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Secondary eclipses in the CoRoT light curves

A homogeneous search based on Bayesian model selection

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Abstract. We identify and characterize secondary eclipses in the original light curves of published CoRoT planets using uniform detection and evaluation criteria. Our analysis is based on a Bayesian statistics: the eclipse search is carried out using Bayesian model selection, and the characterization of the plausible eclipse candidates using Bayesian parameter estimation. We discover statistically significant eclipse events for two planets, CoRoT-6b and CoRoT-11b, and for one brown dwarf, CoRoT-15b. We also find marginally significant eclipse events passing our plausibility criteria for CoRoT-3b, 13b, 18b, and 21b, and confirm the previously published CoRoT-1b and CoRoT-2b eclipses.

1. INTRODUCTION

Secondary eclipse observations of transiting extrasolar planets allow us to study the planetary and orbital properties not attainable by the transit and radial velocity (RV) observations alone. The two main measurables, planet's albedo and brightness temperature, are strongly coupled with the structure and dynamics of the atmosphere, and can be used to educe information about the physical processes governing the atmosphere. Due to the complexity of the physics involved, this additional empirical knowledge is highly valuable when aiming to understand the planetary atmospheres via theoretical modeling. Eclipses also yield information about the planet's orbit. The eclipse center times and durations allow us to constrain the orbit's eccentricity and argument of periastron to a higher precision than with RV observations alone. This is especially true for the planets orbiting faint or rapidly rotating stars, for which precise RV observations are difficult to obtain.

The CoRoT planets are based on one of the highest-precision data sets available, and all of them have been thoroughly characterized in their respective discovery papers. Here we abridge the results of our homogeneous search for secondary eclipses in the light curves of all CoRoT planets published until June 2012, namely CoRoT 1b to 23b, including the brown dwarf 15b, but excluding the yet unpublished planet 22b. A more in-depth view to the work is given in [1].

2. THEORY

2.1 Bayesian statistics

We base our analysis on Bayesian statistics. The first part of the analysis, eclipse search, uses an approach built on Bayesian model selection [2–4], while the model parameter estimation for the found

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eclipses is carried out by calculating the full posterior distributions using Markov Chain Monte Carlo (MCMC) [3, 5].

Bayes' theorem states that the posterior probability distribution $P(A|D)$ for a proposition A with given data D can be derived from the prior probability distribution $P(A)$ and the likelihood of the data for the given proposition, $P(D|A)$, as

$$P(A|D) = \frac{P(A)P(D|A)}{\int P(A)P(D|A)\mathrm{d}A}\,. \tag{1}$$

Assuming normally distributed errors for our observational data D, the logarithm of the posterior probability (using $\ln P$ instead of P is customary for convenience) for a model M with a parameter vector $\vec{\theta}$ is

$$\ln P_M(\vec{\theta}|D) = \ln P(\vec{\theta}) - \frac{N}{2}\ln 2\pi - N\ln\sigma - \chi^2. \tag{2}$$

For model comparison, we need to calculate the global likelihoods for all the models by marginalizing the posterior probability over the model parameters as

$$P(M) = \int P(\vec{\theta})P(D|\vec{\theta})\mathrm{d}\vec{\theta}, \tag{3}$$

and, given the global likelihoods, we can calculate the Bayes factor [2, 3, 6] of a model M_i over model M_j as

$$B_{ij} = P(M_i)/P(M_j). \tag{4}$$

Model probabilities can then be calculated from the Bayes factors, or the Bayes factors can be used directly to give "a rough descriptive statement about standards of evidence" [2].

2.2 Estimation of brightness and equilibrium temperatures

The brightness and equilibrium temperature estimates are calculated in Monte Carlo fashion combining the published estimates for the semi-major axis, radius ratio, and stellar temperature using the flux-ratios estimated from the eclipse depths. The equilibrium temperatures are calculated as

$$T_{\mathrm{eq}} = T_\star \theta_{\mathrm{a}}^{-1/2} \left(f\,(1 - A_{\mathrm{B}})\right)^{1/4}, \tag{5}$$

where $T_\star$ is the estimated stellar temperature, θ_{a} the scaled semi-major axis, f the heat redistribution factor, and A_{B} the Bond albedo. The brightness temperature, T_{br}, is numerically solved from the equation

$$\theta_{\mathrm{f}} = A_{\mathrm{g}}\theta_{\mathrm{a}}^2 + B(T_{\mathrm{br}})/B(T_\star), \tag{6}$$

where the first term represents the reflected light and the second the thermal radiation with θ_{f} being the surface flux ratio, A_{g} the geometric albedo (we use $A_{\mathrm{g}} = 1.5A_{\mathrm{B}}$), and B is Planck's law (i.e., we approximate the stellar radiation with a blackbody). The planet's Bond albedo is allowed to range from 0 to 0.3, and the heat redistribution factor from 1/4 to 2/3. Thus, the reported 95% credible intervals advises us on the possible values of T_{br} and T_{eq} assuming a small albedo and without assumptions about the heat redistribution efficiency.

2.3 Priors

The prior probability distributions are used to encode our prior information of factors affecting the posterior probability distribution. In our case the major factors are the stellar and planetary properties, such as the orbit period, semi-major axis, effective stellar temperature etc. We construct the priors based on the stellar and planetary properties gathered from the latest publications discussing the systems. The adopted planet and host star properties are listed in Tables 2 and 3 of [1].

Table 1. Main results form the combined Bayesian analysis for the planets with detected eclipse candidates.

Planet	B_{10}	Phase	Eccentricity	Depth [‰]	T_{br} [K]	T_{eq} [K]
Previously reported planets						
CoRoT-1b	7.6 ± 0.2	0.495 ± 0.002	0.04 ± 0.03	0.20 ± 0.08	1580 – 2500	1830 – 2430
CoRoT-2b	2.0 ± 0.0	0.501 ± 0.002	0.03 ± 0.03	0.07 ± 0.05	1430 – 2110	1460 – 1930
Statistically significant new eclipse candidates						
CoRoT-6b	10.6 ± 0.7	0.533 ± 0.000	0.06 ± 0.01	0.27 ± 0.10	2230 – 2840	970 – 1270
CoRoT-11b	$(5.5 \pm 1.1) \times 10^4$	0.558 ± 0.002	0.35 ± 0.03	0.36 ± 0.07	2580 – 3020	1650 – 2180
CoRoT-15b	27.2 ± 2.9	0.495 ± 0.001	0.08 ± 0.05	1.37 ± 0.40	3470 – 4710	1580 – 2340
Statistically marginal new eclipse candidates						
CoRoT-3b	2.3 ± 0.0	0.509 ± 0.001	0.06 ± 0.06	0.08 ± 0.05	1940 – 3070	1610 – 2170
CoRoT-13b	3.3 ± 0.1	0.483 ± 0.001	0.08 ± 0.04	0.25 ± 0.12	2150 – 3080	1220 – 1610
CoRoT-18b	3.1 ± 0.1	0.469 ± 0.002	0.10 ± 0.04	0.71 ± 0.30	2130 – 3020	1440 – 1950
CoRoT-21b	1.7 ± 0.0	0.474 ± 0.002	0.05 ± 0.02	0.27 ± 0.15	2210 – 3600	1930 – 2600

3. DATA

We use the latests versions of the CoRoT N2 light curves available publicly from the IAS Data Center[1] as of June 2012. We use the chromatic light curves when available, but include from them only the red channel for the analysis to reduce the number of jumps from cosmic ray hits. We use both the 32 and 512 second time cadences (when available) by assigning the two cadences a separate mean point-to-point scatter (error) estimate in the analysis, and exclude the phase-span near the primary transit completely from the analysis.

4. ANALYSIS

Our analysis consists of three main steps: eclipse identification, false-positive tests, and eclipse candidate characterization. The analysis code combines Fortran2003 for the numerically intensive computations and Python for the high-level functionality. We use simple Monte Carlo (MC) importance sampling to obtain the global likelihood estimates, and Markov Chain Monte Carlo (MCMC) methods to obtain the parameter posterior distributions.

5. RESULTS AND DISCUSSION

Our results are summarized for the planets with found eclipse candidates in Table 1. The first column list the Bayes factors for the favor of the eclipse model against the no-eclipse model, the next three columns show the median estimates for the eclipse center, eccentricity, and eclipse depth from the MCMC analysis. The uncertainties correspond to the 68.2% credible intervals, or the 1σ confidence limits if the posterior distributions are close to normal. Finally, the last two columns list the 95% credible intervals for the brightness and equilibrium temperatures.

5.1 Previously reported eclipses: CoRoT-1b and CoRoT-2b

We used the two CoRoT planets with confirmed eclipses, CoRoT-1b [7] and CoRoT-2b [8], to test our method. We are able to identify both of the eclipses: the eclipse for CoRoT-1b is detected with a Bayes

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factor of 7.6 in favor of the eclipse model, and for CoRoT-2b we obtain a (marginal) Bayes factor of 2.0. The eclipse depth and brightness temperature estimates for both of the planets agree with the published results, and we consider out method to be reliable in finding eclipse candidates.

5.2 New Statistically significant eclipse candidates

We find statistically significant eclipse event candidates for CoRoT-6b [9], CoRoT-11b [10], and CoRoT-15b [11]. The eclipse candidates pass all our false-positive tests, and are unlikely due to a single jump-event in the light curve or correlated noise. However, the candidates all yield high brightness temperatures when considering their theoretical equilibrium temperatures.

While having anomalous T_{br} estimates for all the new eclipse candidates is suspicious, a similar trend has been observed for the secondary eclipses found in the Kepler light curves [12], and may be explained by several different mechanisms. First, a selection bias favors the discovery of deep eclipses (and high T_{br}). Second, the equilibrium temperature is calculated assuming both the planet and the star to behave as black bodies, and considering stellar irradiation as the only heat source. These are strong simplifications, and the existence of external heat sources (tidal and radiogenic heating), or non-LTE emission, may explain the discrepancy.

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