Modeling starspots on low mass star GJ 1243 observed by TESS

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Abstract
Quasi-periodic modulations of the stellar light curve may result from dark spots crossing the visible stellar disc. Since the release of the first TESS sector the possibility of examining such quasi-periodic modulations by assumed dark spots has increased. Thanks to this observations we tried to detect starspot coverage of low mass stars with visible variability of their luminosity. Using the light curves from TESS satellite and the new, BASSMAN package to fit spot models of different complexities, will constructed starspots distribution on individual stars. These models will then be tested to reveal a connection between the starspots and the stellar flares, in order to provide insight into the overall stellar magnetic field. Here we present results of modeling of starspots on GJ 1243 with our new tool and compare the results with the previous reconstructions of the spatial distribution.

Introduction

GJ 1243 (also known as TIC273589987) is fully convective M4.0V dwarf at a distance 11.95 pc, with mass 0.24 $M_\odot$, radius 0.27 $R_\odot$, effective temperature 3261 K (MAST catalog[1]) and rotation period equal P = 0.592596 ± 0.00021 day [1]. GJ 1243 also has estimated differential rotation parameter of equal 0.012 ± 0.002 rad/day [1] (for the Sun $\alpha_\odot = 0.2$ rad/day). This star was observed only during two, lasting ~27 days periods, namely TESS sectors 14 and 15. We selected 33433 individual brightness measurements (with 2-minute cadence) acquired over approximately 47 days of observations. Due to very low differential rotation shear and very slow changes of the minimal flux phase mainly in sector 15 (Fig. 1) we estimated spottedness of each sector separately without taking differential rotation into account. Small changes in phase of minimal flux of GJ 1243 are more likely caused by evolution of one of the spots than the differential rotation. There are no significant changes in phase of maximal flux value. In our analysis we assumed inclination $i = 32^\circ$ estimated by analysis of spectral observations of this star at wavelengths from 3600 Å to 10000 Å and Kepler long cadence data [11]. We estimated the amplitude of GJ 1243 normalized flux as 1.00741 by phasing the light curve from sector 14 and 15 and taking the maximal value of averaged phased data.

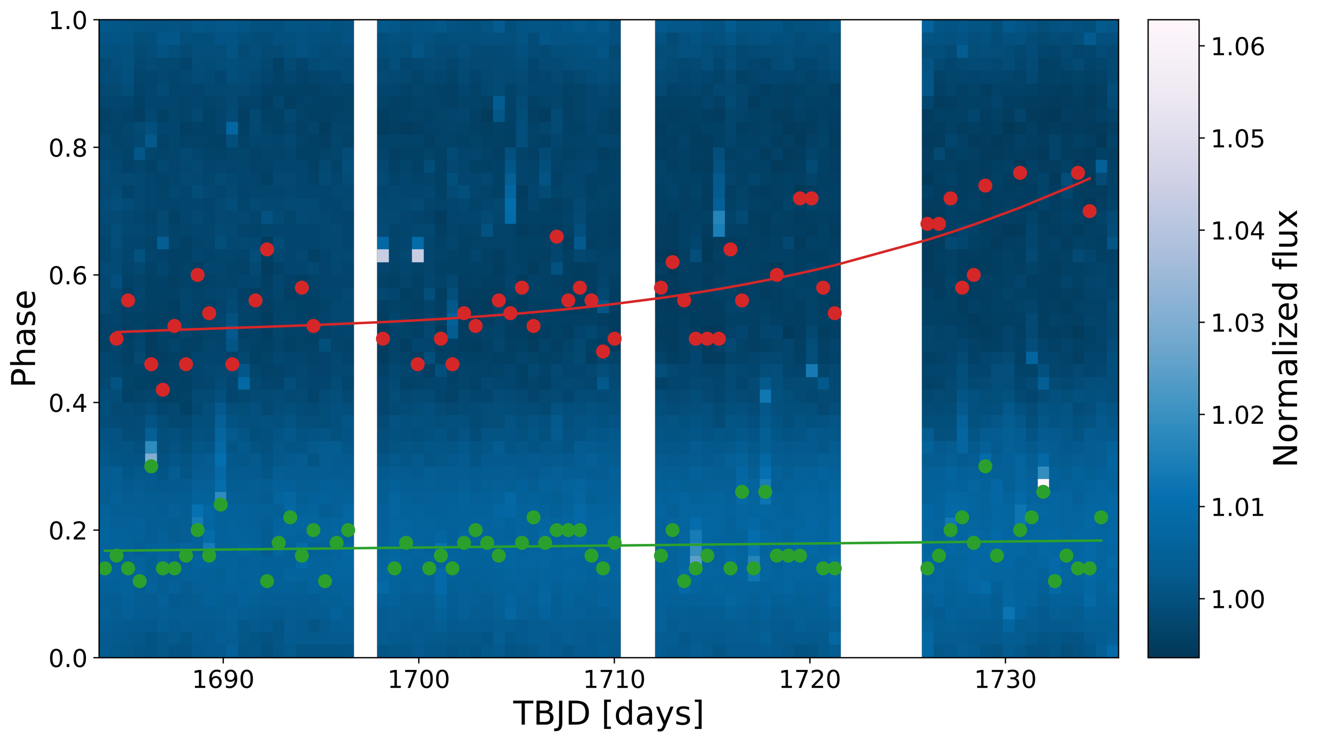

Figure 1: Mapping of relative flux (pixel shade, from dark to light) as a function of rotation phase and time for all TESS data of flux vs. time and phase. Red dots with fitted third degree polynomial represent minimal signal in phases and green dots with fitted linear function represent maximal signal in phase.

Methods

To model starspots on analysed star we used software BASSMAN (Best rAndom StarSpots Model calculAtioN) written in Python 3, by K. Bicz and designed to model starspots on stellar surface using its observational light curve. BASSMAN recreates light curve of spotted star by fitting spot(s) model to data maximising the log probability of star with spots model and is sampling matched model using Markov chain Monte Carlo by fitting contrasts, sizes, stellar longitudes and latitudes of spot(s). The program uses numerous ready-made software packages to model the spots on the star: starry [4], PyMC3 [7], exoplanet [3], theano [12].

We compare our results with analytical solution for average temperature of the spots on a star with effective temperature $T_{\rm eff}$ using [6]:

$$T_{\rm spot} = 0.751 T_{\rm eff} - 3.58 \cdot 10^{-5} T_{\rm eff}^2 + 808 \quad (1)$$

and to estimate percentage of stellar surface covered by spots we use [5, 10]:

$$\frac{A_{\rm spot}}{A_{\rm star}} = 100\% \cdot \frac{\Delta F}{F} \left[1 - \left(\frac{T_{\rm spot}}{T_{\rm eff}}\right)^4\right]^{-1} \quad (2)$$

where $(\Delta F/F)$ is normalized amplitude of light variations, $T_{\rm spot}$ is mean temperature of spots estimated from equation 1 and $T_{\rm eff}$ is effective temperature of the star.

Results

For each sector using BASSMAN we received similar two-spots models that are presented in Table 1 and 2 (and Fig. 2 for sector 15).

Sector 14 of observations of GJ 1243 lasted 26.85 days (18289 observational points), from TBJD 1683.3562 to 1710.2063 (with an observational gap between TBJD 1696.3910 - 1697.3466). The result we obtained in sector 14 is two spots model with spots separated by 235° in longitude (or by 0.64 in phase) with average spot temperature

Table 1: Variations of parameters of spots on GJ 1243 observed in sector 14.

Spot number	Contrast [%]	Size [%]	Temperature [K]	Latitude [deg]
1	0.3	1.60	2863 ± 345	31
2	0.5	1.80	2733 ± 464	0

Sector 15 of observations of the star lasted 26.04 days (15145 observational points), from TBJD 1711.3675 to 1737.4116 (with an observational gaps between TBJD 1721.8090 - 1724.9437 and 1735.6616 - 1737.0672). The result we obtained in sector 15 is two spots model where spots are separated by 245° in longitude (or by 0.67 in phase). Figure 2 presents locations, sizes and contrasts of spots in sector 15.

[1] http://archive.stsci.edu

Table 2: Variations of parameters of spots on GJ 1243 observed in sector 15.

Spot number	Contrast [%]	Size [%]	Temperature [K]	Latitude [deg]
1	0.4	1.96	2882 ± 353	14
2	0.6	1.90	2666 ± 557	2

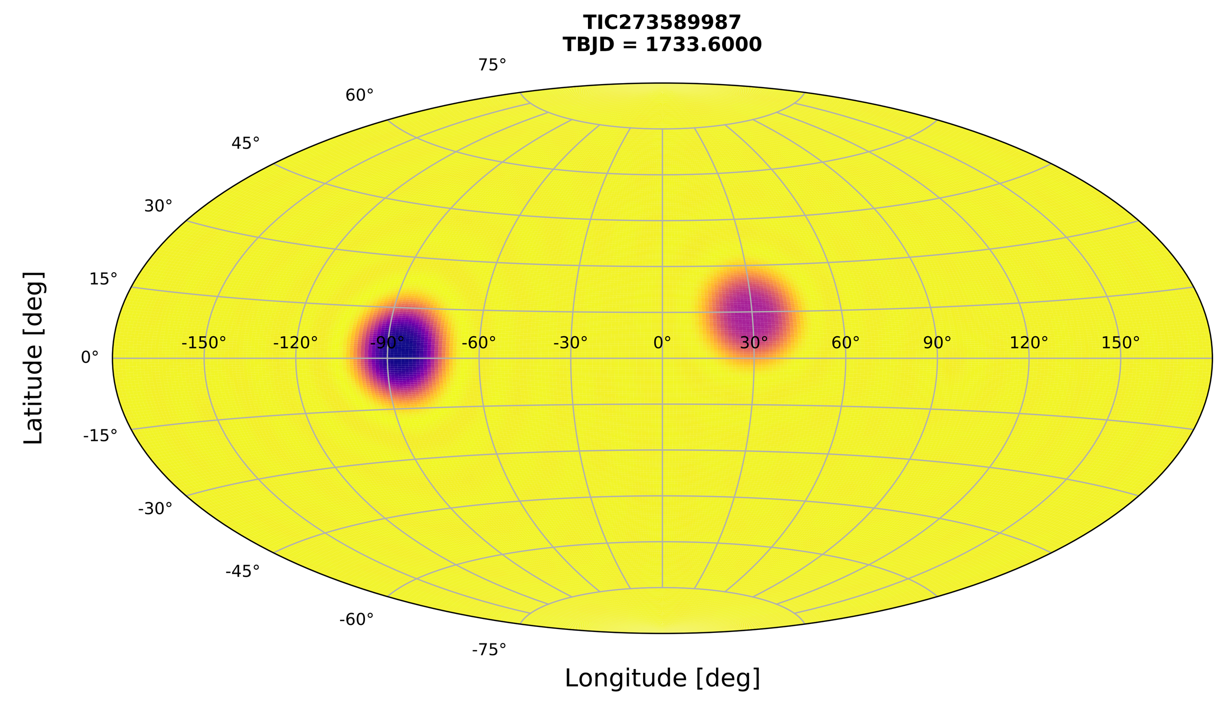

Figure 2: Locations, sizes and contrasts of spots on GJ 1243 in sector 15 for Aitoff projection.

Recreated spots temperatures and sizes (Table 3) fits quite well to analytical estimations received using equation 1 and 2, and is quite similar to the model obtained by [8, 9] with two spots on latitudes between -30° and 30° and separated by approximately 200°. This fits also to observations where GJ 1243 has 2 spots but only one slowly evolving [1]. Our results also fit to [2] where it was claimed that the spots had to evolve since the observations of Kepler, because they do not fit to the model obtained by analysing light curve from Kepler. Our model shows that one spot has not evolved since observations of Kepler but the second spot became near-equatorial.

Table 3: Comparison of analytically estimated spots parameters and received in modeling spots parameters on GJ 1243.

Sector number	Analytical temperature [K]	Model mean temperature [K]	Analytical spots size [%]	Model spots size [%]
14	2876 ± 86	2796 ± 395	3.08	3.4
15	2876 ± 86	2782 ± 470	3.21	3.86

Subtracting model of rotational modulation of the star from observations of sector 14 and 15 (Fig. 3) allowed us to improve automatic detection of flares. Our detection sensitivity increased by 15.5% (from 58 flares to 67 flares). This increase can help in better analysis of flares on GJ 1243 without confusing them with some rotational modulation effects.

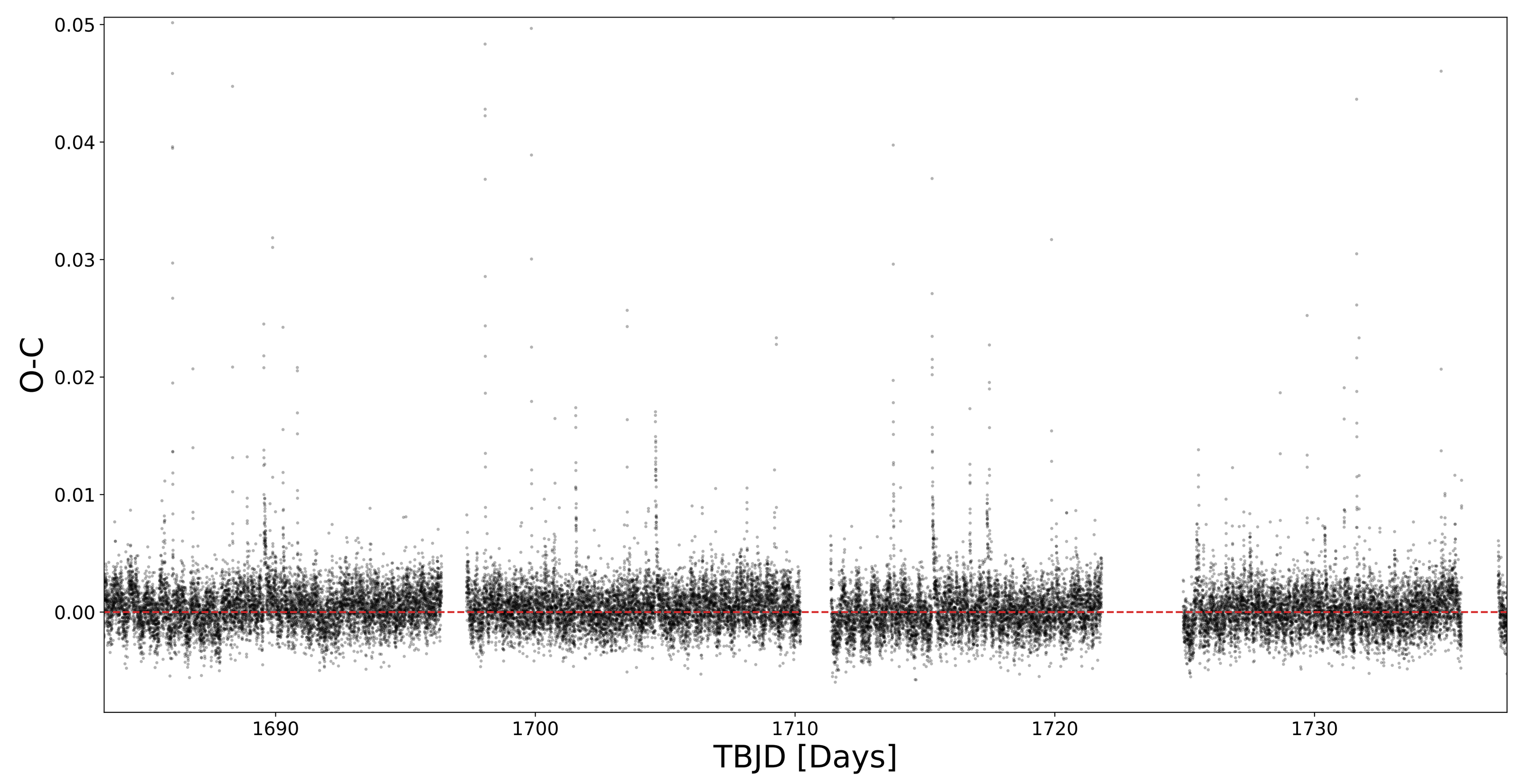

Figure 3: GJ 1243 light curve (sector 14 and 15) corrected for rotational modulation. Red dashed line presents zero level.

References

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