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Studying spot-induced modulations of active solar analog stars

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Abstract. Modulations of stellar light in cool stars are the result of spots crossing the visible stellar disc. Due to differential rotation, spots at different latitudes have different rotation periods. Using synthetic light curves generated with a starspot modeling code we confirm that for cool stars spot latitude and stellar inclination are challenging to be determined uniquely from the photometry alone. We emphasize that spectroscopic rotation measurements are essential. As a first result, we performed a comparative analysis of parameters obtained for κ^1 Cet, a young solar analog observed by MOST, and we show that at least for stars at the same range of magnetic activity, starspot modeling gives coherent solutions. These first results open a door to revisit an entire population of similar stars observed by CoRoT and Kepler (and soon by TESS) and a possibility to constrain parameters of limb darkening and differential rotation at this mass and evolutionary stage. These parameters are fundamental for stellar evolution and exoplanet science.

Resumo. Modulações da luz de estrelas frias são resultantes de manchas cruzando o disco estelar visível. Devido à rotação diferencial, manchas em diferentes latitudes possuem períodos de rotação diferentes. Usando curvas de luz sintéticas geradas por um código de modelagem de manchas, confirmamos que para estrelas frias a latitude e a inclinação são difíceis de determinar apenas pela fotometria. Enfatizamos que medidas espectroscópicas de rotação são essenciais. Como um primeiro resultado, realizamos uma análise comparativa dos parâmetros obtidos para κ^1 Cet, uma jovem análoga solar observada pelo MOST, e mostramos que ao menos para estrelas na mesma faixa de atividade magnética, a modelagem das manchas produz soluções coerentes. Esses primeiros resultados abrem uma porta para revisitar toda uma população de estrelas semelhantes observadas pelo CoRoT e pelo Kepler (e em breve pelo TESS) e a possibilidade de restringir parâmetros de escurecimento de limbo e rotação diferencial nessa massa e estágio evolutivo. Tais parâmetros são fundamentais para evolução estelar e ciência de exoplanetas.

Keywords. Methods: miscellaneous – Stars: solar-type – starspots

1. Introduction

Since the dawn of the starspot hypothesis to explain distortions in some lightcurves, including solar data, astronomers have been deeply interested in the subject in order to obtain some insight about the stellar magnetic field behaviour. Several attempts to approach the problem through the study of lightcurves were made ever since, each one with different assumptions. Some prefer to use numerical integration over the spot areas, which usually are in rectangular shape in a uniform grid, as in the case of Matrix Lightcurve Inversion techniques (Harmon & Crews 2000), while others assume circular spots with a given set of parameters (position and size) and work out analytical models based on the geometry of the problem (Eker 1994).

In the case of analytical models, software has been created in order to find and visualize optimal solutions, as for instance `SpotModeL` (Ribárik, Oláh & Strassmeier 2003) and `StarSpotz` (Croll et al. 2006). In this context, the `Cheetah` code was developed focusing on speed over model visualization, seeking to be suitable for a large scale study of the Kepler dataset, implemented in the widely used programming language Python. Its performance was tested for synthetic lightcurves (Walkowicz, Basri & Valenti 2013) and now we extend the project using real lightcurves for solar-type young stars applying also a Markov Chain Monte Carlo (MCMC) method for assessing the parameter uncertainties.

In section 2 we will discuss the analytic model chosen to parameterize the spotted stars as well as the underlying algorithm used to calculate the best fit plus uncertainties. In section 3 we will take a look at first results from the solar analog κ^1 Cet. At last, in section 4 we will further discuss our conclusions and some future directions.

2. Model and Algorithm

We used the analytic formulation for a single circular spot as in Eker (1994). We assume there are $n_{\rm spots}$ contributing to modulations in a given lightcurve, so our set of parameters is going to be

$$\theta = \left[i \;\; T_{\rm eq} \;\; k \;\; \beta_1 \;\; \lambda_1 \;\; R_1 \;\; \cdots \;\; \beta_{n_{\rm spots}} \;\; \lambda_{n_{\rm spots}} \;\; R_{n_{\rm spots}} \right],$$

where i, $T_{\rm eq}$ and k are stellar parameters (inclination, rotational period at equator and differential rotation coefficient, respectively) and for each spot there are position (latitude β and longitude λ) and size (angular radius R). Each parameter has its boundaries according to the physics of the problem, and the differential rotation profile is given by:

$$T(\beta) = \frac{T_{\rm eq}}{1 - k \sin^2 \beta},$$

which implies that we need at least two spots to fix a single rotation pattern.

Using normalized units for flux (maximum at 1.00) we are able to derive the expected noiseless flux $f(\theta, u_1, u_2, \kappa_\omega)$ for a given set of parameters, where u_1 and u_2 are limb-darkening coefficients and κ_ω is the spot-to-photosphere flux ratio. These were fixed and assumed to be near solar values ($u_1 = 0.70$, $u_2 = 0.00$, $\kappa_\omega = 0.29$).

Each spot is fitted sequentially to the lightcurve via Levenberg-Marquardt non-linear least squares optimization, and every time an additional spot is fitted the whole vector of parameters used so far is optimized simultaneously. In addition to the original boundaries on the nature of the parameters, constraints can be made to the valid parameter space (e.g. a known $v \sin i$

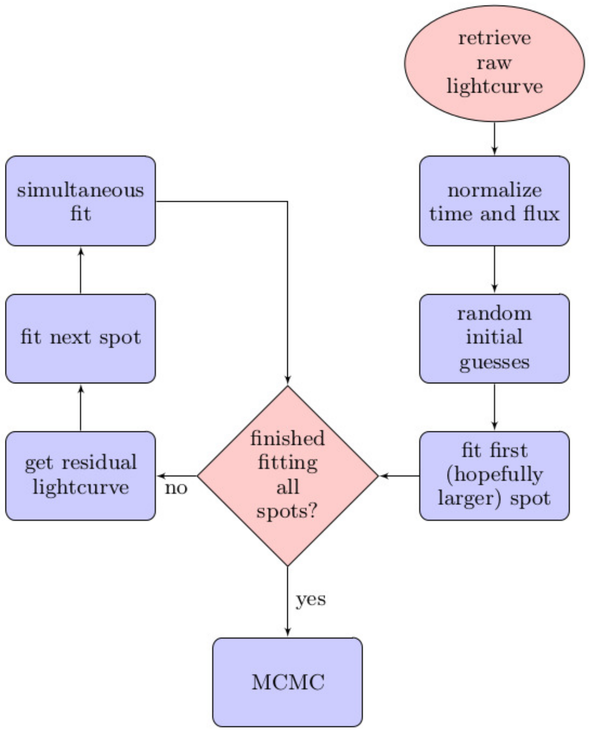

Figure 1. The greedy algorithm used to fit efficiently a given number of spots.

range) to reduce degeneracies. In the end, we apply a MCMC method using the `emcee` python library (Foreman-Mackey et al. 2013) to assess the model goodness of fit. The whole process behind the developed algorithm is indicated schematically in fig. 1.

More details on the multi-fit process can be found on the original documentation for `Cheetah` online[1].

3. First Results

In the direction of evaluating the validity of the proposed algorithm, we elected the solar analog κ^1 Cet as our first case study, mainly because it is a very young and active solar analog, which means it can be reasonably modeled with few (2 or 3) starspots and the assumptions about rotation profile and limb-darkening are justified, but also because there are many such studies in the literature whose results we intend to compare with ours to estimate accuracy. In tab. 1 we compare our findings using a very simple MCMC (500 walkers, 3000 iterations) to the minimum χ^2 solutions reported in Walker et al. (2007). Our solution is shown in fig. 2.

4. Conclusions

We have shown that the greedy algorithm indeed produces coherent solutions according to known results and that the constraints on parameter space reduce errors due to degeneracies. If we apply the same method with a fixed set of parameters we might be able to find the optimal limb-darkening coefficients and κ_ω. We intend to keep perfecting the method and study young open clusters in order to draw conclusions about starspot physics in active stars at the same evolutionary stage.

[1] `https://github.com/lmwalkowicz/Cheetah`

Table 1. Comparative results of fitted parameters.

Parameter	Prior range	MCMC	(Walker et al. 2007)
i (deg) . . .	30 – 80	51.33 – 62.56	60.6
T_{eq} (days)	8.0 – 10.5	8.61 – 8.91	8.784
k	0.00 – 0.30	0.13 – 0.23	0.087
β_1 (deg) .	−10 – 60	14.47 – 27.69	32.4
λ_1 (deg) .	0 – 360	293.74 – 300.45	298[a]
R_1 (deg) .	5 – 30	11.83 – 12.68	11.75
β_2 (deg) .	−10 – 60	44.88 – 58.80	37.2
λ_2 (deg) .	0 – 360	54.21 – 94.15	105[a]
R_2 (deg) .	5 – 30	5.88 – 6.67	5.95

[a] Derived from relative epoch and period.

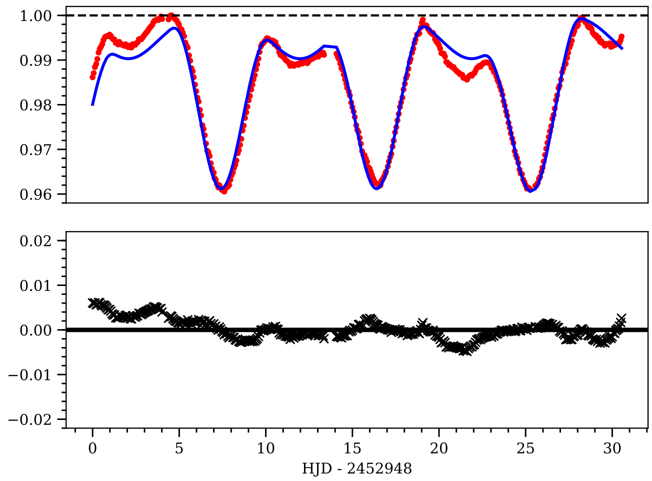

Figure 2. Model fit of two-spot solution for the κ^1 Cet lightcurve of 2003. In the lower panel, residuals on the same scale.

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