Modeling starspots on low mass star YZ CMi 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 YZ CMi with our new tool and compare the results with the previous reconstructions of the spotedness of this star.

Introduction

YZ CMi (also known as TIC266744225) is fully convective M4.0Ve dwarf with strong dipolar magnetic configuration with spot activity on its surface (with possible polar spots in the past [7]) at a distance 6 pc, with mass 0.31 $M_\odot$, radius 0.33 $R_\odot$, effective temperature 3181 K (MAST catalog[1]) and estimated rotation period equal P = 2.7726 ± 0.0000017 day (rotation period error was estimated using PEC (Period Error Calculation) presented by [6]). YZ CMi also has estimated differential rotation parameter of equal 0.049 ± 0.043 rad/day [7]. That small value of differential rotation parameter combined with long rotation period with short observation period of this star by TESS (24.4540 days in sector 7 and 24.9801 days in sector 34), allowed us to estimate spottedness without taking differential rotation into account. In our analysis we assumed inclination i = 60° estimated by [8]. We estimated the amplitude of YZ CMi normalized flux as 1.01904 (Fig. 1) by phasing the light curve from every available sector and taking the maximal value of averaged phased data. We analysed every sector of observations (sector 34 was observed 713 days after sector 7) separately due to drastic change in the light curve (Fig. 1) caused by evolution of spots[2] on surface of this star. Figure 1 also shows that in sector 7 the spotedness of YZ CMi can be higher than in sector 34 due to lower value of minimal flux and also distribution of spots on star's surface in sector 7 is much simpler than in sector 34 due to much more symmetrical light curve.

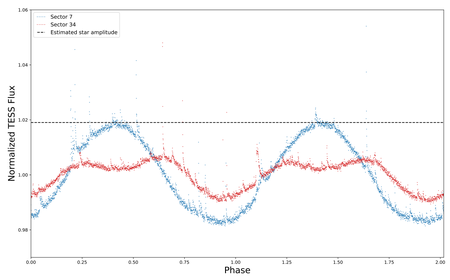

Figure 1: Comparison of light curves of observations of YZ CMi by TESS from sector 7 (blue dots) and sector 34 (red dots) with estimated amplitude of the star (black dashed line).

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 [5], PyMC3 [11], exoplanet [4], theano [13].

We compare our results with analytical solution for average temperature of the spots on a star with effective temperature $T_{\rm eff}$ using [10]:

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

and to estimate percentage of stellar surface covered by spots we use [9, 12]:

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

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

Sector 7 of observations of YZ CMi lasted 24.454 days (16326 observational points), from TBJD 1491.6372 to 1516.0912 (with an observational gap between TBJD 1503.0428 and 1504.7108). The result we obtained is three spots model with spots separated by 70° and 73° in longitude from the middle spot (or by 0.19 and 0.2 in phase) (Fig. 2). Parameters of spots are presented in Table 1.

Table 1: Variations of parameters of spots on YZ CMi observed in sector 7.

Spot number	Contrast [%]	Size [%]	Temperature [K]	Latitude [deg]
1	0.33	4.47	3094 ± 127	4
2	0.53	2.51	2824 ± 381	40
3	0.34	2.51	2949 ± 248	30

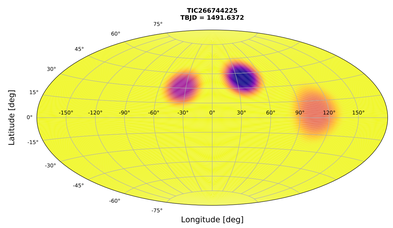

Figure 2: Locations, sizes and contrasts of spots on YZ CMi in sector 7 for Aitoff projection.

Subtracting model of rotational modulation of the star from observations (right part of Fig. 4) allowed us to improve automatic detection of flares. Our detection sensitivity increased by 14% (from 69 flares to 80 flares). This increase can help in better analysis of flares on YZ CMi without confusing them with some rotational modulation effects.

Sector 34 of observations of YZ CMi lasted 24.9801 days (16794 observational points), from TBJD 2229.0897 to 2254.0698 (with an observational gap between TBJD 2240.9105 and 2242.4410). The result we obtained is four spots model with spots separated by 44°, 121° and 275° in longitude from the spot with least longitude (Fig. 3) (or by 0.12, 0.33 and 0.76 in phase). Parameters of spots are presented in Table 2.

Table 2: Variations of parameters of spots on YZ CMi observed in sector 34.

Spot number	Contrast [%]	Size [%]	Temperature [K]	Latitude [deg]
1	0.2	1.53	2912 ± 235	−12
2	0.56	2.14	2696 ± 478	36
3	0.36	1.55	2713 ± 405	50
4	0.49	2.13	2756 ± 420	−36

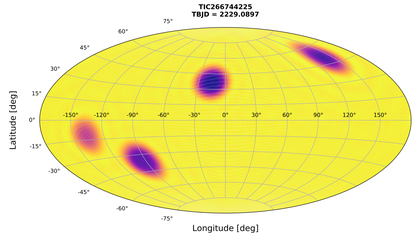

Figure 3: Locations, sizes and contrasts of spots on YZ CMi in sector 34 for Aitoff projection.

Subtracting model of rotational modulation of the star from observations (left part of Fig. 4) allowed us to improve automatic detection of flares. Our detection sensitivity increased by 16% (from 67 flares to 80 flares). This increase can help in better analysis of flares on YZ CMi without confusing them with some rotational modulation effects.

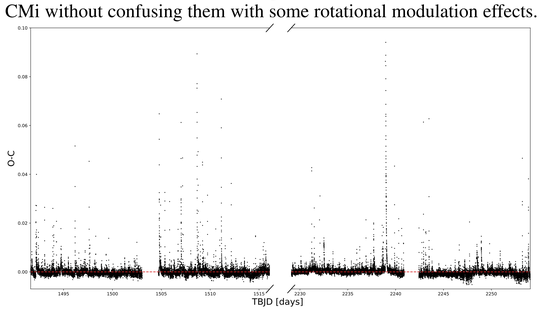

Figure 4: YZ CMi light curve (sector 7 and sector 34) corrected for rotational modulation. Red dashed line presents zero level.

Table 3: Comparison of analytically estimated spots parameters and received in modeling spots parameters on YZ CMi.

Sector number	Analytical temperature [K]	Model mean temperature [K]	Analytical spots size [%]	Model spots size [%]
7	2835 ± 82	2990 ± 157	9.44	9.49
34	2865 ± 82	2765 ± 198	7.35	7.35

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 models obtained by [1, 2, 3, 14] with spottedness variating from 5% to 38%.

References

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[2] Note that throughout the term spot does not strictly mean one sunspot-like structure, but can also be an active region consisting of several individual spots. There is no way to distinguish between these cases from light-curves.