Flexible Image Transport System) format, which contains various stellar parameters. We specifically utilized the flux and time columns, along with the header information, which includes the star's effective temperature, radius in solar radii, mass in solar masses, and surface gravity (Log(g)) in the CGS system.

Figure 3 shows the light curve of the Kepler star: the upper part of the graph displays the quarterly light curves, which are not connected. The lower part of the graph shows the same data, but the flux values are normalized to the median flux. The x-axis represents the Julian Date (in days), and the y-axis represents the flux (the number of photons received by the CCDs).

For our study, we utilized the catalogues of McQuillan et al. (2014) and Santos et al. (2019), Santos et al. (2021). Unfortunately, we were unable to incorporate the catalogue of Reinhold & Gizon (2015), as the star rotation periods in their dataset differed significantly from those of the McQuillan and Santos catalogues. The results in both catalogues were derived using three methods: Lomb-Scargle periodogram analysis, autocorrelation, and wavelet analysis.

From the astronomical database, we downloaded the relevant catalogues and isolated the stars for which rotation periods had been precisely measured. We combined the Santos 2021 and 2019 catalogues from Santos and took 51,000 stars with spectral types F, G, K, and M, such as McQuillan's. We chose stars that had measured rotation periods from both authors and selected 37,000 stars. We then compared McQuillan's and Santos' results to ensure that they were similar to 99%. We took the absolute value of the difference between Santos and McQuillan stars, divided it by the period of Santo stars, and multiplied it by 100 to obtain the percentage difference.

After classifying our data, we applied the Lomb-Scargle method to build periodograms for these 25,000 stars. We only considered periods with a value greater than 5 sigma for further analysis. For this, we wrote

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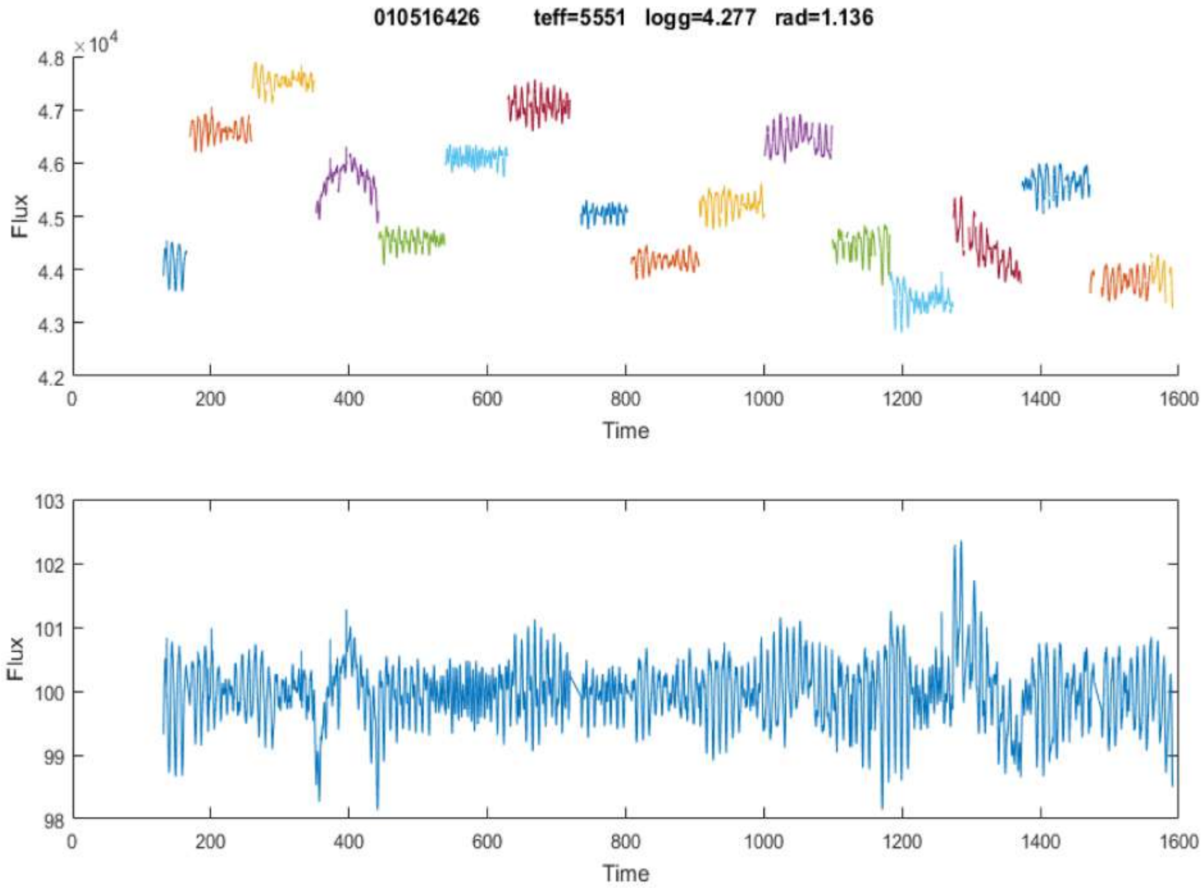

Figure 3. Light curve of Kepler star. Upper pane: quarterly light curve, bottom panel: the flux values are normalized to the median flux.

a program that searched for peaks corresponding to our specific questions. This program identified the existence of a differential rotation, its direction, and the corresponding coefficient. In addition, we created a second program to calculate DR using a different method.

5. Results

5.1. Two Peak Method

We used the formula given by Reinhold and Arlt, specifically targeting two closely spaced peaks, which were distant in relation to their peak heights. To ensure peak reliability, we selected periodograms in which the half-maximum peaks could also be observed. Before writing the program, we manually inspected periodograms by eye from 25,000 stars to 4,000 stars to detect characteristics and restrict the graphs. We set a 20% limit on both the left and right sides of the peaks. Within these limits, the program searched for peaks, ensuring that one of them was not shorter than 50% of the peak height. From this we identified 1,700 stars, but the results required further visual inspection. After this review, we selected 500 stars and created a database.

As mentioned earlier, Reinhold and Arlt derived the differential rotation (DR) for 12,300 stars (from the Q1-Q14 quarters). Our results were similar and different from their catalogue. For 500 stars, DR was measured for the first time in nearly 300 stars. We analysed the star graphs and classified them by rotation type: solar and anti-solar differential rotation. We found an approximately 10% asymmetry between them, meaning that most stars rotate slower at the equator and faster at the poles. Some examples of these stars are shown below.

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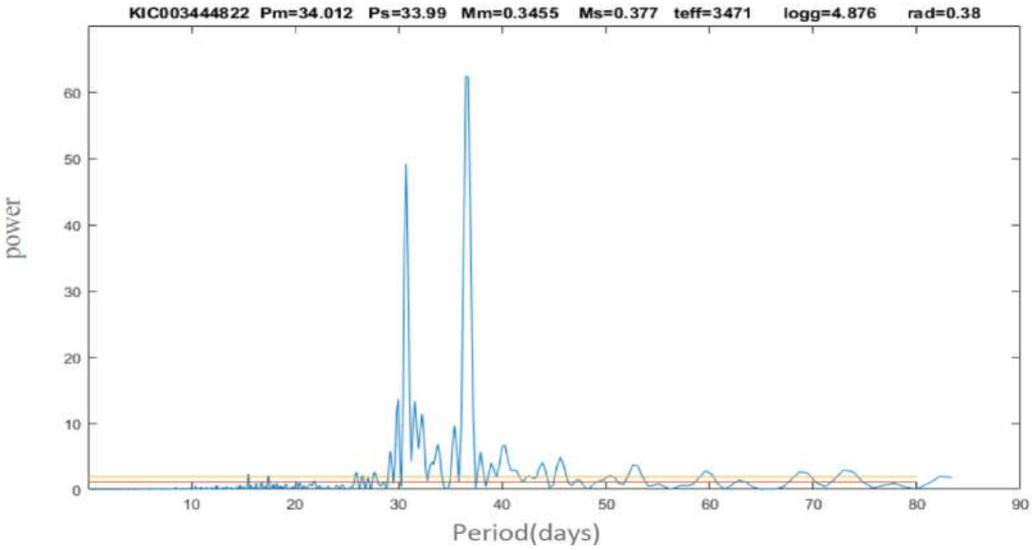

1.Solar-like differential rotation

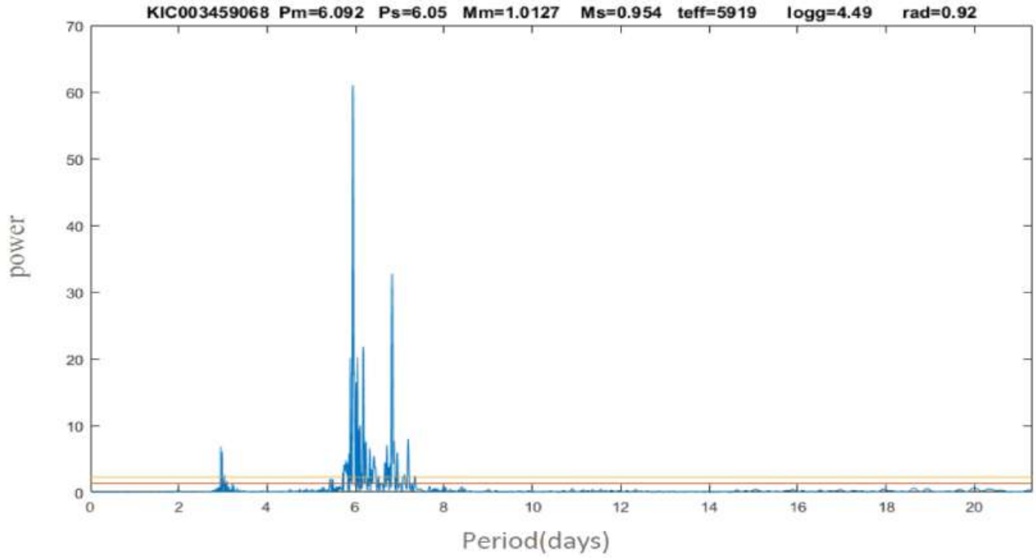

Figure 4. Differential rotation. Upper panel: solar-like and bottem panel: nti-solar

5.2. Gaussian Distribution Function Method

In the article "Surface Rotation and Photometric Activity for Kepler Targets. I. M and K Main-sequence Stars," the authors noted that the full width at half maximum (FWHM) of the periodogram's Gaussian distribution can serve as an indicator of a star's differential rotation. Based on this, we used our 25,000 stars to search for the presence of DR using this method. We wrote a program to fit a Gaussian distribution function to the stars' periodograms:

$$f(x) = a \cdot e^{-\left(\frac{x-b}{c}\right)^2} \tag{2}$$

For limits, we used the FWHM value and ensured that the fit accuracy exceeded 0.98. From the given 200 stars, we separated 10 solar-like stars (with effective temperature, mass, radius, and rotation period) and described their differential rotation.

6. Conclusion

In our research, we identified differential rotation in 500 stars using the "Two-Peak Method" and in 200 stars (including 10 solar-like stars) using the "Gaussian Distribution Function Method." From the first method, we found an approximately 10% asymmetry between solar and anti-solar differential rotation. For

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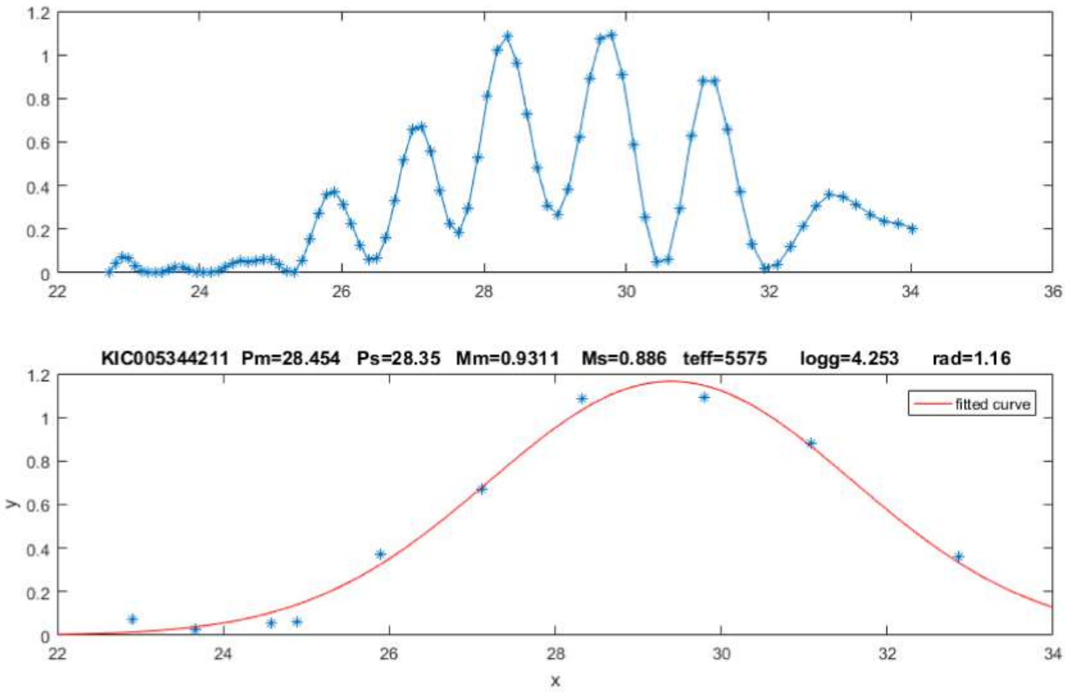

Figure 5. Period(days)

these 500 stars, DR was measured for the first time in nearly 300 stars. We also present the statistical characteristics (rotation period, temperature, radius, log g, and mass) of these stars in relation to the differential rotation coefficient. For future research, we could explore the TESS database for similar studies, particularly for faster-rotating stars. Additionally, measuring DR for early spectral classes or studying the phenomenon of anti-solar differential rotation would be valuable too.

References

McQuillan A., Mazeh T., Aigrain S., 2014, Astrophys. J. Suppl. Ser. , 211, 24

Reinhold T., Gizon L., 2015, Astron. Astrophys. , 583, A65

Reinhold T., Reiners A., Basri G., 2013, Astron. Astrophys. , 560, A4

Santos A. R. G., Cunha M. S., Avelino P. P., García R. A., Mathur S., 2017, Astron. Astrophys. , 599, A1

Santos A. R. G., García R. A., Mathur S., Bugnet L., van Saders J. L., Metcalfe T. S., Simonian G. V. A., Pinsonneault M. H., 2019, Astrophys. J. Suppl. Ser. , 244, 21

Santos A. R. G., Breton S. N., Mathur S., García R. A., 2021, The Astrophysical Journal Supplement Series, 255, 17

doi: https://doi.org/10.52526/25792776-2025.72.1-78