USING STAR SPOTS TO MEASURE THE SPIN–ORBIT ALIGNMENT OF TRANSITING PLANETS

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ABSTRACT

Spectroscopic follow-up of dozens of transiting planets has revealed the degree of alignment between the equators of stars and the orbits of the planets they host. Here we determine a method, applicable to spotted stars, that can reveal the same information from the photometric discovery data, without need for follow-up. A spot model fits to the local light curve, parameterized by the spin orientation of the star, predicts when the planet will transit the spots. Observing several spot crossings during different transits then leads to constraints on the spin–orbit alignment. In cases where stellar spots are small, the stellar inclination, $i_s$, and hence the true alignment, rather than just the sky projection, can be obtained. This method has become possible with the advent of space telescopes such as CoRoT and Kepler, which photometrically monitor transiting planets over a nearly continuous, long time baseline. We apply our method to CoRoT-2 and find the projected spin–orbit alignment angle, $\lambda = 4.7 \pm 12.3^\circ$, in excellent agreement with a previous determination that employed the Rossiter–McLaughlin effect. The large spots of the parent star, CoRoT-2, limit our precision on $i_s$: $84^\circ \pm 36^\circ$, where $i_s < 90^\circ (>90^\circ)$ indicates that the rotation axis is tilted toward (away from) the line of sight.

Key words: planets and satellites: general – stars: individual (CoRoT-2) – starspots – techniques: photometric

1. INTRODUCTION

Transit observations of several systems, e.g., HD 209458 (Silva 2003), TrES-1 (Charbonneau et al. 2007), HD 189733 (Pont et al. 2007), and CoRoT-2 (Alonso et al. 2008; Silva-Valio et al. 2010), reveal anomalous flux rises during transit, most likely the result of the planet occulting a dark spot on the stellar surface. Spots on the stellar surface complicate the estimation of planetary parameters from transit photometry and can lead to errors in planet size measurements if not accounted for (e.g., Czesla et al. 2009).

On the other hand, spots introduce structure into out-of-transit and in-transit observations, which may offer new opportunities to learn about the planet, its orbit, and the host star. Silva-Valio (2008) pointed out the possibility of estimating the rotation period of transit host stars, if an observer is able to catch the transiting planet occulting the same spot on two consecutive transits. The key to the method is measuring the displacement of the spot perturbation along the transit chord and modeling the displacement as due to rotation of the star. Applying the method to Hubble Space Telescope observations of HD 209458b, and implicitly assuming alignment in the projected spin–orbit alignment angle ($\lambda = 0^\circ$) and a stellar inclination of $i_s = 90^\circ$, Silva-Valio (2008) constrained the rotation period of the star to be either 9.9 or 11.4 days. Rotation period estimates from long-term photometric observations of out-of-transit variability in HD 209458 find a value consistent with the 11.4 day estimate. Dittmann et al. (2009), in a similar analysis of TrES-1b, generalized the method by considering when $\lambda \neq 0^\circ$ and $i_s \neq 90^\circ$, but found that this freedom introduced large uncertainty in the estimation of the rotation period.

We propose to reverse the chain of inference. Because space-based transit monitoring missions, such as Kepler and CoRoT, observe each target over a nearly continuous, long time baseline, we can robustly determine the rotation period and rotational phase of the occulted spot at the time of each transit by fitting a spot model to the global light curve. By comparing the position of the spot perturbation along the transit chord with the spot’s rotational phase, we can constrain $\lambda$ and $i_s$.

Constraints on the projected spin–orbit alignment angle via Rossiter–McLaughlin (RM) measurements (e.g., Gaudi & Winn 2007) have yielded unique science. For instance, it appears that misaligned systems are preferentially found around F-type stars (Schlaufman 2010) which may point to a connection between alignment and the larger convective envelopes of cooler stars (Winn et al. 2010a). Meanwhile, attempts are being made to understand the relative importance of two (or more) modes of planetary migration, which bring planets from their formation zone into close-in orbits (Morton & Johnson 2011). Planet–planet scattering followed by tidal circularization (Chatterjee et al. 2008) and Kozai oscillations followed by tidal circularization (Fabrycky & Tremaine 2007), both lead to misalignment, while migration through a gaseous disk should, as currently understood (Lin et al. 1996), lead to alignment.

In this Letter, we describe our method to constrain the spin–orbit alignment and demonstrate an application to the CoRoT-2 system. A similar concept has been developed by Sanchis-Ojeda et al. (2011) and was applied to WASP-4b, finding $\lambda = -1^{14}_{-12}$ deg. Our method and analysis were developed independent of Sanchis-Ojeda et al. (2011), whose analysis was reported while this manuscript was in preparation. In Section 2, we discuss the CoRoT observations of CoRoT-2, measure the timing of in-transit spot crossings, and estimate the timing uncertainty. In Section 3, we describe a spot model to the global CoRoT-2 photometry and our model for the in-transit spot timings. We confront the spot-timing model with the CoRoT-2 spot-timing measurements. We conclude in Section 4 with a discussion of our results and contrast our method with that of Sanchis-Ojeda et al. (2011).

2. DATA

2.1. Observations

CoRoT-2 was continuously monitored over approximately 140 days by the CoRoT space telescope (Alonso et al. 2008). The first week of observations was conducted with a sampling of 512 s, and 32 s for the remainder of the observations. We identified the transits using the ephemeris of Alonso et al. (2008), $T_E = E \times 1.7429964 + 2454237.53562$ BJD, where
$E$ denotes the transit number. For analysis of the global spot
model, we removed in-transit observations and re-binned the
data to 512 s resolution. For analysis of transit data, we retain
the 32 s sampling. The relative root-mean-square (rms) scatter
at 32 s sampling is 720 parts per million (ppm).

2.2. Spot-crossing Time Measurements

For each transit, which has duration of approximately 1.9 hr,
we select an 8 hr window bracketing the time of mid-transit. We
derive a linear fit using the out-of-transit data within the 8 hr
time window, and normalize the data (including the in-transit
observations) by dividing off the linear fit. We then determine
the residuals to the transit model, using transit parameters derived
by Gillon et al. (2010). Because of the difficulty of identifying
spot crossings that occur on the limb of the star, we only attempt
timing measurements for spot crossings which show a clear
signal between transit ingress and egress.

The shape of a spot perturbation to a transit light curve
depends on the relative sizes of the planet and star spot, and the
brightness distribution of the star spot. The ability to resolve the
time of spot crossing is limited by the planet size and spot size,
with the best case occurring when the spot is much smaller than
the planet. In the case of CoRoT-2, the spot (or perhaps, complex
of small spots) in consideration is at least as large as the planet.
This is evident because the durations of the spot perturbations are
longer than transit ingress/egress. For simplicity, we identify the
spot-crossing timing as the time of maximum spot perturbation.
In the modeling of Section 3, we associate this time with
the time of maximum spot perturbation.

This correspondence is of course a simplifying approximation, which may fail due to limb darkening and
do not consider the spot perturbations in the flat-bottomed portion
of the transit light curve. To compensate for the diminution
of the spot-crossing signal caused by limb darkening and
foreshortening of the stellar surface, for irregularly shaped spots,
and for spots on the limb of the star. We mitigate these effects by
only considering spot perturbations in the flat-bottomed portion
of the transit light curve. To compensate for the diminution
of the spot-crossing signal caused by limb darkening and
foreshortening, we normalize the residuals to the transit model,
and divide by the “instantaneous” transit depth ($1 - F_{\text{transit}}$), where
$F_{\text{transit}}$ is the model specified by the parameters of Gillon et al.
(2010). Even after these steps, the approximation is imperfect,
but we expect any errors introduced to be small compared to the
timing uncertainty.

To measure the timing and timing uncertainty of the spot
crossing, we have used the following non-parametric procedure.
(1) We construct 10,000 realizations of the observed data set by
adding to each observed value a random number drawn from a
normal distribution with mean 0 and standard deviation equal
to the rms scatter of 720 ppm. (2) We normalize the residuals,
and divide by the “instantaneous” transit depth ($1 - F_{\text{transit}}$). This
normalization is performed on each of the 10,000 realizations
of the data set. (3) For each normalized realization, we note the
time of maximum residual. (4) We take the spot-crossing timing
and uncertainty to be the mean and standard deviation of the
10,000 noted times.

3. METHOD WITH APPLICATION TO COROT-2

3.1. Global Light Curve Spot Model

Characterizing stellar spots by fitting a spot model to the
global light curve is complicated by a large number of free
parameters, degeneracies between parameters, spot evolution,
and the need to make assumptions about spot shape. Our goal
with spot modeling is the robust determination of the rotational
phase of each spot at any given moment of time, which is
possible despite the above concerns. Because star spots may
change shape, migrate, appear, and disappear over the entire
135 day observing window of CoRoT-2, we analyze a shorter
75 day segment from BJD 2454247.5 to 2454322.5 of the
CoRoT-2 data set, which we further subdivide into three 25 day
subsets. We determine an independent best-fit spot model for
each of the three subsets, thus allowing for spot evolution from
one data subset to the next. The 25 day window length is a
compromise between the need for several stellar rotations in
order to reliably determine spot longitudes, and the need to
model over a time window that is ideally no longer than the
evolutionary timescale of the starspots. We note that Lanza et al.
(2009) find a typical spot lifetime of approximately 55 days for
CoRoT-2, and a cyclic oscillation in the total spotted area with
a period of approximately 29 days.

We adopt the analytical spot model of Dorren (1987), which
assumes circular spots and linear limb darkening. Following
Fröhlich et al. (2009), we adopt a three-spot model for CoRoT-2.
We allow for differential rotation by fitting the period of each
spot independently. Our model includes five parameters for
each spot: spot radius, latitude, spot-star brightness ratio, and
the period and epoch of rotation. The model also includes a
linear limb-darkening parameter and the stellar spin inclination.
One possible improvement to the spot modeling would be to
extend the Dorren (1987) analytical model to include quadratic
limb darkening, however, we opted for the relative simplicity
of linear limb darkening. We expect that the differences in the
estimated rotational phases resulting from an improved model
would have insignificant effect on the determination of the
spin–orbit alignment, given the relatively large uncertainties
in the spot-crossing timings.

We searched for the best-fit solution to each 25 day subset
using a downhill simplex method. The combined, 75 day best-fit
model is depicted in Figure 1. Previous attempts to fit a single
model to the entire 75 day time series led to a significantly worse
fit to the global light curve than that of the three-subset model
adopted in this study. While the fit is imperfect, the local minima
and maxima are reproduced accurately, indicating a reliable
determination of the spot rotational phases. The best-fit model
(in each of the three data subsets) is characterized by one spot
with period near 4.94 days, and two spots with slightly different
periods near 4.55 days, which are separated in rotational phase
by approximately 155° at BJD BJD 2454247.5, though drifting
apart due to differing rotation periods. The latter two spots
correspond well with the two active longitudes described in
Lanza et al. (2009).

Upon finding the best-fitting spot model, we determine the
rotational phase, $\alpha$, of each spot at the time of each transit. We
define a spot’s $\alpha$ so that it ranges from $-180°$ to $180°$ and equals
zero when the spot is coincident with the projected stellar spin
axis. To place an upper bound on the uncertainty of the rotational
phases, we performed a Markov Chain Monte Carlo (MCMC)
analysis on each of the three data segments. The acceptance
probability for new samples in the chain was calculated with
$\chi^2 = \sum_i (F_i - F_{i,\text{mod}})/\sigma^2$, and where $F_i$
and $F_{i,\text{mod}}$ give the flux and model fluxes, respectively. We set
$\sigma$ to 1%, a factor of 100 greater than the rms residual to the
best-fit model. We adopted this greatly inflated value for $\sigma$
to conservatively account for the correlated residuals of the
data and because we were only interested in placing an upper
bound on the uncertainty of the rotational phases. With these
inflated measurement errors, we found the $1\sigma$ uncertainties
in the rotational phases to be approximately 3°. Given the uncertainty in spot-crossing timings, this is an adequate level of accuracy for our analysis, and, therefore, we ignored the uncertainty in rotational phases below.

In this Letter, we focus on one of the two fitted spots with period near 4.55 days, which shows evidence of being occulted by the planet in several transits. Over the observational window that we analyze, we note that during each transit for which the rotational phase of this spot was between −70° and 70°, there is a clear spot-crossing bump in the transit light curve. Arranging the transit light curves in order of increasing \( \alpha \) for this spot, the spot-crossing bumps recur later and later along the transit light curve (see Figure 2). The simplest explanation for this phenomenon is that the planet’s orbit is prograde and relatively well aligned with the projected stellar spin axis, and that the bumps shown in Figure 2 represent the same spot being occulted by the planet multiple times. In our modeling below, we assume that each of the perturbations in the transit light curves is due to this spot. In Table 1, we list the rotational phases of this spot at the time of transit center, for each of the transits that we analyze below.

### 3.2. Spot-crossing Model

Given the rotational phase and latitude, \( l \), of a spot, the stellar spin inclination, \( i_s \), the projected spin–orbit alignment angle, \( \lambda \), and transit impact parameter, \( b = a/R_\star \cos i_p \), we can predict the time during transit of maximum spot perturbation. In an analysis of CoRoT-2 transit photometry, Gillon et al. (2010) find \( b = 0.221^{+0.017}_{-0.019} \). The uncertainty in \( b \) is insignificant for our purposes, so we fix \( b = 0.221 \). We assume that the time of maximum spot perturbation occurs when the transiting planet is at minimum sky-projected separation from spot center (see Section 2.2).

Any given spot-crossing model is specified by three parameters, \( \lambda, i_s, \) and \( l \). We do not enforce consistency of \( i_s \) and \( l \) with best-fit values determined from the spot model fit to the global light curve, as these values are poorly constrained by the global photometry. Our \( \chi^2 \) statistic is defined as follows:

\[
\chi^2 = \sum_{E=1}^{8} \frac{(T_E(\lambda, i_s, l) - t_E)^2}{\sigma_E^2} + P_E, \tag{1}
\]

where \( T_E(\lambda, i_s, l) \) is the model predicted spot-crossing timing for transit \( E \), \( t_E \) is the measured timing, and \( \sigma_E \) is the measurement uncertainty (see Table 1). \( P_E \) is a penalty term which is zero whenever the spot center at the time of transit is within 30° spherical distance of the transit chord, and a punitively large number (we picked 99) otherwise. Because we do not know exactly how large the spot is, we chose a conservatively large value of 30° for the required spot proximity.

The intuition behind the goodness-of-fit of a spot-crossing model is demonstrated in Figure 3. For a good fit, a model must accurately predict both the existence and timings of observed spot crossings. In the misaligned example of Figure 3, the starspot on the left would not produce a perturbation, thus incurring a penalty term if one was indeed observed; whereas in the aligned example, the starspot on the left would produce

![Figure 1. Global light curve of CoRoT-2 over the time window we have analyzed. The solid curve depicts the best-fit spot model. The transits have been cut out of this data. Below are residuals to the best-fit model, with a constant offset to +0.97.](image-url)
Figure 2. Series of transit light curves shown in order of increasing spot rotational phase. Generally, the spot is occulted at progressively later positions in the transit light curve, with black bars indicating the spot-crossing timing as measured with the technique described in Section 2.2. The gray bars indicate the expected spot-crossing time for a well-aligned planet with $\lambda = 0$ and $i_s = 90^\circ$. The time axis is scaled so that ingress and egress, defined here by the time when the planet center crosses the stellar limb, occur at $-1$ and $1$.

Figure 3. Schematic of spot crossings for a well aligned (left) and a misaligned (right) planetary orbit, with spot (gray) shown before and after a $120^\circ$ rotation of the star. The relative size and impact parameter of the planet (black) reflect that of the CoRoT-2 system. A planet must be well aligned to exhibit spot crossings along the entire transit chord. The exact timing of a spot crossing during transit, given the rotational phase of the spot, further constrains $\lambda$, while $i_s$ is largely degenerate with the spot latitude.

We emphasize that, given the large and uncertain star spot sizes on CoRoT-2, the latitude of spot center is not constrained to be in the band occulted by the disk of the planet. This limitation, combined with the large spot-crossing timing uncertainties, leads to a degeneracy of $i_s$ with $l$; almost any $i_s$ can be allowed by adjusting the spot latitude, such that the spot is near the occulted band. In the limit of a spot that is much smaller than the planet, we would require the projected distance between spot center and the transit chord to be less than the radius of the planet. This constraint, especially if accompanied by well-determined spot-crossing timings, would allow for the degeneracy between $i_s$ and $l$ to be broken, and allow for a reliable determination of the stellar spin inclination.

To determine the posterior probability distribution for the parameters, we employed MCMC, with acceptance probability calculated with the likelihood $\exp(-\chi^2/2)$. We assumed prior distributions that are uniform in $\lambda$, $\cos(i_s)$, and $\sin(l)$. We take the measured value and $1\sigma$ uncertainty for each parameter to be the mean and standard deviation of the MCMC samples. We find $\lambda = 4^\circ.7 \pm 12^\circ.3, i_s$ and $l$ are very poorly constrained and the MCMC samples demonstrate strong degeneracy between these two parameters. Nevertheless, we report these values for completeness: $i_s = 84^\circ \pm 36^\circ$ and $l = 14^\circ \pm 30^\circ$, where $i_s < 90^\circ$ indicates the rotation axis tilted toward the line of sight and

a maximum perturbation just after ingress. In this way, we can distinguish misalignments of tens of degrees.
$i_r > 90^\circ$ indicates the rotation axis tilted away from the line of sight.

To see how important the influence of the penalty term is on the determination of $\lambda$, we repeated the analysis using the $\chi^2$ statistic without the penalty term. We find $\lambda = 0:3 \pm 16:8$. As evident from the larger error bar, the penalty term is an important, though not the dominant constraint within our method.

4. DISCUSSION

In this Letter, we have described a new method to determine the spin–orbit alignment of a transiting planet, and applied it to CoRoT-2b, finding $\lambda = 4:7 \pm 12:3$. This planet was also the subject of RM measurements by Bouchy et al. (2008), who found $\lambda = 7:2 \pm 4:5$. Compared to the results of Bouchy et al. (2008), our result is consistent, though less precise. We also placed a weak constraint on the stellar inclination, $i_s = 44^\circ \pm 36^\circ$. Although this constraint is uninformative, we expect that applying our method to systems with starspots that are smaller than the planet will yield accurate determinations of the stellar inclination. This possibility illustrates one advantage of our method over the RM method, which is entirely insensitive to differences in the stellar inclination.

Our method possesses other advantages over RM measurements. RM measurements require costly radial velocity follow-up, while our method makes use of “free” data, in the sense that the data were already obtained for other purposes. RM measurements are generally only possible for stars with relatively large projected rotational velocities, ruling out slow rotators, or relatively fast rotators that are nearly pole-on. The RM method requires relatively large transit depths; the smallest planet that requires relatively fast rotators that are nearly pole-on. The RM method favors large transit depths, we expect that applying our method to systems with starspots that are smaller than the planet will yield accurate determinations of the stellar inclination. This possibility illustrates one advantage of our method over the RM method, which is entirely insensitive to differences in the stellar inclination.

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The method described in this Letter is similar, in concept, to that described by Sanchis-Ojeda et al. (2011), and applies similar geometrical constraints. In contrast to Sanchis-Ojeda et al. (2011), our method relies on global light curve measurements of the rotational period and phase of the occulted spot. This has the disadvantage of requiring a continuous, long time baseline of observations, which is generally only possible with space-based photometric monitoring, such as provided by the CoRoT and Kepler missions. However, there is a great advantage to knowing where the spot is on the stellar surface. For instance, only one transit of a planet over a spot is required to tell rough spin–orbit alignment. If we know, from out-of-transit monitoring, that the spot is on the approaching side of the star (i.e., negative rotational phase), then a spot crossing near the beginning of the transit indicates a probable prograde orbit, while a spot crossing near the end of the transit indicates a probable retrograde orbit (with some exceptions for nearly pole-on stellar rotation). To achieve good precision, of course, our method favors multiple spot crossings at varying spot phases.

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