Monitoring the Behavior of Star Spots Using Photometric Data

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Abstract. We use high accuracy photometric data to monitor the behavior of star spots. We develop an algorithm to determine the size and longitude of spots or spot groups, using *Kepler* light curves. Our algorithm separates the light curve in rotational-period sized intervals and calculates the size and longitude of the star spots by using limb darkened spot crossing models. The results can then be used to identify populations of spots, active regions on the stellar surface, mean spot lifetimes or even evidence for activity cycle evidences. To check the efficiency of our code we calculate the spot positions and sizes for the planet host star Kepler-210.

1. Introduction

The launch of the space missions *CoRoT* (Baglin et al. 2006) and *Kepler* (Koch et al. 2010) with their high accuracy and long, non-interrupted measurements revealed that many field stars display pseudo-periodical modulations in their flux, which most probably are caused from star spots on their surface. A famous object with activity modulations of ∼4% is the host star of the CoRoT-2 b planet (Alonso et al. 2008).

In contrast to *CoRoT*, the *Kepler* mission, has allowed the almost continuous observation of more than 200000 stars for a time span of about four years.The study of the activity modulations for such long time can reveal stellar properties as the rotational period and flux variabilities, the size of which is analogous to the size and life time of spots on the stellar surface. Also one should be able to directly observe other characteristics which, until recently, could only to be observed on the Sun, i.e., differential rotation.

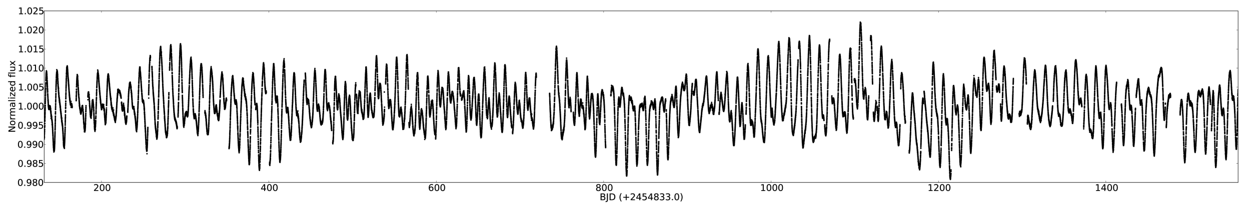

Figure .1: The complete lightcurve of the Kepler-210 (1400 days), normalized and with the planetary transits excluded.

2. Data and Analysis

2.1 Stellar data

For our study we use the Kepler-210 system which consists of a K dwarf star with at least two planets orbiting it (Ioannidis et al. 2014). The 1400 days long light curve of Kepler-210 shows modulations with amplitude of 2%, as shown in Figure.1. From the full lightcurve we construct a Lomb-Scargle periodogram (Fig. .2:a) and identify the largest peak at 12.330 days as the rotational period of the star. Clearly, the Lomb-Scargle diagram shows evidence for power on other time scales which we would like to explore. We next phase-fold the actual lightcurve (as shown in Fig. .2:b) with the period of 12.330 days. As is clear from Fig. .2:b the the star has an active longitude between phases 0.5 to 0.9, however there is clearly substantial variability and no two lightcurves from adjacent rotations are identical, thus the lightcurve is in continuous change.

2.2 Method

In order to describe light curve changes we consider 12.33 days chunks of the overall light curve (cf., Fig..1) separated by a quarter rotation period, i.e., the light curves we consider are not independent. Each such light curve is modelled with a five spot model (Fig..3), based on the three spot model which was introduced by Lanza et al. (2003). We assume dark circular spots, as the shape and temperature can easily be calibrated later by increasing the values of radius. In the same fashion, the latitude of the spots is considered equal to zero degrees as it is also strongly correlated to the covered surface. Due to the fact that Kepler-210 is a system and taking additionally in account the size of the modulations, we feel secure to assume that the stellar inclination is $\simeq 0°$, thus there no should be no significant circumpolar regions.

The need for the extra two spots in the model came after the realization that the modulations are not stable enough, from one rotation to another (Fig..2:b) so none of the light curve chunks are identical and therefore that combined model of three spots is not able to cover correctly the edges of each phased light curve. To address this we added two more spots, running for longitudes $\leq 90°$ and $\geq 270°$. Here it is important to mention that the role of those two spots is strictly auxiliary and their calculated values are not taken in account for our later results. Two adjacent light curve chunks are correlated as they share 75% of their data points, however, the estimation of the longitude for each spot is done more than once improving statistically the results.

We use a MCMC (Marcov-Chain Monte-Carlo) approach to estimate the size and the longitude of each spot. Since the star is always covered with spots, it is impossible to know the correct normalization of the lightcurve, thus the algorithm also estimates the normalization. With the five pairs of longitudes and sizes, plus the normalization factor, our algorithm is using 11 free variables.

In Fig..3 we show a typical fit to one of our light curves. One can immediately identify the models for spots #3, #4 and #5. Spot #1 cannot be not seen as it is covered under the combined model (thick red line). It is obvious that without spot #1, which does not share the same characteristics with spot #5, the section of the light curve with <947.5 BJD (+2454833.0) would have been impossible to cover. Thus as a result, we obtain for each chunk (379 light curves in total) the sizes and longitudes of the assumed equatorial spots assumed to be causing the observed modulations. Finally, in order to check the validity of our results we used the results of the 9 fixed spot model suggested by Huber et al. (2009). Our tests showed that we obtain identical results using both methods, although our method yields the longitudes of the spots with better accuracy.

3. Results

In Fig..4 we show the results of our spot analysis on Kepler-210, where we show the positions of the modelled spots (on the x-axis) vs. time (on y-axis). The color-coded plot shows the phase-folded lightcurve (as in Fig..2), and the calculated spot longitudes are over-plotted at the appropriate spot longitudes. The size of each dot represents the calculated size of the spot. The calculation of the star spot sizes and longitudes shows some interesting features in the behavior of the spots on Kepler-210. First, there is the obvious preference in the spot longitudes, while other surface areas remain more or less spot-less. Using our algorithm we calculated that there is an area of about 100 degrees in longitude that it is covered by spots only during 20% of the total observation time.

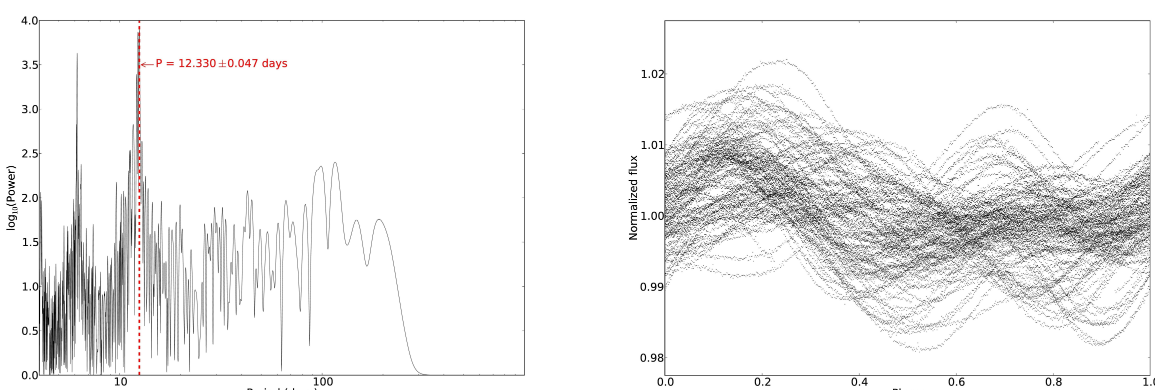

Figure .2: a: The Lomb-Scargle periodogram result. b: The lightcurve phase folded with the period of 12.33 days.

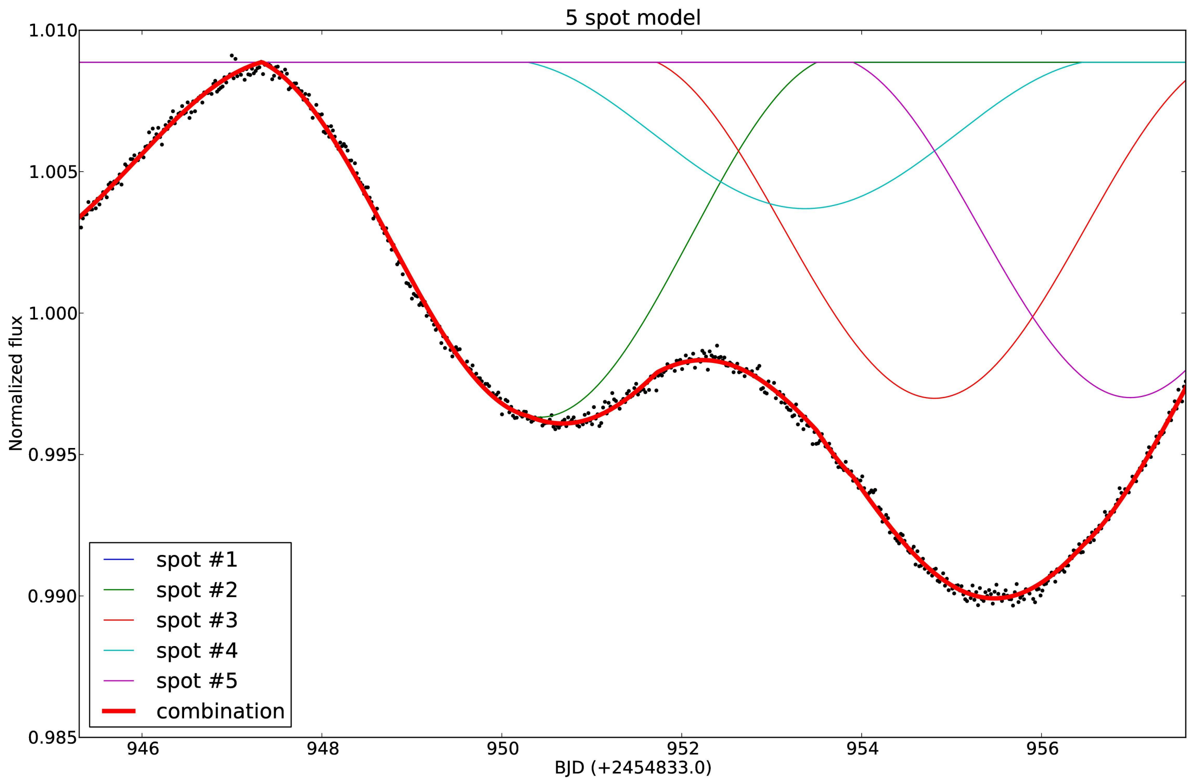

Figure .3: Visual representation of the 5 spot model. Each of the thin colored lines represents the flux reduction caused from each of the spots during a full rotation. The combined flux reduction is given from the aggregation of the five spots models (thick red line).

Second, as one can see in Fig..4 the calculated positions of the spots show relative motions between the different active regions. This can be taken as evidence for differential rotation, although we are not ready to confirm that yet. The calculation of the spot sizes shows the spot coverage of the star is not stable. While we are far away from claiming any cyclic variations, we observe a variation with amplitude 2% and a period of 600 days. Finally one can identify that there is formation of spots in areas which were empty before and disappearance of others.

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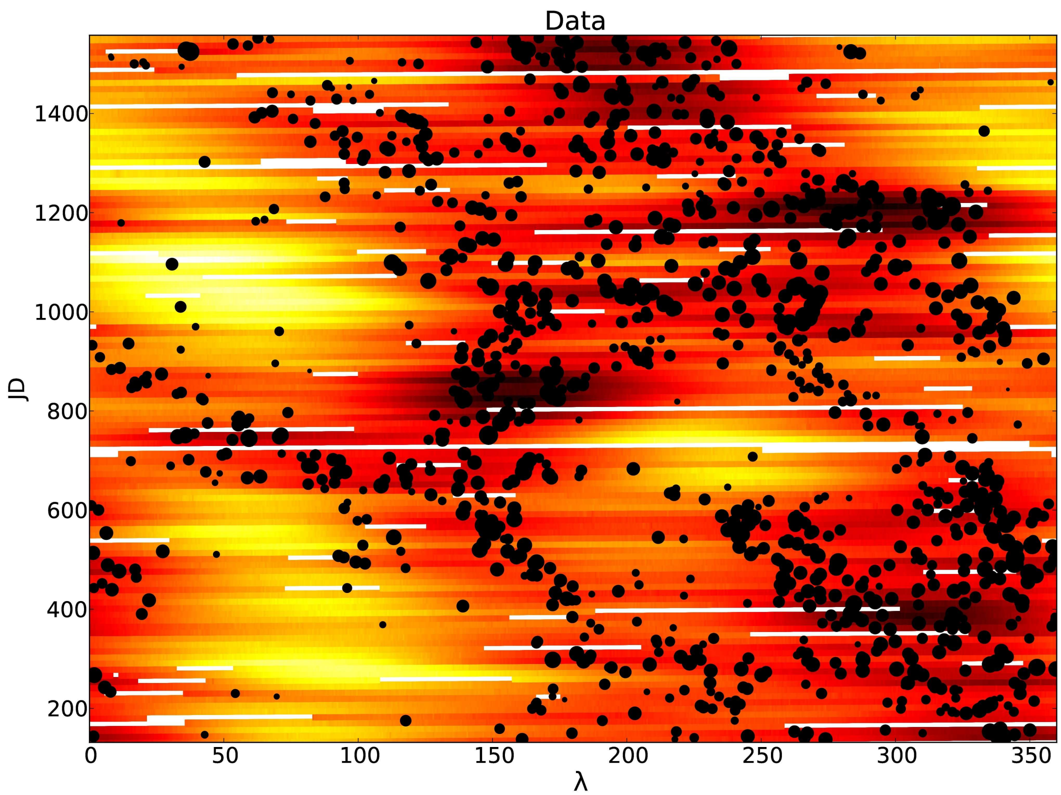

Figure .4: The phase folded data, with over-plotted the calculated spot longitudes.

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