Kepler - 411 stellar activity from the modeling of planetary transits.

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Abstract

Kepler-411 is a K2V-type star with an average rotation period of 10.52 days, radius of 0.79 Rsun and mass of 0.83 Msun. This active star has at least four planets, three of them eclipse the star, the three larger planets are mini Neptunes with radii of 2.2, 3.47 and 3.46 Earth radii, and periods of 3.0, 7.8 and 58.0 days, respectively. This star was observed by the Kepler satellite for about 600 days showing a total number of 195 transit for planet Kepler-411 b, 76 transits Kepler-411c and 10 transits for planet Kepler-411d. When a planet transits its host star, it may occult a spot causing a detectable signal in the light curve. In this work we apply the model described in Silva (2003), to characterize the starspots, which resulted in the detection of a total of 45 spots in Kepler-411b, 143 spots in Kepler-411c transits and 10 spots in Kepler-411d transits. Analysis of the spots detected on the different transit latitudes of these planets yields a differential shear of 0.050 rd/d or a relative differential rotation of 8.3%, assuming a solar like rotation profile. Also, a total of 66 flares and superflares were detected on the light curve. Here, we discuss the relationship between the size and temperature of the starspots with statistical data on flares and superflares.

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Introduction

Flares usually occur in the Sun in association with sunspots or groups of spots. Other stars are also believed to exhibit spots. The intensity and frequency of these spots decrease over the life of a star, due to angular momentum loss identifying its effect on the stellar dynamo. Understanding the relationships between flares and starspots is extremely important, as these processes drastically impact the planetary, atmospheric, and biological environment. As a consequence, it can affect the habitability of exoplanets.

Model

Spots on the surface of the Kepler-411 star were modeled based on the following parameters: size, intensity, and location (longitude and latitude). The starspot is modeled as a circular disc and it was possible to obtain:

- The size of the spot in the planetary radius units (Rp);
- Intensity: intensity of the spot with respect to the brightness of the stellar disc center;
- Position: longitude and latitude on the star disc.

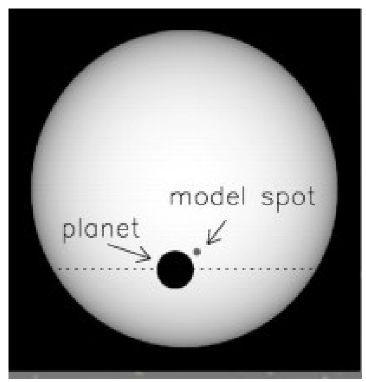

Figure 1 – Synthetized image of a star with limb darkening with a spot, and a planet represented by a dark disc of radius Rp/Rs on a circular orbit. The dashed line shows the planetary orbit according to the model.

Parameter	Kepler-411 b	Kepler-411 c	Kepler-411 d
Radius[Rj]	0.168	0.292	0.296
Semi major axis[AU]	0.0375	0.0739	0.279
Inclination(°)	87.4	88.61	89.43
Orbital Period [d]	3.0051	7.83442788	58.02035
Latitude(°)	-11.06	-21.6	-49.2

Table 1 – Parameters of the three exoplanets Kepler-411b, Kepler-411c, and Kepler-411 d.

Analysis

Kepler-411 was observed by the Kepler satellite for about 600 days showing a total number of 195 transits for planet Kepler-411b, 76 for Kepler-411c, and 10 transits Kepler-411d. The planetary transit model was applied to the star Kepler-411 having resulted in the detection of a total of 45 spots in the transit light curve of Kepler-411b, 143 spots in Kepler-411c transits, and 10 spots for Kepler-411d. The characteristics of the spots are shown on Figure 3.

The spots were separated into three latitude bands, according to the orbit inclination and semi-major axis of each planet. For each latitude band, a 1D map of the stellar surface was built for each transit assuming a rotation period (Figure 2). By observing the same spot at the same longitude on subsequent transits allowed us to determine the rotation period in each of these latitude bands. Then, a solar like profile of differential rotation was fit, and the result was surprisingly similar for latitudes from -11° to -49°, yielding a rotational shear of 0.05 rd/d.

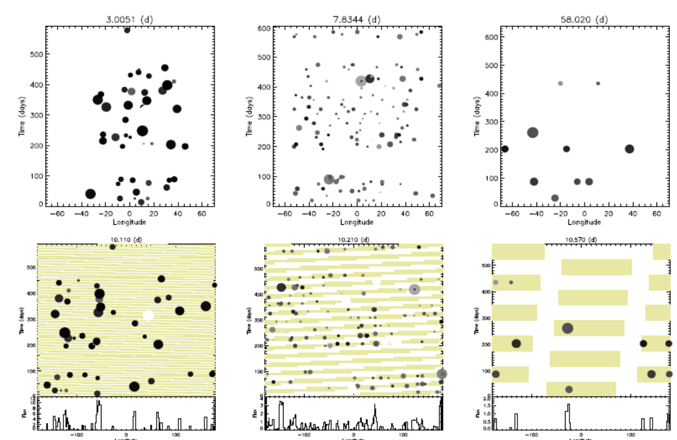

Figure 2 - Surface map of Kepler-411 for the latitude band between -26° and -16°.

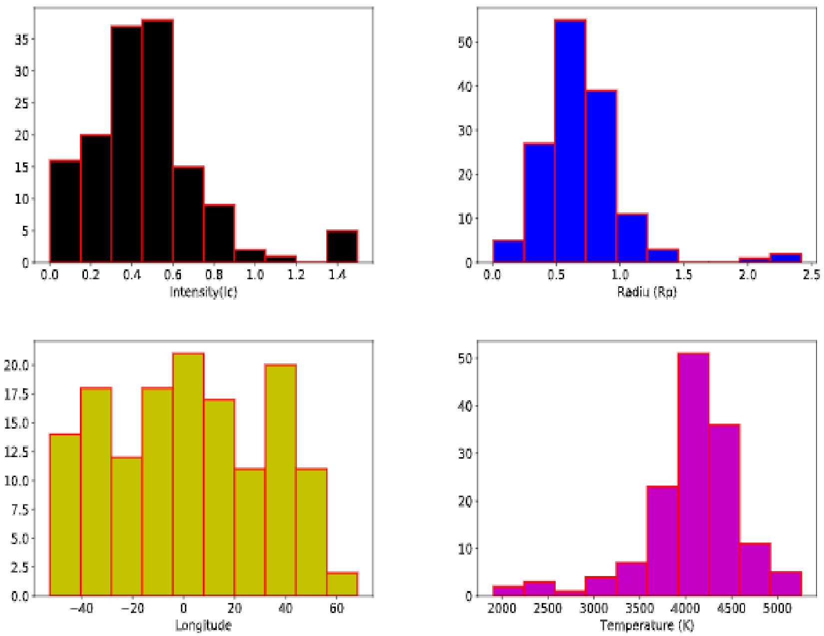

Figure 3 - Histograms of Kepler-411 spots. Upper right panel: Radius in Rp units; Top panel: intensity in Ic units; Lower panel: Longitude of spots; Right Bottom panel: Temperature of the spots in Kelvin.

Lomb-Scargle periodogram

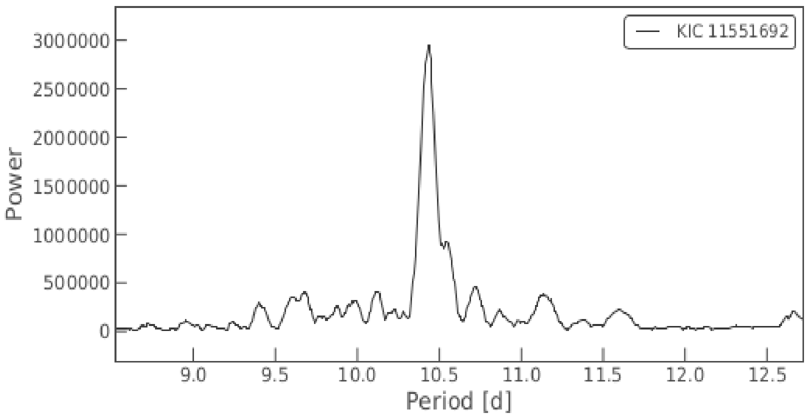

Figure 4 – Lomb-Scargle periodogram shows a strong peak at 10.52 days, that is taken as the average rotation period of the star.

Rotation profile of stars

Rotation profile with latitude of solar-type:

$$\Omega = A - B \sin2 (\alpha)$$

Where the rotation period is $P = 2\pi/\Omega$. The constants A and B are obtained fitting the measured periods at the transit latitudes:

Planet	Latitude (º)	Period (d)	Ω (rd/d)
Kepler-411b	-11.06	10.11	0.621
Kepler-411c	-21.63	10.20	0.616
Kepler-411d	-49.26	10.57	0.594

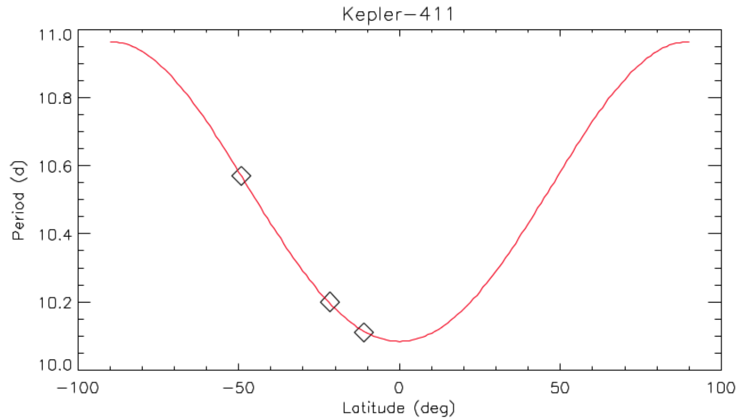

Figure 5 - Differential rotation of Kepler-411.

Kepler-411 is orbited by 3 planets, the two larger ones are smaller than Neptune, where as the smaller one is a Super-Earth. Their orbits are such that they transit their host star in three different latitudes: -11º, -21º and -49º. Spots were identified on the transits of all planets and the transit modelling method of Silva (2003) applied. By identifying the same spot on a later transit, it was possible to estimate the rotation period of the star at that latitude. Combining the rotation period at the three planet crossing latitude, and assuming a solar like differential rotation profile, we concluded that Kepler-411 has a solar like rotation with a 0.050 rd/d shear and a relative differential rotation of 8.3%.

Flare energy

Superflares are very energetic explosions, with bolometric energy released from 10^{33} to 10^{36} erg. This is 10 to 10^4 times greater than the largest solar flares (10^{32} erg). In this work, we analyzed the Kepler-411 light curves in a short cadence data (1 min) searching for flares. The energy was estimated as described in Shibayama et al (2013). The objective was to find possible correlations between flares and the star surface covered by starspots, modeled through the planetary transit model. As a result, we detected 66 flares and 195 spots. From the temporal correlation between flares and the presence of spots detected in the light curves during planetary transit, we conclude that the frequency of flares decreases as there are fewer spots on the surface of the star for a given latitude.

$$L_{flare} = \sigma_{SB} T^4{}_{flare} A_{flare} \quad A_{flare} = C_{flare} \pi R^2 \frac{\int R_\lambda B_\lambda(T_{eff}) d\lambda}{\int R_\lambda B_\lambda(T_{flare}) d\lambda} \quad E_{flare} = \int_{flare} L_{flare}(t) dt.$$

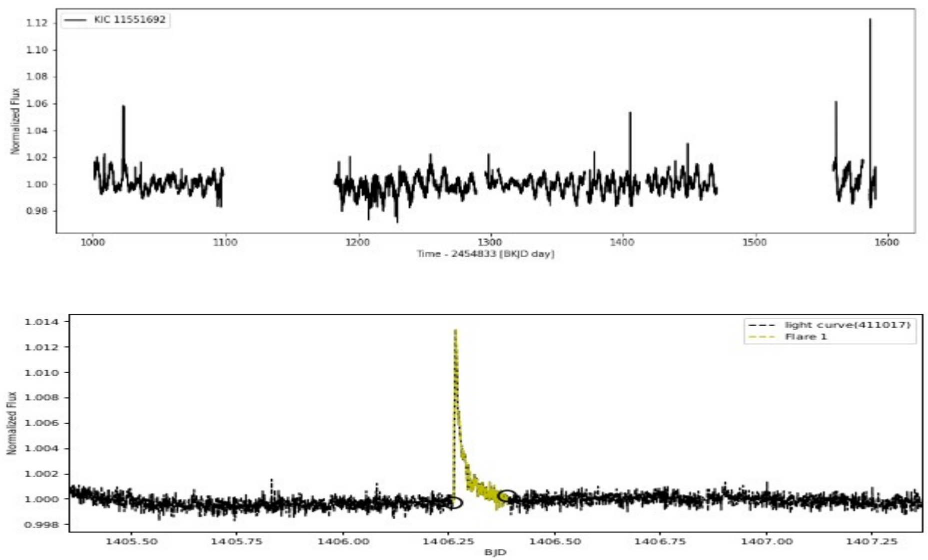

Figure 6 – Light Curve Kepler-411 and Flare Kepler-411.

LC	Start	Stop	Duration (min)	Risetime (min)	Decaytime(min)	Energy(erg)	Peaktime	Peakflux
607	1002.94787	1002.95809	14.71185	4.90381	9.80804	2.48167e+33	1.00416	1002.95128
607	1010.87115	1010.88136	15.69256	4.90427	10.78829	6.34905e+33	1.00366	1010.87796
607	1015.73421	1015.74034	8.82710	4.90347	3.92363	1.15983e+33	1.00149	1015.73762
607	1023.34891	1023.41226	91.21276	1.96129	89.25147	1.62051e+34	1.03450	1023.35028
607	1025.30095	1025.31116	14.71160	4.90431	9.80728	2.34295e+33	1.00258	1025.30435
607	1028.49939	1028.50824	12.75023	3.92336	8.82686	1.95858e+33	1.00242	1028.50211
607	1030.60466	1030.61897	20.59639	3.92320	16.67319	3.33449e+33	1.00227	1030.60739
404	1045.75160	1045.76454	18.63485	2.94240	15.69245	3.38343e+33	1.00149	1045.75364
404	1047.35150	1047.37057	27.46175	2.94225	24.51950	5.38433e+33	1.00324	1047.35354
404	1050.97153	1050.98719	22.55799	2.94225	19.61574	4.00240e+33	1.00511	1050.97357

Table 2 -Statistical values for the first 10 flares

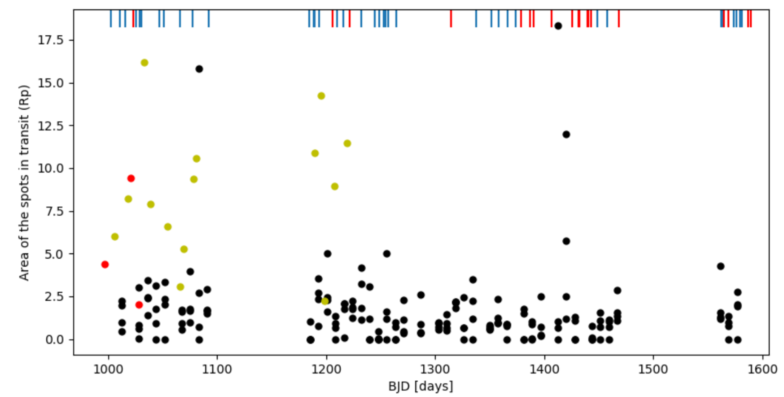

Figure 7 - Temporal distribution of spots and flares. Blue lines (10^{33} erg energy flares) Red lines (10^{34} and 10^{35} erg energy flares) .

Conclusion

In this poster we present a study of stellar activity Kepler-411. We carried out the modeling of stellar spots from planetary transits and estimated the stellar differential rotation. We identified 198 stellar spots and detected 66 stellar flares. In the temporal distribution of stellar spots and flares, we observed that flares with energy between 10^{34} erg and 10^{35} erg are more frequent with the presence of stellar spots with a larger area.

Reference

Silva, A. V. 2003, ApJL, 585, L147

Shibayama T. et al. Superflares on solar-type stars observed with Kepler. I. Statisticalproperties of superflares,The Astrophysical Journal Supplement Series, 2013,vol. 209, p. 5