Disentangling planetary and starspots features in the CoRoT-2 light curve

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Abstract

We develop a software for the combined fit of transits and stellar activity features in high-precision long-duration photometry. We take advantage of the modeling to derive correct stellar and planetary parameters, even in the case of strong stellar activity. The light curve is modeled analytically. The code KSint, modified by adding the evolution of active regions, is implemented into our transit modeling package PASTIS. The code is then applied to the light curve of CoRoT-2. The light curve is divided in segments, to reduce the number of free parameters needed by the fit. We find variations in the transit parameters of different segments, and show that these are mostly due to the cut applied to the light curve. We show that faculae should be taken into account when fitting the transits. Our fit yields an inflated radius for the planet (1.475 ± 0.031 R_J), as other authors found while neglecting stellar activity.

1 Introduction

Stellar activity is one of the main sources of uncertainty in the field of planet detection and characterization. It produces dark spots and bright faculae on the stellar photosphere, which alter the total flux emitted by the star. All these active regions cross the visible stellar disk as the star rotates; they are distributed in groups, and vary in size, temperature, and position on the stellar disk along an activity cycle. Such features can induce systematic errors in the determination of the planetary parameters. Czesla et al. (2009) showed that transit normalization is affected by non-occulted dark spots on the stellar disk, which cause an overestimate of the planet-to-star radius ratio. They and Silva-Valio et al. (2010) discussed how spots occulted during a transit act in the opposite way, producing an underestimate of the planet-to-star radius ratio. Léger et al. (2009) showed how activity can induce to underestimate the stellar density; Csizmadia et al. (2013) studied the effect of starspots on the estimate of limb darkening coefficients; Alonso et al. (2008), Barros et al. (2013) and Oshagh et al. (2013) showed how stellar activity can induce apparent transit timing variations (TTVs), and introduce errors in the determination of the transit duration, too.

Several approaches have been tried to disentangle the signal produced by the planets from that coming from active features at the surface of the star. The main attempts focus on the data reduction. Czesla et al. (2009) proposed to adopt a different normalization than the standard one. The standard normalization consists in dividing each transit by a low-order polynomial fitted to the flux adjacent to both sides of the transit. With the normalization of Czesla et al. (2009), the out-of-transit flux modulations are kept into account. Moreover, they proposed to consider a lower envelope of the deepest transits as the closest one to the “true” transit, if dark spots are dominant over faculae. They applied this approach to CoRoT-2 b and found a 3% larger planet-to-star radius ratio than the one found in the
discovery paper (Alonso et al. 2008) where a standard approach was used. In this work, we develop a fitting method to take into account the imprint of activity features on the transit parameters. We implement an existing activity feature model that we updated into our transit modeling package PASTIS, and use it to fit the light curve of CoRoT-2. The clearly visible activity pattern of the star of this system, both outside and inside the transits, made it a case widely studied in literature.

2 Method

Analytic models for the computation of light curves affected by stellar activity are order-of-magnitudes faster than computational models, but require restricting constraints on the parameters to simplify the equations. They require simple circular shapes for the activity features, limitations on their size, and the restriction to cases of non-overlapping features and transits (Kipping 2012). Analytic models overcoming these limitations have been recently presented, and implemented in freely available codes (e.g. KSint, Montalto et al. 2014). Moreover, Markov chain Monte Carlo (MCMC) fitting has been proven to be an effective method to find best-fit values, uncertainties, correlations, and degeneracies for the photometric spot modeling problem (Croll 2006). We implemented the analytic code KSint into the MCMC framework of PASTIS (Díaz et al. 2014; Santerne et al. 2015).

KSint models a light curve containing both planetary transits and activity features. The transits, modeled with the formalism of Pal (2012), are characterized by the planet-to-star radius ratio $k_r$, orbital period $P_{\text{orb}}$, orbital inclination $i_p$, eccentricity $e$, planet argument of pericenter $\omega$, and mean anomaly $M$. The star is assigned an inclination angle $i_\star$, a rotation period $P_\star$, a density $\rho_\star$, and quadratic limb-darkening coefficients $u_a$ and $u_b$. The activity features are characterized by the same limb darkening law as the star.

The activity features (both spots and faculae) are assumed to be spherical caps. Each of them is described by four parameters: longitude $\lambda$, latitude $\phi$, angular size $\alpha$, and contrast $f$. The time evolution of the features, which has been observed for many stars, is not included. To model a light curve corresponding to more than just a few stellar rotations, we introduced a simple law for activity features evolution in KSint. We used a linear variation of the angular size, following the prescription of Kipping (2012). The size parameter $\alpha$ was translated into the maximum size reached by a feature during its evolution, $\alpha_{\text{max}}$. Then, four parameters were added to the description of every feature: 1) the time at which the maximum size is reached, $t_{\text{max}}$; 2) the time during which the feature keeps its maximum size, $t_{\text{life}}$; 3) the time of growth from zero to maximum size, $I$; 4) the time of decay from maximum to zero size, $E$.

The features of our model have to be considered as representative of groups of features, more than features taken individually. This allows to use large sizes and lifetimes, without losing physical sense.

3 Application to CoRoT-2

CoRoT-2 A is a young (< 500 Myr old), G7V-type star observed during the LRc01 run of the CoRoT space telescope. It hosts the Hot Jupiter CoRoT-2b (Alonso et al. 2008) which has mass $3.31 \pm 0.16 M_J$ and radius $1.465 \pm 0.029 R_J$. The orbit of the planet has a period of 1.74 days, and is almost aligned with the stellar equator (Bouchy et al. 2008). Its radius is about 0.3 $R_J$ larger than expected for an irradiated hydrogen-helium planet of this mass. Models strive to explain a longer contraction time during the evolution of the planet (e.g. Guillot & Havel 2011).

The light curve, shown in figure 1, indicates that a varying fraction of the stellar surface is covered by activity features, up to a few tens of percent (Lanza et al. 2009; Huber et al. 2010; Silva-Valio et al. 2010). Fits with a few and with several features have been performed on CoRoT-2, independently from the study of the planet. All these approaches are complementary, but none of them offers a complete modeling of both the light curve and the transits in a consistent model. The evolution of the active features is not included, and transits and out-of-transit flux are not fitted simultaneously. In particular, the impact of the active regions on the transit parameters is only partially explored.
3.1 Data reduction

We used the light curve processed by the CoRoT N2 pipeline[1] Only the part sampled every 32 s was used (∼145 over 152 days of observation), to take advantage of the full resolution inside transits. The points classified as poor in quality, included those related to the South Atlantic Anomaly, were discarded. The data were first 3σ-clipped and the transits identified with the ephemeris given by Alonso et al. (2008).

We prepared the following data sets, used for the two fits described later.

Data set $SP$. We followed Huber et al. (2010) and sampled the out-of-transit flux every 2016 s (33.6 min). The transits were sampled every 160 s. This sampling keeps enough information to force some features to be modeled inside the transits. The uncertainty of the binned data was calculated as the standard deviation of the points in each bin, divided by the square root of the number of points in the binning window. The average relative uncertainty on this data set is $3.9 \cdot 10^{-4}$. After resampling, the flux was divided by its maximum value and no transit normalization was performed.

Data set $SPT$. This data set was prepared for active regions and transit fitting. It was prepared as data set $SP$, but full resolution was kept inside the transits. The average relative standard deviation on this data set is of $1.12 \cdot 10^{-3}$.

3.2 Modeling approaches

For almost every Markov chain that is run, a successful combination of the parameters is explored and converges to a local maximum of the likelihood. Therefore, this modeling was carried out in two steps. First, only the parameters of the active regions were fitted; then, given these parameters, the transits were fitted.

Fit of active regions (Fit $SP$). This fit takes into account non-occulted active regions, and prepares the fit of the transits with the occulted active regions. The light curve modeling was carried out on the data set $SP$. The transit parameters ($P_{orb}, \rho, i, b, e, \omega, u_r, u_b$) were fixed to the values of Alonso et al. (2008). A uniform prior was imposed for the mean anomaly $M$. Following Bouchy et al. (2008), the stellar spin axis was assumed to be perpendicular to the planetary orbit. The planet inclination was found by Alonso et al. (2008) to be of 87.84° with respect to the plane of the sky; therefore, we fixed the stellar inclination to the same value with respect to the line of sight. A uniform prior, centered on the value found by Lanza et al. (2009) was set for the stellar period $P_*$. Non-informative priors were used for all the parameters of the activity features. For each feature, $r_{max}$ was limited between 0 and 30°. The largest size was found sufficient for the modeling. Both dark spots and faculae were included in the fit, setting a prior for the contrast $f$ between 0.3 and 1.3. For each feature, a uniform prior was set for $t_{occ}$. The contamination term was fixed to the value found by Gardes et al. (2012) (8.81%). This parameter was fixed because active regions can be considered as a contaminant factor Csizmadia et al. (2013). An uniform prior was set for the flux relative offset and the jitter.

The optimal number of active regions was determined by trials. We increased it until we obtained residuals with a normally-distributed dispersion, centered to zero and with a width comparable to the photometric data dispersion. Our model needs several tens of active regions to model the entire light curve as a whole, in agreement with the results of Silva-Valio et al. (2010) and Silva-Valio & Lanza (2011). As our computer cluster cannot handle the hundreds of resulting free parameters, the light curve was divided in shorter parts which need the modeling of less features. These segments have a duration of ∼15 – 25 days (four-six stellar rotations), and can be fitted with six to nine evolving features. Longer segments tend to produce worse fits. In figure[1] the segments are highlighted by color. It can be noticed how the segments are related to the different phases of activity in the light curve. The brightness variations grow in amplitude, reach a maximum, and shrink again. The duration of the segments is consistent with the lifetime of individual spots and active regions found by Lanza et al. (2009) i.e. between 20 and 50 days.

To connect the solutions of consecutive segments, the features with non-zero size at the end of a given segment were kept for the initial values of the features of the next segment. Chains up to $3 \cdot 10^6$ iterations-long were run for

each segment. A chain was considered converged after its likelihood did not increase for some thousand steps after the end of its burn-in phase. From the chain of a given segment reaching the highest likelihood, the best-likelihood solution was extracted.

**Spot-transit fit (fit SPT).** Using as input the results of fit $SP$, we carried out a simultaneous fit of both non-occulted and occulted features, and included the fit of the transits. This fit was performed on data set $SPT$, divided in segments as for fit $SP$. The transit parameters were fitted while fixing the parameters of the active regions to their best solution of fit $SP$, except the size $a_{\text{max}}$ and the longitude $\lambda$ of the activity features. The parameter $a_{\text{max}}$ affects primarily the planet-to-star radius ratio; the longitude affects the position of a feature in the transit profile, so it can affect the transit duration, and therefore the limb-darkening coefficients, $i_p$, and $\rho_\star$. We used a normal prior with standard deviation equal to $5^\circ$, centered to the best likelihood value.

In this phase, ten chains from $1.5 \times 10^5$ steps were employed to reach convergence for each segment. For each segment, the chains were then thinned according to their correlation length and merged into a single one. The results and the uncertainties for each segment were obtained from the respective merged chains.

![Figure 1: The model light curve from KSint plotted over the data. The eight segments of the fit are divided by color. The residuals are shown in the lower panels, and error bars are not shown for clarity. The larger amplitude of the residuals in correspondence of the transits is due to the full resolution kept for the transits. The out-of-transits binning is of 2016 s, and inside the transits 32 s.](image)

**4 Results**

**4.1 Parameters of the active regions**

Figure 1 presents the best model of fit $SPT$, plotted over the light curve, where the segments are highlighted by color.

The posterior distributions given by the best-likelihood chains give information about the parameters of the features in these maxima. Our fit, therefore, yields a map of the stellar surface.

- In figure 2, the effective coverage factor of the stellar surface is plotted as a function of the segment of light curve, divided for spots and faculae. For each segment, this is defined as

$$C = \sum_i a_{\text{max}}(1 - f_i),$$

where the sum is run over all the features $i$ with maximum area $a_{\text{max}}$ and contrast $f$. For this calculation, only the most probable values of the solutions were used. A facula has $f > 1$, hence contributes negatively to the sum. The absolute value of $C$ is plotted for the faculae, for the purpose of illustration.

Figure 2 shows an increase, followed by a decrease, of $C$ for spots in the first activity cycle (segments 1 to 3, see figure 1), and indicates a similar behaviour for the third cycle (segments 7 and 8). The second cycle (segments 4 to 6) does not show this trend. This is reflected by a larger impact of faculae in segments from 3 to 6.

- Faculae (features with $f > 1$) are present in every segment.
In every segment, one or two features (either dark spots or faculae) are found to cross the transit chord. Therefore, occulted features are a minority.

No preferred values are found for the fitted evolution times $t_{\text{max}}$, $t_{\text{life}}$, $I$, and $E$.

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**Figure 2:** Effective coverage factor as a function of the segment of light curve.

**Figure 3:** Transit parameters as a function of the effective coverage factor, for all the segments. The values of the $t$-statistics are indicated.
4.2 Transit parameters

Table 1 reports the transit parameters of all fits. The results are the average of all the results obtained on each segment.

Table 1: Transit parameters with their 68.3% confidence intervals.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$k_i$</th>
<th>$i_p$ [degrees]</th>
<th>$\rho_*$ [$\rho_\odot$]</th>
<th>$P_{\text{orb}}$ [d]</th>
<th>$u_a$</th>
<th>$u_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1670 ± 1.2 · 10^{-3}</td>
<td>88.19 ± 0.51</td>
<td>1.369 ± 0.033</td>
<td>1.74299 ± 1.2 · 10^{-5}</td>
<td>0.415 ± 0.030</td>
<td>0.050 ± 0.013</td>
</tr>
</tbody>
</table>

In figure 3 all the transit parameters found with fit SPT are plotted as a function of the effective coverage factor $C$ of the stellar surface, introduced in section 4.1. For some segments, the results of fit SPT are in poor agreement one to each other. The transit depth $k_i$ on segment 5 is lower than those estimated from the other segments, and oppositely for $i_p$ and $\rho_*$. The large contribution of faculae to spots in this segment (see figure 2) might indicate that faculae are more difficult to correct for than dark spots and bias the transit parameters estimate.

The orbital period $P_{\text{orb}}$ is scattered among the segments of fit SPT. This could be related to an erroneous measure of the transit duration. Indeed, apparent activity-induced TTVs cannot be excluded. The possible presence of TTVs needs a transit-by-transit analysis, which our code is not able to perform. In fit SPT, $u_a$ results in a poor agreement among the segments, despite the imposed tight normal prior. An explanation can be the difficulty of our code to recover the limb-darkening coefficients if only a few transits are available. A poorly fitted $P_{\text{orb}}$ could contribute to this problem, as well.

4.2.1 Impact of stellar activity on the transit parameters

In each panel of figure 3, the value of the Student’s $t$-distribution for the plotted couple of variables is reported. The parameter $k_i$ increases with $C$ and the $t$-statistics yields 0.712. This value has a small significance, suggesting that the impact of the activity features on $k_i$ is corrected for by fit SPT. In that case, the scatter between segments is not due to non-disentangled activity-induced effects. A slightly larger significance is observed for the $t$-value between $C$ and $\rho_*$ (-1.184), indicating a lower $\rho_*$ measured with increasing $C$. This might be linked with an underestimate of $i_p$ with increasing $C$; however, the $t$-value between these parameters is not remarkably significant (-0.864). This suggests that our code does not properly correct for the effect of spots on the transit edges. It has to be observed that, in this statistics, the low values of these parameters fitted on segment 8 have an important weight.

As previously noticed, the possible underestimate of $\rho_*$ could be an effect of apparent activity-induced TTVs. The $t$-value between $P_{\text{orb}}$ and $C$, however, is almost null (0.043). The limb-darkening coefficient $u_a$ was found to be anticorrelated with $C$, oppositely to $u_b$ ($t = -1.084$ and 0.593, respectively). Csizmadia et al. (2013) showed that limb darkening coefficients vary with the fraction of the stellar surface covered by activity features. Our result confirms theirs, and therefore indicates that further developments in the fitting method are needed to disentangle this effect, especially when faculae are included in the fit.

4.3 Least distorted transit

According to Czesla et al. (2009), the deepest transits are those that are less affected by occulted features; therefore, their planet-to-star radius ratio should be closer to the true one. Working on CoRoT-2, they interpolated a lower envelope to an average of the deepest transits. They fitted only $k_i$ and $i_p$, and obtained $k_i = 0.172 ± 0.001$ (i.e. a 3% larger $k_i$ than Alonso et al.) and $i_p = 87.7 ± 0.2$. Their method assumes the dominance of dark spots over faculae, as found by Lanza et al. (2009) by fitting the out-of-transit light curve.
With our approach, the assumption of the prevalence of dark spots could be checked. We adopted a similar approach to Czesla et al. (2009), but worked on the deepest transit only, in order not to average any activity feature. We considered the sixth transit as the deepest one. This transit was isolated from data set SPT. The configuration of the active regions obtained with fit SPT for the corresponding segment was fixed. The transit parameters $k_0, \rho_0, \rho_*$ were fitted. Because of the low number of points in a single transit, the limb-darkening coefficients were fixed. The MCMC yielded the values $k_0 = 0.1734_{-0.0018}^{+0.0016}$, $i_0 = 86.02 \pm 0.27^\circ$, and $\rho_* = 1.093 \pm 0.038 \rho_\odot$. The planet-to-star radius ratio is in $1\sigma$ agreement with Czesla et al. (2009) result. The low values of $i_0$ and $\rho_*$, instead, have to be attributed to the distorted transit profile. The fit finds that this transit is affected by a facula, whose position during the transit is shown on the left side of figure 4. A facula increases the apparent $k_0$, contrarily to a dark spot. Fitting a single transit, our code does not disentangle the facula from the transit profile.

To check whether a dark spots-only solution can be found by our model, we fixed the planet-to-star radius ratio to the Czesla et al.’s value, and imposed three dark spots (i.e., with $f \leq 1$) for the fit of the deepest transit. A minimum of three spots was considered necessary. Indeed, two occulted spots at the borders of a transit can mimic a facula at the center of the transit; a third non-occulted spot is needed to generate a possible out-of-transit flux variation, if the other two are not sufficient. The contrast of the spots was fixed to the conservative solar value of 0.67 (Sofia et al. 1982). The latitude of the occulted spots was fixed close to $-2.16^\circ$, to lie on the transit chord. Their longitudes were forced to lie in the visible stellar disc, to help the fit. The latitude of the non-occulted spot was set to $30^\circ$. The best spots-only configuration is plotted in the center of figure 4; this solution and the one with a facula are compared on the right side of the figure. Without a facula, the distortions of the transit profile are not recovered: the Bayesian Information Criterion (BIC, Schwarz 1978) favors the model with a facula over the one with dark spots only. Indeed, $\text{BIC}_{\text{facula}} - \text{BIC}_{\text{dark spots}} \approx -4$, corresponding to a Bayes factor $\sim e^{-4} \approx 0.018$ between the dark spots-only and the facula model. This result suggests that Czesla et al. (2009) approach is flawed by the fact that faculae are not taken into account, and so lead to an overestimate of $k_0$. The fit of occulted activity features inside transits requires the presence of faculae in the model.

Figure 4: Left: Planet (black) and starspots (blue) configuration during the deepest transit, with faculae allowed. The faculae are crossed by the planetary disc. Center: The solution with three dark spots, colored in red. Right: The deepest transit fitted with the spot-facula configuration (blue) and the three-spots model (red, shifted). The residuals are shifted for clarity and use the same color code.

### 4.4 Planet radius

Our results indicate that a fit like the combination of fit SP and SPT has the potential to measure the transit parameters in the most unbiased way. In fact, it is not affected by the transit normalization issue, and takes the occulted activity features into account. However, our modeling approach is limited by the need of cutting the light curve in parts, which introduces a scatter in the results because of the lower number of points to be fitted. We adopted the following approach as a compromise. The out-of-transit model fitting data set SP was recomputed without the planet, and used to normalize the transits. Then, the transits were fitted using a standard transit model,
with the EBOP code \cite{Nelson1972,Etzel1981,Popper1981}. This code was used because of its higher computation speed compared to KSint. Despite neglecting occulted spots, this fit is neither affected by the normalization issue discussed by \cite{Czesla2009}, nor by the chop of the light curve into segments. We used $k_0$ and $\rho_*$ obtained from this fit (0.16820 ± 7.8 · 10^{-4} and 1.390 ± 0.013 $\rho_\odot$, respectively) to derive the radius of CoRoT-2 b. We used the Geneva stellar evolutionary tracks \cite{Mowlavi2012} and the updated stellar atmospheric parameters of \cite{Torres2012} ($T_{\text{eff}} = 5575 \pm 70$ K, $[\text{Fe}/\text{H}] = -0.04 \pm 0.08$). This yields $R_p = 1.475 \pm 0.031 R_J$. These values are about ~1% different from the one found by \cite{Alonso2008} (1.465 ± 0.029 $R_J$). The inflated radius of the planet is confirmed.

5 Future developments

We identified the following caveats, which need to be addressed to improve the quality of our fits.

- The fixed number of activity features. By manually adding features to the fit, short-lived features inside the transits could have been missed. An automatic incremental addition of features, especially inside the transits, is suitable.

- Fitting $\lambda$ and $\alpha_{\text{max}}$ might not be the optimal method to propagate the uncertainties from fit SP to fit SPT.

- The degeneracies between multiple features. When two or more features are in the visible stellar disk, their individual contribution to the total flux is not distinguished by the model. This prevents the MCMC to converge. This problem has been mitigated in literature by dividing the stellar surface in fixed, non-overlapping active regions \cite[e.g.][]{Lanza2009,Huber2010}.

6 Conclusions

We presented a method for the fit of transit photometry which takes into account the impact of activity features on the transit parameters. This approach is based on an improved version of the analytic code KSint, which includes both non-occulted and occulted features. The method was applied to the light curve of CoRoT-2. Two main types of fit were performed: one takes into account both non-occulted and occulted features, and one includes only the non-occulted ones.

We compared the results of our method with other approaches presented in literature. It was confirmed that a standard “local” transit normalization causes an overestimate of the planet-to-star radius ratio. We quantified the underestimate induced by \cite{Czesla2009} normalization, due to neglecting the role of faculae. With our model, these problems are avoided; however, the transit parameters are not importantly modified. The inflated radius of CoRoT-2 b is confirmed.

We found that faculae should be taken into account in the transit modeling. This prevents from the simple use of the lower envelope of the transits to estimate the planet-to-star radius ratio. With such an approach, faculae are neglected while they artificially increase the planet-to-star radius ratio.

The stellar density, as well as the linear limb darkening coefficient, are slightly anticorrelated with the level of activity. This could be related to the prior given to the stellar inclination, or to apparent activity-induced TTVs. Their presence was suggested by \cite{Alonso2009}; our model does not take them into account. A detailed analysis of TTVs would benefit from a dedicated study.

Thanks to the modeling of the time evolution of the features, it was possible to model longer parts of light curve with respect to previous attempts presented in literature. Despite this, it was still necessary to cut the light curve in segments and to fit them separately. Hence, the most important developments needed by our method are related to the modeling of feature evolution. Indeed, the fit of a large (at least ~ 40) number of transits is needed to be confident about the derived transit parameters.

This study is a first step towards a consistent modeling of activity and transit features in transit photometry. Important improvements are still needed to model light curves affected by stellar activity covering two or three years of observations, such as those which will be provided by PLATO 2.0 \cite{Rauer2014}.
References


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