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Modelling secondary eclipses of *Kepler* exoplanets

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Abstract. We have selected several *Kepler* objects with potentially the deepest secondary eclipses. By combination of many single phased light-curves (LCs) we have produced a smooth LC with a larger SNR and made the secondary eclipses more distinct. This allowed us to measure the depth of primary and secondary minimum with greater accuracy and then to determine stellar and planetary radii by simplex modelling.

1 Introduction

The occultation of the transiting exoplanet by its parent star will manifest on the LC as a shallow secondary minimum. The precise photometry obtained by the *Kepler* spacecraft theoretically allows to distinguish the corresponding drop in flux. From a list [2] of objects with potentially sufficient depth of secondary eclipse we have selected objects with high planet-to-star luminosity ratio (L_P/L_S) and a high significance of the detection of the secondary minimum (σ_{II}). KOI-1541.01 and KOI-1543.01 both with highest L_P/L_S show flux variations due to the presence of photospheric spots, thus we decided not to impose additional possible trends to the LC by an irregular de-trending. To compare our approach to the existing data we have selected systems KOI-2.01 and KOI-13.01 with previously identified secondary minima. Additional objects KOI-10.01, KOI-254.01 were investigated to search for the presence of the secondary minimum.

2 Data preparation and method

We have used publicly available data from quarters Q0-Q16 from the Mikulski Archive for Space Telescopes (MAST). All LCs were plotted with fluxes processed via an updated PDC pipeline (see [10] and [9]) and normalized. To keep better time resolution we limited the selection only for short-cadence (58.85 s) LCs. We have applied a running linear fit with anchor points around orbital phases $\varphi = 0.25$ and $\varphi = 0.75$ to de-trend the raw data. Additionally, we have corrected the measured flux of KOI-13.01 by $\sim 45\%$ [11] of total maximum flux to remove the parasitic light of the second stellar component. We have modelled the depth of the secondary minimum with respect to the reflection and ellipsoidal variations [6]. We divided the time series into separate epochs. Then we have selected only phased LCs with time series longer than 0.5×transit period which contained data around the planetary occultation at $\varphi = 0.5$. We have then used a spline interpolation based on the Hermite polynomials [7] to co-add the particular number of phased LCs (row "LCs" in table 1). The noise in normalized flux dropped down to 20 – 50% of it's value before the co-addition and we have measured the depths of primary Δ_{I} and some secondary minima Δ_{II} (see table 1). We have used an simplex algorithm to minimize analytical expressions of the transit geometry [5] to fit both primary and secondary minima. Initial values of the ratio of planetary and stellar radii R_P/R_S, the ratio of the stellar radius to the separation R_S/a and the time of primary minimum (t_0) were adopted from the table of *Kepler* candidates at MAST. Initial

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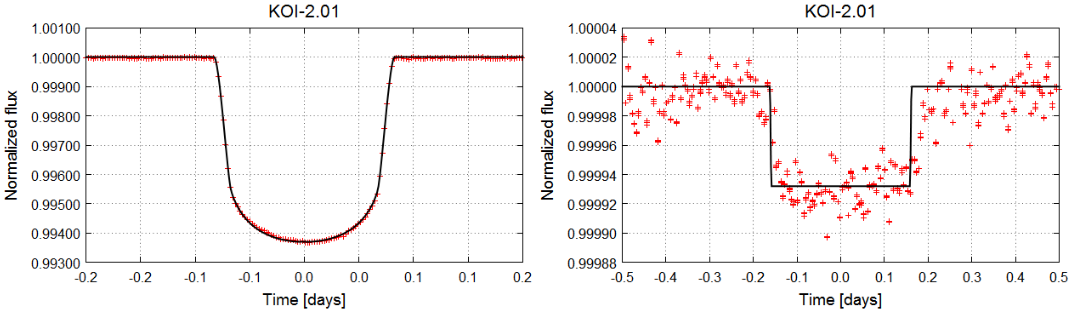

Fig. 1. Best fit (solid lines) for KOI-2.01 primary (left) and secondary (right) minima.

Table 1. Results (bold face) from our modelling of the primary and secondary minima. Values marked with "!" were adopted and fixed during the modelling. Previous results are cited for comparison.

	KOI-2.01			KOI-13.01			KOI-10.01			KOI-254.01		
LCs	148			93			98			280		
i [deg]	**83.68**	83.92	[2]	**81.00**	79.79	[2]	**84.26**			**87.19**	87.00	[4]
Δ_{I} [ppm]	**6297**	6716	[1]	**7831**	4644	[1]	**9463**	9390	[1]	**40969**	32040	[4]
Δ_{II} [ppm]	**68**	130	[1]	**157**	120	[11]	-			-		
R_P [$R_\odot$]	**0.100**	0.104	[2]	**0.204**	0.165	[2]	**0.148**	0.142	[3]	**0.104**	0.096	[4]
R_S [$R_\odot$]	**1.336!**	1.336!	[2]	**2.454!**	2.454!	[2]	**1.56!**	1.56!	[4]	**0.55!**	0.55!	[4]
Δ_{II}/Δ_{I}	**0.011**	0.019		**0.020**	0.026		-			-		
R_P/R_S	**0.075**	0.078		**0.083**	0.067		**0.095**	0.091		**0.189**	0.175	
u_1	**0.3135**			**0.3532**			**0.2496**			**0.2526**		
u_2	**0.3102**			**0.2876**			**0.2910**			**0.2932**		

inclination (i) was adopted from [2]. Quadratic limb darkening coefficients (u_1, u_2) were interpolated from [8]. Modelling of KOI-2.01 and KOI-13.01 shows a promise of this method, however we were unable to distinguish secondary minima in KOI-10.01 and KOI-254.01. This method requires large number of individual phased LCs and with short cadence to provide many data points per single LC.

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