Transiting Planets
Proceedings IAU Symposium No. 253, 2008
Frédéric Pont, Dimitar Sasselov & Matthews Holman, eds.

doi:10.1017/S1743921308026756

How to use the Phoebe code to solve transiting exoplanet light curve

Stanislav Poddaný[1,2]

[1]Astronomical Institute, Charles University, Faculty of Mathematics and Physics, V Holešovičkách 2, Prague, Czech Republic

[2]Štefánik observatory, Observatory and Planetárium of Prague, Petřín 205, Prague, Czech Republic

email: poddany@observatory.cz

Abstract. A brief demonstration of photometric light curves solutions for eight transiting exoplanets using the Phoebe 0.29c code is presented. We determined radii and inclinations for TrES-1b, TrES-2b, Wasp-1b, XO-1b, XO-2b, OGLE-TR-10b, OGLE-TR-111b and HD 189733b. All our results are in good agreement with the last results published.

1. Introduction

Many authors present analyses of transit light curves using their own codes. There are only a few homogeneous studies of higher numbers of known transiting planets. We decided to use Phoebe 0.29c (Prša and Zwitter 2005) for transiting exoplanet light curve solutions for eight well-observed extrasolar planets because it is a well-known code based on the Wilson-Devinney method (Wilson and Devinney 1971) that is frequently used to simulate the light curve of eclipsing binaries and to determine parameters of systems based on these models. Transiting planets are almost the same physical problems as eclipsing binaries, so that this powerful tool can be used to model exoplanet transits.

2. Observations

In this work we used the high-precision light curves of eight exoplanets. We modelled a z-band (Sloan Digital Sky Survey filter - SDSS) light curve of TrES-1 that was obtained by Winn *et al.* (2007a). This dataset of 1149 datapoints covers three consecutive transits. The light curve of the exoplanet TrES-2 was obtained by Holman *et al.* (2007b). This light curve was also made in the z-band, it contains 1033 observations and covers 13 orbital cycles. An excellent I-band light curve of the exoplanet Wasp-1b that was used in our simulations was obtained by Shporer *et al.* (2007) and covers two transits (583 points). To study the exoplanet XO-1b we light curves in variety passbands from Holman *et al.* 2006. These authors obtained a precise z-band light curve (821 observations) from theFLWO 1.2-m that covers two transits. From the Palomar 1.5-m telescope obtained an R-band light curve (208 obs.) and from the TopHAT 0.26-m an I-band light curve (279 obs.). The light curve of XO-2 studied here is taken from Burke *et al.* (2007). They presented a good R-band light curve containing 1389 datapoints. For OGLE-TR-10b, we analyzed the light curves from (Holman *et al.* 2007a). They obtained light curves in two passbands, one in the I-band (387 obs.) and one almost one year later in the B band (104 obs.). The dataset for OGLE-TR-111 used for our analysis was obtained by Winn *et al.* (2007b). This dataset contains as I-band light curve with 386 observations. The last exoplanet studied in this work was HD 189733b. We solved the light curve presented by Bakos *et al.* (2006) (127 observations in the *B* band, 301 in the *R* band) and the light curves obtained by Winn *et al.* (2006) - the FLWO 1.2-m *z*-band light curve (1661 obs.) and the Wise 1.0-m *I*-band light curve (344 obs.).

3. Solution technique

Setting the Phoebe code

Because of the extremely small mass ratio and the low luminosity of exoplanets, we had to change some default values in the Phoebe code. First we increased *"Stellar surface fine grid raster"* from 20 to 60 and *"Stellar surface coarse grid raster"* from 5 to 15. The iteration step in *"Primary and secondary surface potentials"* had to be changed as well (see below).

In this work the logarithm limb darkening law was used and the coefficients for fitting were taken from the Van Hamme limb darkening tables. Most of the excellent light curves solved here were made in the *z*-band. Unfortunately, this type of band is not included in the current version of the Phoebe code yet (it will be included in the next version). Because of this, we solved them as the *I* Johnson standard filter.

With the light curve alone (without radial velocity measurement) it is not possible to determine all system parameters. Hence we use semi-major axes, mass ratios and orbital periods as published in the latest papers (Table 1). Other parameters like primary stars temperature were obtained from a spectral model Harmanec (1988). The planet temperatures were set at 3000 K (this parameter is not relevant to the fit).

The primary and secondary albedo coefficients we assumed to be 0.5 (Rucinski 1969) because the temperature of all parent stars is lower than 7200 K. The gravity darkening coefficients was assumed to be 0.32 (Lucy 1968) also because of the temperature.

The fitting process.

The fitting process of each system was started with mass ratio 0.1 and inclination 88 degrees. First, we fitted the primary and secondary star luminosities (HLA), after combining HLA with surface potentials (PHSV, PCSV) and inclination (INCL). Then we changed the mass ratio (from 0.1 to 0.08) and repeated the fit for the luminosities. We continued in such sequences until we got the mass ratio of the modeled system (Table 1). When the mass ratio reaches a value under 0.01, we had to change the default iteration step in *"Primary and secondary surface potentials"* (from 0.1 to 0.01). Finally we fitted several different combinations of parameters until the synthetic light curves were in a good agreement with the observed data (see the Figures 1 and 2, χ^2 of the synthetic light curves are lower than 0.002).

Reading the results.

The result for the inclination can be directly seen in the *"System-related"* table. The radii of the components (and the masses as well) are hidden in the *"Light Curve Plot"* window. Unfortunately, in the Phoebe 0.29c code only three decimal places are used for this results (the solar units are used). For higher accuracy it is necessary to increase the semi-major axis (100 times) and later compensate it in the derived values.

4. Conclusion

We determined radii and inclinations for eight exoplanets TrES-1, TrES-2, Wasp-1b, XO-1b, XO-2b, OGLE-TR-10b, OGLE-TR-111b and HD 189733b using the standard code for eclipsing binaries systems. Even if we have used the *I* Johnson standard filter

Table 1. Adopted parameters.

System	**Orbital period** (days)	**Semi-major ax** (AU)	**Mass ratio**	**Reference**
TrES-1	3.030065	0.0393	0.00085	*Winn et al. 2007a*
TrES-2	3.030065	0.0367	0.00120	*Holman et al. 2007b*
Wasp-1b	2.519961	0.0382	0.00075	*Shporer et al. 2007*
XO-1b	3.941534	0.0488	0.00100	*McCullough et al. 2006*
XO-2b	2.615857	0.0369	0.00056	*Burke et al. 2007*
OGLE-TR-10b	3.101278	0.0416	0.00056	*Holman et al. 2007a*
OGLE-TR-111b	4.014447	0.0470	0.00070	*Winn et al. 2007b*
HD 189733b	2.218573	0.0312	0.00140	*Winn et al. 2006*

Table 2. Comparison of determined planets inclinations and radii with latest results.

System	**Radius** (R_J)[1]	**Inclination** (deg.)	**Radius** (R_J)[2]	**Inclicnation** (deg.)[3]
TrES-1	1.11	88.53 ± 0.52	1.08 ± 0.03	89.99 ± 0.97
TrES-2	1.29	83.53 ± 0.25	1.24 ± 0.09	83.55 ± 0.12
Wasp-1b	1.51	87.57 ± 0.32	1.40 ± 0.08	87.30 ± 2.30
XO-1b	1.20	88.86 ± 0.45	1.18 ± 0.03	88.71 ± 0.38
XO-2b	0.97	88.73 ± 0.21	0.97 ± 0.03	88.32 ± 0.36
OGLE-TR-10b	1.25	85.57 ± 0.33	1.26 ± 0.07	86.04 ± 0.65
OGLE-TR-111b	1.11	88.32 ± 0.27	1.07 ± 0.05	88.11 ± 0.51
HD 189733b	1.13	85.89 ± 0.35	1.15 ± 0.03	85.74 ± 0.17

Notes: [1]It is impossible to determine the error of the radius in the Phoebe 0.29c code (This will be possible in the next version, probably Phoebe 0.32 or higher). [2]Burrows *et al.* 2007 [3]Southworth J. 2008

instead of the z SDSS band, all our results in good agreement (inside error bars) with the latest results published by Southworth and Burrows *et al.* (Table 2).

The next version of the Phoebe code will include this SDSS band and the CoRoT:exo filter (that is already included in the last version - Phoebe 0.31a). With this properties and the possibility of simulating the spots on the star surface, this code becomes a powerful tool in the field of exoplanet as well.

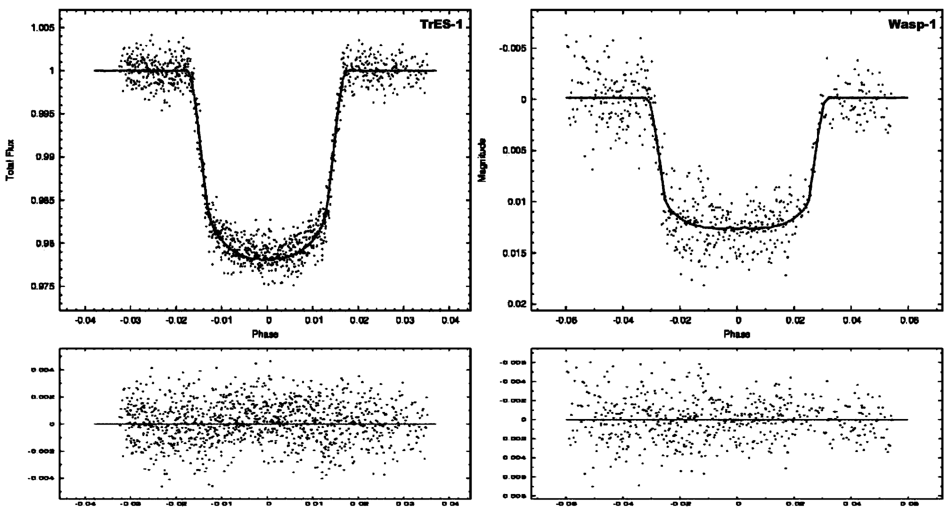

Figure 1. Transiting light curves of the TrES-1 (Winn *et al.* 2007a) and Wasp-1 (Shporer *et al.* 2007). Relative flux (magnitudes) against the orbital phase, with the best-fitting model. Residuals, derived by the subtraction of the model from the measurements, are plotted at the bottom.

https://doi.org/10.1017/S1743921308026756 Published online by Cambridge University Press

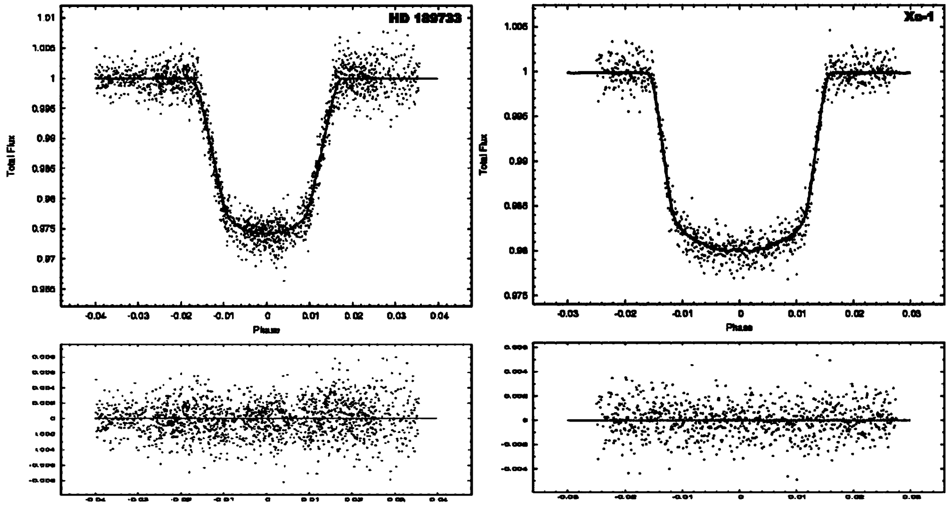

Figure 2. Transiting light curves of the HD189733 (Winn *et al.* 2006) and XO-1 (Holman *et al.* 2006). Relative flux against orbital phase, with best-fitting model. Residuals, derived by the subtraction of the model from the measurements, are plotted bottom.

5. Acknowledgements

We thank Marek Wolf for his helpful advices and Petr Zasche for his help with the Phoebe code. This investigation was supported by the Grant Agency of the Czech Republic, grants No. 205/08/H005. We also acknowledge the support from the Research Program MSM0021620860 of the Ministry of Education.

References

Alonso R. & Brown T. M., *et al.* 2004, *ApJ*, 613, L153
Bakos G. A., Knutson H., & Pont F., *et al.* 2006, *ApJ*, 650, 1160
Burrows A. & Hubeny I., *et al.* 2007, *ApJ*, 661, 502
Burke C. J. & McCullough P. R., *et al.* 2007, *ApJ*, 671, 2115
Harmanec P. 1988, *Bull. Astr. Inst. Czech.*, 39, 329
Holman M. J. & Winn J. N., *et al.* 2006, *ApJ*, 652, 1715
Holman M. J. & Winn J. N., *et al.* 2007a, *ApJ*, 655, 1103
Holman M. J. & Winn J. N., *et al.* 2007b, *ApJ*, 664, 1185
Lucy L. B. 1968, *ApJ*, 151, 1123
McCullough P. R., Stys J. E., & Valenti J. A., *et al.* 2006, *ApJ*, 648, 1228
Prša A. & Zwitter T. 2005, *ApJ*, 628, 426-438
Rucinski S. M. 1969, *Acta Astronomica*, 19, 245
Shporer, A., Tamuz, O., Zucker, S., & Mazeh, T. 2007, *MNRAS*, 376, 1296
Southworth J. 2008, *MNRAS*, 386, 1644
Wilson R. E. & Devinney E. J. 1971, *ApJ*, 166, 605
Winn, J. N., Johnson J. A., & Marcy G. W., *et al.* 2006 *ApJ*, 653, L69
Winn, J. N., Holman, M. J., & Roussanova, A. 2007a, *ApJ*, 657, 1098
Winn, J. N., Holman, M. J., & Fuentes, C. I. 2007b, *AJ*, 133, 1828

https://doi.org/10.1017/S1743921308026756 Published online by Cambridge University Press