STELLAR MAGNETIC CYCLES IN THE SOLAR-LIKE STARS KEPLER-17 AND KEPLER-63

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ABSTRACT

The stellar magnetic field plays a crucial role in the star internal mechanisms, as in the interactions with its environment. The study of starspots provides information about the stellar magnetic field and can characterize the cycle. Moreover, the analysis of solar-type stars is also useful to shed light onto the origin of the solar magnetic field. The objective of this work is to characterize the magnetic activity of stars. Here, we studied two solar-type stars, Kepler-17 and Kepler-63, using two methods to estimate the magnetic cycle length. The first one characterizes the spots (radius, intensity, and location) by fitting the small variations in the light curve of a star caused by the occultation of a spot during a planetary transit. This approach yields the number of spots present in the stellar surface and the flux deficit subtracted from the star by their presence during each transit. The second method estimates the activity from the excess in the residuals of the transit light curves. This excess is obtained by subtracting a spotless model transit from the light curve and then integrating all the residuals during the transit. The presence of long-term periodicity is estimated in both time series. With the first method, we obtained \( P_{\text{cycle}} = 1.12 \pm 0.16 \) year (Kepler-17) and \( P_{\text{cycle}} = 1.27 \pm 0.16 \) year (Kepler-63), and for the second approach the values are \( 1.35 \pm 0.27 \) year and \( 1.27 \pm 0.12 \) year, respectively. The results of both methods agree with each other and confirm their robustness.

Key words: stars: activity – stars: magnetic field – starspots

1. INTRODUCTION

Magnetic fields comparable to that of our Sun appear in the internal regions of all cool, low-mass solar-type stars in small or higher scales (Luftinger et al. 2015). The presence of the magnetic field can affect the evolutionary stages of a star and is responsible for its magnetic activity. The evidence of the magnetic field presence is the emergence of dark spots in active regions on the stellar surface. The number of spots appearing and disappearing in the stellar disk varies in cycles. This behavior observed in the Sun shows an 11 year cycle, but it also happens in other stars.

The HK-project using the Mount Wilson Observatory, investigated hundred of stars by observing the Ca II HK lines to find stellar cycles similar to the solar case, with 52 of them showing this periodic behavior (Baliunas et al. 1995). Using the Mount Wilson data, Saar & Brandenburg (1999) also studied stellar cycles and multiple cycles. From these observations, they established the relation between stellar rotation period, \( P_{\text{rot}} \) and magnetic cycle period, \( P_{\text{cycle}} \) as a function of the Rossby number, dividing the stars into active (A) and inactive (I) branches, which were distinguished by the number of rotations per cycle and activity level. Later, several long photometric records for a significant sample of stars became available, and other studies of the stellar cycles were performed (Messina & Guinan 2002; Oláh et al. 2009; Lovis et al. 2011).

Along with the 11 year cycle of the Sun, there are other short-duration cycles, known as quasi-biennial oscillations (QBOs). Fletcher et al. (2010) found a quasi-biennial period of 2 years in the low-degree solar oscillation frequencies of the Sun after separating this signal from the influence of the dominant 11 year solar cycle. In addition, Bazilevskaya et al. (2014) reported solar QBOs with a timescale of 0.6–4 years. In other stars, some short-period variations were also reported. The first were detected by Baliunas et al. (1995) in two stars from the Mount Wilson survey: HD 76151 with 2.52 years and HD 190406 with 2.60 years. Oláh et al. (2009) found 15 stars showing multiple cycles using the analysis of Ca II emission. Using high cadence SMARTS HK data, Metcalfe et al. (2010) discovered a 1.6 year magnetic activity cycle for the solar twin \( \varepsilon \) Horologii and found two cycles in \( \varsigma \) Eridani, one of 2.95 years and a long-term cycle of 12.7 years. Egeland et al. (2015) also found a short-period \( \sim 1.7 \) year for the solar analogue HD 30495. Using \textit{Kepler} observations, Salabert et al. (2016) discovered from the analysis of frequency shifts a 1.5 year variation for the solar analog KIC 10644253, which could be a short-period or quasi-biennial oscillation.

Other techniques such as monitoring starspots can provide information on stellar cycles. Evidence of the spots can be found by analyzing planetary transits in the star’s light curve (Nutzman et al. 2011; Sanchis-Ojeda & Winn 2011; Oshagh et al. 2013). Small variations in the light curve occur because when the planet eclipses the star it may occult spots on the stellar surface, causing an increase in the luminosity during the transits. Silva (2003) developed a method to infer the properties of starspots from high precision transit photometry, such as size, position, and intensity. Here we use this model to characterize the magnetic cycle of two active solar-type stars: Kepler-17 and Kepler-63. To cross check this model, we adopted a new technique, called transit residual excess, to verify the variation of the level of activity in both stars.

This paper is organized as follows. Section 2 provides an overview of the observations for Kepler-17 and Kepler-63. Section 3 explains the first method adopted in this work, whereas the Section 4 describes the physical parameters of the modeled spots. Section 5 presents the second method and the results for the activity cycles obtained with both methods. The paper finishes with the discussions and conclusions, presented in Sections 6 and 7, respectively.
Table 1
Observational Parameters of the Stars

| KIC Number | Mass ($M_\odot$) | Radius ($R_\odot$) | Age (Gyr) | Effective Temperature (K) | Rotation Period (days) | Reference |
|------------|------------------|-------------------|-----------|---------------------------|------------------------|-----------|
| Kepler-17  | 10619192         | 1.16 ± 0.06       | <1.78 Gyr | 5780 ± 80                 | 11.89 ± 0.15           | (1), (2)  |
| Kepler-63  | 11554435         | 0.984 ± 0.035     | 0.2 Gyr   | 5580 ± 50                 | 5.401 ± 0.014          | (3)       |

References. (1) Bonomo et al. (2012), (2) Désert et al. (2011) and (3) Sanchis-Ojeda et al. (2013).

Table 2
Observational Parameters of the Planets

| KIC Number | Mass ($M_jup$) | Radius ($R_jup$) | Radius ($R_{star}$) | Orbital Period (days) | Inclination, $i$ (deg) | Semimajor axis, $a$ (au) | Semimajor axis, $a$ ($R_{star}$) | Reference |
|------------|----------------|------------------|---------------------|-----------------------|------------------------|--------------------------|----------------------------------|-----------|
| Kepler-17b | 10619192        | 2.45 ± 0.014     | 1.442               | 1.485                 | 87.2 ± 0.15            | 0.0279                   | 5.729               | (1), (2)  |
| Kepler-63b | 11554435        | <0.3775          | 0.593               | 9.434                 | 87.8 ± 0.016           | 0.081                    | 19.35               | (3)       |

Note. * Modified values to obtain a better fit of each transit light curve.

References. (1) Bonomo et al. (2012), (2) Désert et al. (2011) and (3) Sanchis-Ojeda et al. (2013).

2. OBSERVATIONS

The stars analyzed in the present work, Kepler-17 and Kepler-63, were observed by the *Kepler* satellite. This mission was responsible for collecting data of thousand of stars and planets (Borucki et al. 2010). The duration of the mission was scheduled for 3.5 years, initially scheduled to finish in 2012, but was extended to 2016 (K2 mission) (see Howell et al. 2014). The telescope has an aperture of 95 cm and explores a field of 150 deg². It was projected to discover Earth-sized planets located in the habitable zones of stars (dwarfs F to K). To keep the solar panel toward the Sun, the spacecraft needed to rotate about its axis by 90° every 93 days; this time interval is known as a “quarter.” A total of 2327 planets have been confirmed thus far, and there are 4706 planet candidates.

The light curves can be obtained from the MAST² (*Mikulski Archive for Space Telescopes*) database. The observations of the target stars were made during 16 quarters and consist of long (one data point each, 29.4 minutes) and short cadence data (~1 minute time resolution). For our study, we selected only short-cadence light curves, because we are interested in short-timescale variations, with planetary transits over the whole period of operation of the satellite.

The stars analyzed here are active solar-type stars. Kepler-17 is a G2V star with age ≈1.8 Gyr and Kepler-63 is also a young G-type star (subclass still unknown) of about 200 Myr. Both stars are accompanied by a giant planet in close orbit (a hot Jupiter): Kepler-17b has ≈2.5 Jupiter masses and an orbital period of 1.486 days (Désert et al. 2011), while Kepler-63b has ≈0.4 Jupiter masses and an orbital period of 9.434 days. During the 1240 days of observation of the *Kepler* mission, a total of 834 possible transits were detected for Kepler-17, while Kepler-63 was observed for 1400 days and 150 transits were registered. The light curves of these stars show that they are very active and marked by rotational modulations caused by the presence of starspots, with a peak-to-peak variation of 6% for Kepler-63 and 4% for Kepler-17. The active region of Kepler-17 was previously analyzed by Bonomo & Lanza (2012) who found a spot area 10–15 times larger than the solar one and evidence of a differential rotation in latitude similar to the those presented in the Sun. A study of spot evolution in this star was also performed by Davenport et al. (2015). The physical properties of the stars and their planets are shown in Tables 1 and 2, respectively.

3. SPOT MODELING

To characterize the spots, we adopted the transit model proposed by Silva (2003) which uses small transit photometry variations to infer the properties of starspots. The passage of the planet in front of the star may occult solar-like spots on the stellar surface, producing a slight increase in the luminosity detected during a short period (minutes) of the transit. This occurs because the spot is darker (a cooler region) than the stellar photosphere and causes a smaller decrease in the
intensity than when it blocks a region without spots. This effect is shown in Figure 1.

This model simulates a star with quadratic limb darkening as a 2D image and the planet is assumed to be a dark disk with radius $R_p/R_{\text{star}}$, where $R_p$ is the radius of the planet and $R_{\text{star}}$ is the radius of the primary star. For each time interval, the position of the planet in its orbit is calculated according to its parameters: inclination angle $i$ and semimajor axis $a$. The simulated light curve results from the intensity integration of all the pixels in the image for each planet position during the transit. All the simulations are performed considering a circular orbit that is null eccentricity. Applications of such a model are described in Silva (2003) for HD 209458, Silva-Valio et al. (2010), and Silva-Valio & Lanza (2011) for the active star CoRoT-2.

An example of the application of this model is shown in Figure 2 for the 120th transit of Kepler-17, where the top panel shows the fit with three spots (red curve), together with the model of a star without any spots (yellow curve). The bottom panel of Figure 2, shows the residuals from the subtraction of the spotless model, where the spots became more evident, as the three “bumps” seen in the residuals. An estimation of the noise presented in the Kepler data is given by the Combined Differential Photometric Precision (CDPP, see Christiansen et al. 2012), computed for each quarter in the light curve. We considered the uncertainty in the data, $\sigma$, as being the average of the CDPP values in all quarters. Only the “bumps” that exceed the detection limit of $10\sigma$ are assumed as spots and modeled. The modeled spots are constrained within a longitude of $\pm70^\circ$ (dashed lines) to avoid any distortions caused by the ingress and egress branches of the transit. In this region the light curve measurements are much less accurate than in the central part of the transit due to the steep gradients in intensity. The maximum number of spots modeled per transit was set to four, with an exception for only one transit of Kepler-17, where it was necessary to fit five spots.

The model assumes that the spots are circular and described by three parameters: size (in units of planetary radius $R_p$), intensity with respect to the surface of the star (in units the maximum intensity at disc center, $I_d$), and longitude (allowed range is $\pm70^\circ$ to avoid distortions of the ingress and egress of the transit). For Kepler-17, where the orbital plane is aligned with the stellar equator, the latitude of the spots remains fixed and equal to the planetary transit projection onto the surface of the star. This latitude is $-14^\circ6$ and corresponds to an inclination angle of $87^\circ84$, which was arbitrarily chosen to be South. Moreover, the foreshortening effect is taken into account for the spots near the limb. Due to the high obliquity of the orbit of Kepler-63b, the planet occults several latitudes of the star from its equator all the way to the poles.

|                | Kepler-17 | Kepler-63 |
|----------------|-----------|-----------|
| Radius ($R_p$) | 0.6 ± 0.3 | 0.8 ± 0.3 |
| Radius (km)    | $(57 \pm 28) \times 10^3$ | $(33 \pm 12) \times 10^3$ |
| Intensity ($I_d$) | 0.54 ± 0.19 | 0.47 ± 0.16 |
| Temperature (K) | 5000 ± 600 | 4800 ± 400 |
| Longitude ($^\circ$) | $-3 \pm 30$ | $-7 \pm 30$ |

Figure 2. The 120th transit from Kepler-17 illustrates a typical example of the spot fit by the model developed by Silva (2003). Top: transit light curve with the model of a spotless star overplotted (yellow). Bottom: residuals of the transit light curve after subtraction of a spotless star model. The red curve shows the fit to the data “bumps” on both panels.

Table 3: Average Values for the Parameters of the Spots
It was necessary to refine the values from the semimajor axis and planet radius taken from the literature (Désert et al. 2011) for Kepler-17b and (Sanchis-Ojeda et al. 2013) for Kepler-63b to obtain a better fit for each transit light curve. Therefore, we used 5.729 $R_{\text{star}}$ (Kepler-17b) and 19.35 $R_{\text{star}}$ (Kepler-63b) for the semimajor axis, while for the planet radius we adopted 0.0662 $R_{\text{star}}$ and 0.138 $R_{\text{star}}$, respectively (see Valio et al. 2016 and Netto & Valio 2016). These values represent 8% and 6% (radius) and 4% and 1% (semimajor axis) increase, respectively, for Kepler-17 and Kepler-63, with respect to the initial values given in (Bonomo et al. 2012) and Sanchis-Ojeda et al. (2013).

The residuals from each transit light curve were fit using this model. We performed initial guesses manually, for the longitude of the spot, $\text{lg}_{\text{spot}}$, obtained from the approximate central time of the “bump,” $t_s$ (in hours), computed as

**Figure 3.** Histograms of the spots parameters for Kepler-17: spot intensity (in units of $I_c$) (top), spot radius (in units of $R_p$) (middle), and temperature (bottom).

**Figure 4.** Same as Figure 3 but for Kepler-63.
follows:

\[ t_s = \left( 90^\circ - \arccos \left( \frac{\sin(l_i) \cos(lat)}{a} \right) \right) \frac{P_{\text{orb}}}{360^\circ} \text{24 hr} \]  \hspace{1cm} (1)

where \( P_{\text{orb}} \) is the orbital period, \( \text{lat} \) is the latitude of the spot in the stellar surface and \( a \) is the semimajor axis. The number of spots was determined a priori for each transit. For the radius and intensity, we considered initial guesses of 0.5 \( R_p \) and 0.5 \( I_c \).
The parameters for the spots are chosen from the best fit obtained by the minimization of the $\chi^2$, calculated using the AMOEBA routine (Press et al. 1992).

4. PHYSICAL PARAMETERS OF SPOTS

Using the model transit light curve proposed by Silva (2003) and described in the previous section, we analyzed each transit separately and the small variations in the luminosity detected during the transit were interpreted as the presence of a spot occulted by the planet. A total of 507 transits for Kepler-17 and 122 for Kepler-63 showed “bumps” in the light curve residuals above the adopted threshold of 10 CDPP. From the analysis of these “bumps,” we obtained a total of 1069 (Kepler-17) and 297 spots (Kepler-63) and estimated their average parameters (radius, intensity, and longitude). Furthermore, from the relative spot intensity it is possible to estimate its temperature by considering that both the photosphere and the spots radiate like a blackbody, according to the equation:

$$\frac{I_{\text{spot}}}{I_{\text{star}}} = \frac{e^{h\nu/K_B T} - 1}{e^{h\nu/K_B T} - 1}$$  \hspace{1cm} (2)

from which we obtain the temperature of the spots:

$$T_0 = \frac{K_B}{h\nu \ln (f_i (e^{h\nu/K_B T_{\text{eff}}}) - 1) + 1}$$  \hspace{1cm} (3)

where $K_B$ and $h$ are the Boltzmann and Planck constants, respectively, and $\nu$ is the frequency associated with a wavelength of 600 nm, $f_i$ is the fraction of spot intensity with respect to the central stellar intensity $I_c$ obtained from the fit, and $T_{\text{eff}}$ is the effective temperature of the star. Considering an effective temperature of 5781 K for Kepler-17 and 5576 K for Kepler-63, we found an average spot temperature of $5000 \pm 600$ K and $4800 \pm 400$ K, respectively, for both stars.
These results are summarized in Table 3. The distributions of the parameters are presented in Figures 3 and 4. In the case of Kepler-63, we can observe that the radii of the spots are between the range 0.3 up to 2.0 $R_p$. For the intensity, we have a variation from 0.1 to 0.8 $I_c$. The temperature varies from 3000 to 5400 K. The longitude varies from $-50^\circ$ to $+50^\circ$. For the other star, Kepler-17, the variation of the spots parameters are the following: 0.1–2.0 $R_p$ for the radius, 0.1–1.0 $I_c$ for intensity, 2000–6000 K for the temperature, and $\pm50^\circ$ is the range for the longitude. Note that in Kepler-17 the longitude of the spots are

Figure 9. Three-folded data of Kepler-17 for both number of spots and total flux deficit, the 410 days periodicity clearly showing.

Figure 10. Same as Figure 9 but for Kepler-63, indicating the periodicity of 460 days of the spot data.
concentrated preferentially in the center of the transit, and for this reason, there is a decrease when the values approach $\pm 70^\circ$, however, the same does not happen for Kepler-63, due to the fact that the orbit of the planet crosses several latitudes. For further details of the spot modeling, see Valio et al. (2016) and Netto & Valio (2016) for Kepler-63.

5. STELLAR MAGNETIC ACTIVITY

Our aim is to characterize the magnetic cycles of Kepler-17 and Kepler-63. For this purpose we adopted two different methods as proxies for the stellar activity: (1) number and flux deficit of the spots modeled in the previous section and (2)
estimate of the excess residuals during transits. These procedures were applied to a total of 583 transits for Kepler-17 and 131 transits for Kepler-63. Details and results from both methods are described below.

5.1. Spot Modeling

In the case of the Sun, the number of spots on the solar surface is the most common proxy of its activity cycle and displays a periodic variation every 11 years or so. Similarly, the number of spots that appears at the surface of a star varies in accordance with the stellar magnetic cycle. Thus by monitoring the number of spots during the approximately 4 years of observation of the Kepler stars, it is in principle possible to detect stellar cycles.

Another way to estimate stellar activity is by calculating the flux deficit resulting from the presence of spots on the star surface. The spots’ contrast is taken to be \(1 - f_i\), where \(f_i\) is the relative intensity of the spot with respect to the disk center intensity \(I_c\). A value of \(f_i = 1\) means that there is no spot at all. The relative flux deficit of a single spot is the product of the spot contrast and its area; thus for each transit the total flux deficit associated with spots was calculated by summing all individual spots:

\[
F \approx \sum (1 - f_i)R_{spot}^2.
\]

To the resulting flux deficit and spot number we apply a running mean over a range of five data points. Note that due to this process, the number of spots may have non-integer values. Also, to remove possible aperiodic or long duration trends in these time series, we applied a quadratic polynomial fit to the data and then subtracted it. Due to this procedure, the number of spots and the flux deficit can be negative. Figures 5 and 6 show these treated results for the number of spots (top, in blue) obtained from modeling each transit and the total flux deficit (bottom, in green) for both stars.

A Lomb–Scargle periodogram (LS; Scargle 1982) is performed on these time series to obtain the period related to the magnetic cycle. In addition, we applied a significance test to quantify the significance of the peaks from the LS periodogram. For this, we assumed the null hypothesis as: (a) there is no periodicity in the data, and (b) the noise has a Gaussian distribution, thus the periodogram power spectrum in any frequency of the data will be exponentially distributed. The statistical significance associated to each frequency in the periodogram is determined by the \(p\)-value \((p)\). The smaller the \(p\) value, the larger the significance of the peak. The corresponding values for \(p\) in critical values are given by \(z = \sqrt{(2\pi)^{-1}(1 - 2p)}\). We adopted the significance level \(\alpha\) as being \(3\sigma\ (p \pm 0.0013)\). If the \(p\) value is less than or equal to the significance level, our null hypothesis is rejected; otherwise, it is not rejected. The result of the significance test is plotted below the periodogram for each star in Figures 7 and 8. The uncertainty of the peaks in the periodogram is given by the FWHM of the peak power.

By computing the LS periodogram, it is possible to detect the existence of a periodicity in the spot number and flux deficit throughout the 4 years of observation. This result is presented...
In Figures 7 and 8, a prominent peak is seen at 410 ± 60 days (number of spots) and 410 ± 50 days (flux deficit). There is also another significant periodicity in ~414 days (f = 0.0096 days^{-1}) appearing in both cases. This peak might be a harmonic, because it is approximately four times the value of the frequency from the main peak (f = 0.0024, P = 410 days). However, as we are interested only in long-term periodicities, we adopted P_{cycle} = 410 days as being the most relevant peak for our case. This yields a magnetic cycle of approximately 1.12 year.

Kepler-63 shows a periodicity of 460 ± 60 days, taking into account the total number of spots, and 460 ± 50 days for the flux deficit as shown in Figure 8. This corresponds to a cycle of about 1.27 ± 0.16 year. There is also a strong peak at ~111 days for the total flux deficit, however this period appears at the number of spots periodogram with a very small significance, thus we do not consider this peak.

We folded the data of both spot number and total flux deficit by the dominant period obtained in the periodograms. These results are presented in Figures 9 (Kepler-17) and 10 (Kepler-63), and in both cases we obtained three periods during the time of observation of the stars (1240 days for Kepler-17 and 1400 days for Kepler-63).

5.2. Transit Residuals

The second method adopted in this work consists of subtracting from the transit light curves a modeled light curve of a star without spots. The result from this subtraction is the residual. An example of this method is shown in Figure 11 for the 100th transit of Kepler-17. An excess during the transit is clearly seen and is due to the presence of spots occulted by the planet. Next we integrated all residual excess within ±70° longitude of the star (delimited by the dashed lines of Figure 11) thus obtaining another proxy for the stellar activity. This residual excess resulting from all transits is plotted in Figure 12 and is seen to oscillate during the period of observation.

A quadratic polynomial fit was also applied to this time series and subtracted, removing any possible trends. Its LS periodogram is shown in Figure 13, where a noticeable peak is seen at 490 ± 100 days (1.35 ± 0.27 year) for Kepler-17 and 460 ± 40 days (1.27 ± 0.12 year) for Kepler-63. These periodicities show a p value below the 3σ significance level, confirming their significance. The value obtained for Kepler-63 is similar to that from the first approach, and corresponds to a 1.27 year cycle. There is also a notable peak at ~205 days (f = 0.00485 days^{-1}), but this peak does not appear in the first approach (neither for spot number or flux deficit), thus we do not consider it. The three-folded data with the obtained periodicity is shown in Figure 14 for Kepler-17 and Kepler-63. On the other hand, the cycle period estimate for Kepler-17 agrees within the uncertainty, as shown in Figure 15. All the results for the magnetic cycle obtained with the two methods are listed in Table 4.

6. DISCUSSION

We have estimated the period of the magnetic cycle, P_{cycle}, for two active solar-type stars, Kepler-17 and Kepler-63, by applying two new methods: spot modeling and transit
residual excess. The results obtained from both methods are presented in Table 4. For Kepler-63, we found the same result in the different approaches. The other star, Kepler-17, however, has a $P_{\text{cycle}}$ obtained with the second method that is within the uncertainty range from the first approach. Considering that, we confirm that the results in both methods agree with each other and assure the robustness of the methods.

Next, we compare our results to those stars, with their magnetic cycle, $P_{\text{cycle}}$, reported in the literature. The observational data from Saar & Brandenburg (1999) and Lorente & Montesinos (2005) are the records of the Ca II H&K emission fluxes of the stars observed at the Mount Wilson Observatory and also analyzed by Baliunas et al. (1995). Oláh et al. (2009) studied multi-decadal variability in a sample of active stars with photometric and spectroscopic data observed during several decades. Messina & Guinan (2002) performed long-term photometric monitoring of solar analogues. Lovis et al. (2011) took a sample of solar-type stars observed by the HARPS spectrograph and used the magnitude and timescale of the Ca II H&K variability to identify activity cycles.

Two distinct branches were reported for the cycling stars (Saar & Brandenburg 1999; Böhm-Vitense 2007): the active (blue line) and inactive (green line), classified according to their activity level and number of rotations per cycle (plotted in Figure 16). The majority of the stars analyzed by Lovis et al. (2011) fall in the inactive branch, the Sun, however, with its 11 year cycle appears in between the two branches. In Figure 16 we observe the relation between $P_{\text{cycle}}$ (stellar cycle period) and $P_{\text{rot}}$ (stellar rotation period) for all selected samples, first studied by Baliunas et al. (1996). The vertical dashed line joins data for the same star (stars with multiple periodicities detected). Kepler-63 (blue star in Figure 16) is an active star and in the rotational period-cycle relation follows the trend set by stars in the active branch. On the other hand, Kepler-17 (blue star) lies close to the inactive stars branch, but shows a cycle period quite close to the short-period cycle obtained by Egeland et al. (2015) for the active star HD 30495, of $P_{\text{cycle}} \sim 1.7$ year, $P_{\text{rot}} = 11$ days, and the one analyzed by

![Figure 15. Comparison between the peak significance obtained from the first method for the flux deficit (green) and the second method (purple). The frequency peak obtained in the second method falls inside the uncertainty from the first approach.](image)

![Figure 16. Activity cycle periods, $P_{\text{cycle}}$, vs. stellar rotation period, $P_{\text{rot}}$, for a sample of stars cited in the literature. The dashed vertical lines connect different periods found for the same stars, i.e.,: stars exhibiting two cycles.](image)

### Table 4

| Star     | $P_{\text{cycle}}$ (years) | $P_{\text{rot}}$ (days) | $P_{\text{rot}}$ (days) |
|----------|----------------------------|--------------------------|--------------------------|
| Kepler-17 | $1.12 \pm 0.16$           | $1.12 \pm 0.13$         | $1.35 \pm 0.27$          |
| Kepler-63 | $1.27 \pm 0.16$           | $1.27 \pm 0.14$         | $1.27 \pm 0.12$          |
Salabert et al. (2016) for the young solar analog KIC 10644253 ($P_{\text{cycle}} \sim 1.5$ year, $P_{\text{rot}} = 10.91$ days).

7. CONCLUSIONS

In the present work we applied two new methods to investigate the existence of a magnetic cycle: spot modeling and transit residuals excess. Two active solar-type stars were analyzed, Kepler-17 ($P_{\text{rot}} = 11.89$ days and age $< 1.8$ Gyr) and Kepler-63 ($P_{\text{rot}} = 5.40$ days and age $= 0.2$ Gyr). With the first method, we obtained $P_{\text{cycle}} = 1.12 \pm 0.16$ year (Kepler-17) and $P_{\text{cycle}} = 1.27 \pm 0.16$ year (Kepler-63), and for the second approach: $P_{\text{cycle}} = 1.35 \pm 0.27$ year (Kepler-17) and $P_{\text{cycle}} = 1.27 \pm 0.12$ year (Kepler-63). The results from both methods agree with each other, considering that the value found for Kepler-17 in the second approach falls within the uncertainty of the first method. Kepler-17 and the solar analogue HD 30495 found by Egeland et al. (2015) have a rotation period of approximately 11 days, and both show a short-cycle, which is $\sim 1.7$ year for HD 30495. However, this star also shows a long cycle of $\sim 12$ years, which agrees well with the active branch. As observed previously by Böhm-Vitense (2007), some stars that are located in the active branch could also show short cycles falling in the inactive branch. This might be the case for Kepler-17, which is also an active star, showing a spot area coverage of $6\%$, much higher than the Sun, where it is less than $1\%$, and may also have a long cycle periodicity. Unfortunately, as we are constrained by the period of observation ($\lesssim 4$ years) of the Kepler telescope, it is not possible to investigate if Kepler-17 has a longer cycle. On the other hand, $P_{\text{cycle}}$ of the young star Kepler-63, fits well within the active stars branch. Moreover, Metcalfe et al. (2010) found a 1.6 year magnetic cycle for the exoplanet host star $\iota$ Horologii observed during 2008 and 2009, which seems to be in between Kepler-17 and Kepler-63 in the cycle–rotation relation.

The intensity of a magnetic field is controlled by the dynamo process and associated with differential rotation. Our analysis to identify activity cycle periods is essential for a deep investigation about how stellar dynamos work. Böhm-Vitense (2007) and Durney et al. (1981) suggest that the two branches of stars in the $P_{\text{rot}}$–$P_{\text{cycle}}$ diagram are possibly ruled by different kinds of dynamo, exhibiting different ratios for $P_{\text{cycle}}/P_{\text{rot}}$. In addition, Böhm-Vitense brings up that the active branch can be driven by a dynamo operating in the near-surface shear layer, while in the inactive star branch, the shear layer of the dynamo is located at the base of the convection zone. This combination between the analysis of the time variation in the stellar activity and the stellar rotation periods can also be crucial to determine the differential rotation rates of the star, which is fundamental to generate the magnetic field in the stellar interiors. All these findings indicate that activity cycles play a key role in understanding the evolution of stars.

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