Disentangling planetary and starspots features

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We develop a tool for the combined fit of planets and starspots features in transit photometry. Our aim is to derive consistent stellar and planetary parameters, even in case of strong stellar activity. An analytic model is adopted, by using the code KSint, which is modified with the addition of the spots' time evolution. We implement the modified version of KSint into the Bayesian-oriented PASTIS software. The MCMC algorithm included in PASTIS is then employed to fit the light curve of CoRoT-2. We explore two modelings. 1) Transits are not normalized. The complete light curve, including spots and transits, is fitted. 2) Transits are normalized with the spot model fitting the out-of-transits brightness variations, and fitted with a classic transit model. The transit depths found in this two ways are in agreement, and are smaller than if the transits are locally normalized. The fit of the spots inside transits requires bright faculae: this indicates the risk to overestimate the planet size if the fit is carried out on a lower envelope to the deepest transits, contrarily to what has been suggested in literature. Orbit inclination and stellar density are overestimated if the spots occulted by the planet are not taken into account.

Context

- The **magnetic activity** of cold stars causes dark spots and bright faculae to appear on the stellar surface.

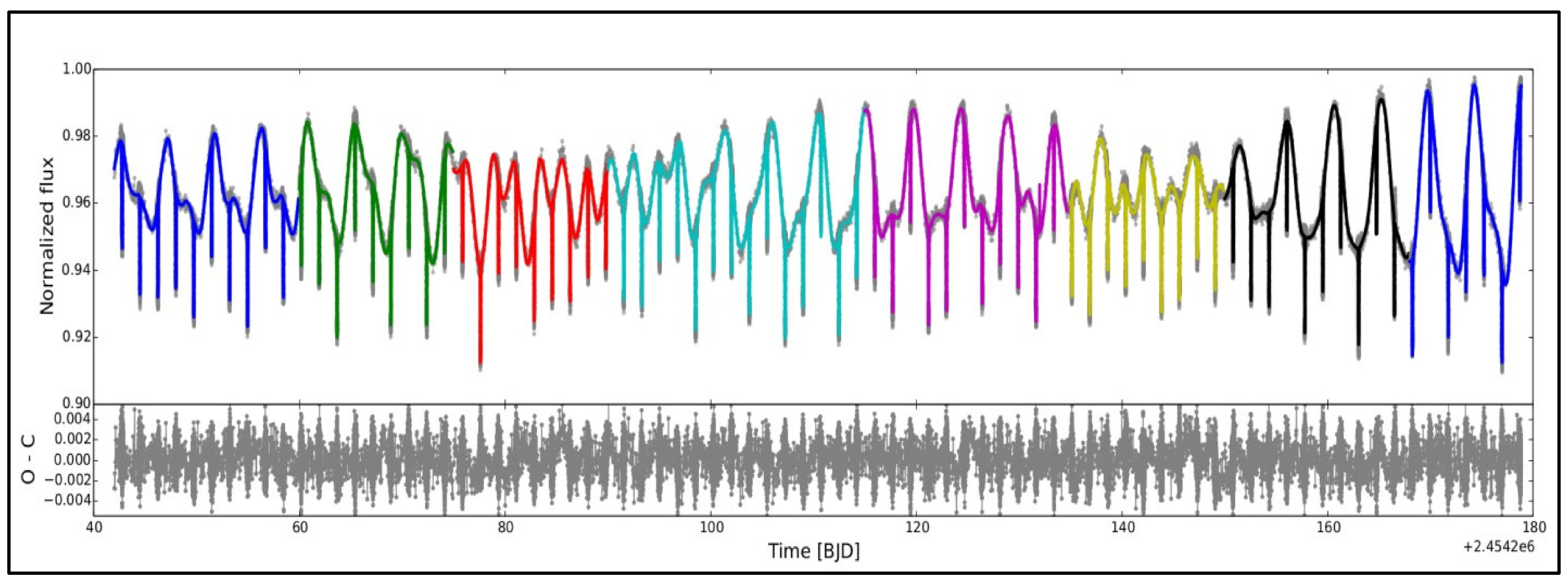
- **Starspots** are an important source of **uncertaint**y in the characterization of exoplanets. In transit photometry, they mainly affect the **transit shape and depth**, therefore the planet radius determination. In radial velocity, they primarily perturb the **mass** measurement.

- In transit photometry, the activity signal is often **filtered out** before fitting the data (e.g. Czesla et al. 2009). Surface reconstruction has been attempted in some cases (e.g. Lanza et al. 2009), and least-squares fitting of spots and transits has been tried (e.g. Huber et al. 2010). These approaches neglect the variation of the activity cycle through time and the correlations between spots and transit parameters.

- **Analytic models** for starspots can be implemented in codes with a faster execution time than computational models. They are therefore more suitable to be implemented in codes for **MCMC fitting**.

- **CoRoT-2** is an active star hosting a hot Jupiter. Its high-precision, long duration light curve makes the activity cycle clearly distinguishable, and allows to resolve the spots inside the transits. It has been widely used as a benchmark case for the modeling of spots and transits. We choose this star to test our method.

Fig. 1.The model light curve plotted over the data. The eight slices of the fit are divided by color. The residuals are shown in the lower panels, and error bars are not shown for clarity.



Method

- Analytic model for spots and transits. We use the code **KSint** (Montalto et al. 2014). **Spots evolution** is added by following the prescription of Kipping (2012), through a linear variation of the size.

- The modified version of KSint is implemented into the Bayesian-oriented **PASTIS** software (Díaz et al. 2014). With use the **MCMC** algorithm of PASTIS to fit the light curve of CoRoT-2. We proceed in two ways.

1) We fit the **whole light curve**. The out-of-transit flux is sampled to a lower resolution to reduce the computation time. We perform the fit in two steps. First, we fit the spots' parameters, and keep the transit parameters fixed. Notwithstanding the modeling of the spots' evolution, the quality of the fit decreases for data samples longer than some tenths of days. We therefore **divide the light curve in eight parts**, whose length is related to the lifetime of the active regions (about 20-30 days, Lanza et a. 2009; fig. 1).
Then, we fix the spots' parameters to their best likelihood value, and fit the transit parameters. During this second fit, we fit again longitude and size of the spots, to derive more realistic uncertainties on the transit parameters. We obtain a set of transit parameters for each part of the light curve.

2) We fit only the transits. The **spot model which fits the out-of-transit flux is used to normalize them.** The uncertainty on the baseline parameter of the normalizing curve is used to derive an uncertainty on the normalization process. A standard transit model is then employed to fit the transits.

Results

- The flux variations are correctly recovered (fig. 1). Some **bright faculae are necessary** for the fit of the bottom of the deepest transits (fig,2). Faculae decrease the flux value in the bottom of the transits. Therefore, considering a lower envelope of the deepest transits, suggested by Czesla et al. (2009) to obtain an unperturbed transit profile, leads to an important overestimation of the planetary radius.

- The **transit depths** derived with the two fits **are in agreement**, and they are lower than when transits are locally normalized (fig.3).

- The fit on separate parts of the non-normalized light curve yields precisely determined values. The transit depth of the different parts have small uncertainties, but are **slight scattered**, indicating the limitations of our approach.

- **Stellar density and orbital inclination** are found to be **lower** if the transits are not normalized, and the spots inside the transits are fitted.

- The orbital period is found slightly different among the slices. This could be an **indication of activity-induced transit timing variations**.

- The limb darkening coefficients, fitted on parts of the light curve, result scattered. By fitting all the normalized transits together, instead, well-determined posteriors are obtained.

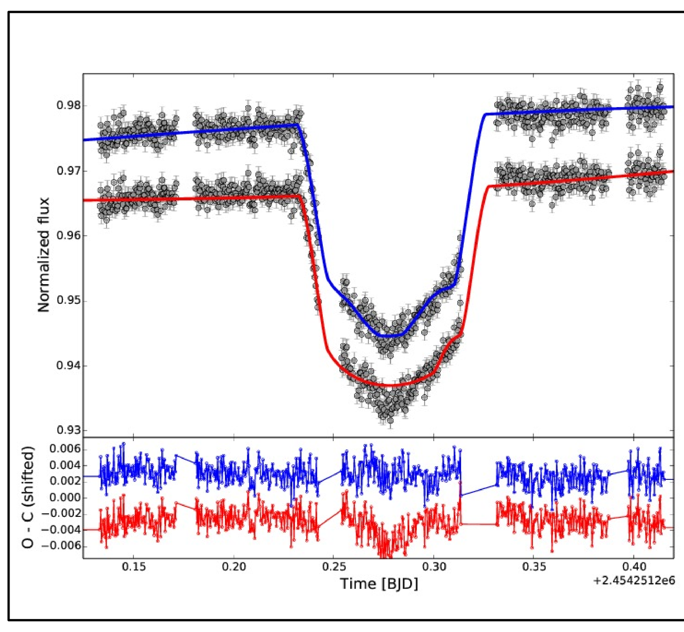


Fig. 2: The deepest transit fitted with a spots and faculae configuration (blue) and a spots-only model (red, shifted). The residuals are shifted for clarity and use the same color code.

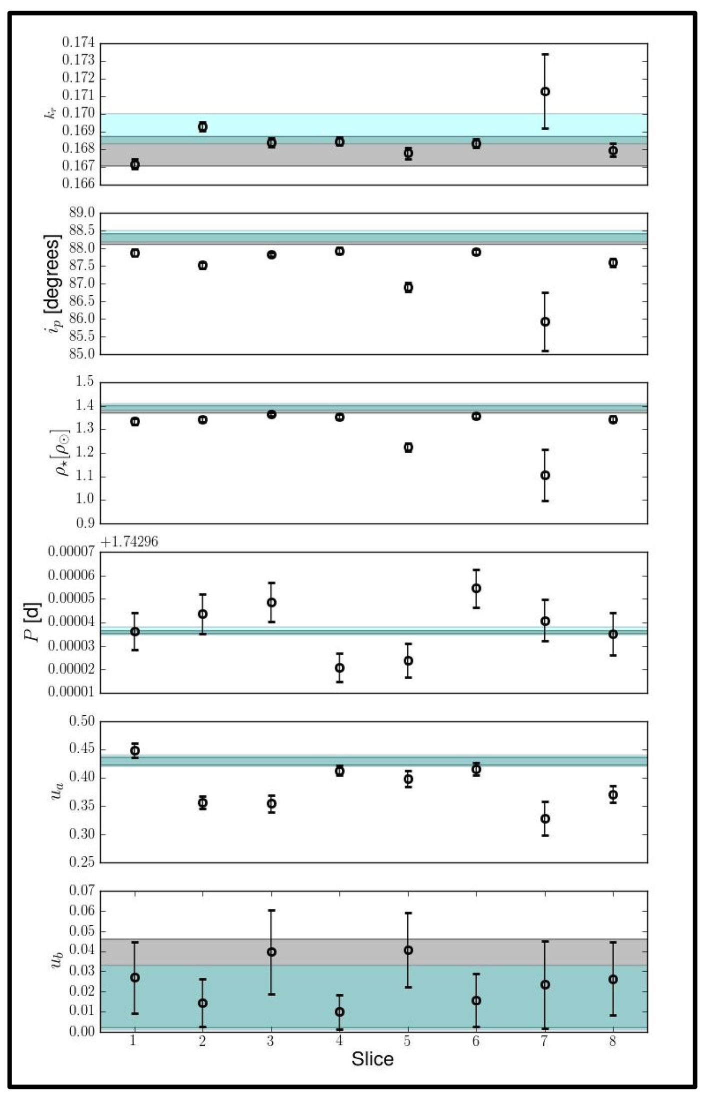


Fig. 3: 68.3%-confidence intervals for the posterior distributions of k_r, i_p, ρ_*, P, u_a, and u_b for the different parts of light curve, fitted separately. The shaded regions indicate the results for the model-normalized (gray) and the locally normalized (light blue) transits.

Conclusions

- The choice of the **normalization** process affects the transit depth. Using a model to normalize the transits yields a lower transit depth than if a local normalization is performed.

- The out-of-transits flux variations (non-occulted spots) are **dominant** over the inside-of-transits ones (occulted spots) in the measurement of the transit depth.

- The **underestimation** of the orbit inclination could be related to wrongly determined transit times. Another explanation could be a wrong assumption on the stellar inclination. This parameter was kept fixed during the fit to the value found with the Rossiter-Mc Laughlin effect (Bouchy et al. 2008). The uncertainty on the spots' latitudes prevent to check this assumption.

- Our method can be **improved** by introducing the fit of the number of spots, of their longitudinal migration and of the stellar differential rotation.

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