Earth Moon Planet (2009) 105:385–389
DOI 10.1007/s11038-009-9338-3

Exomoon Simulations

A. E. Simon · Gy. M. Szabó · K. Szatmáry

Received: 23 December 2008 / Accepted: 30 June 2009 / Published online: 29 July 2009

Abstract We introduce and describe our newly developed code that simulates light curves and radial velocity curves for arbitrary transiting exoplanets and its satellite. The most important feature of the program is the calculation of radial velocity curves and the Rossiter–McLaughlin effect in such systems. We discuss the possibilities for detecting the exomoons taking the abilities of Extremely Large Telescopes into account. We show that satellites may be detected also by their RM effect in the future, probably using less accurate measurements than promised by the current instrumental developments. Thus, RM effect will be an important observational tool in the exploration of exomoons.

Keywords Planetary systems · Planets and satellites · Photometry · Radial velocities · Numerical methods

1 Introduction

The number of known transiting exoplanets is rapidly increasing, which has recently inspired significant interest as to whether they can host a detectable moon (e.g., Szabó et al. 2006; Simon et al. 2007; Deeg 2009). There has been no such example where the presence of a satellite was proven, but several methods have been investigated for such a detection in the future (barycentric transit timing variation, Sartoretti and Schneider 1999; Kipping 2008; photometric transit timing variation, Simon et al. 2007; transit duration variation, Kipping 2009, Time-of-Arrival analysis of pulsars, Lewis et al. 2008). Deviations from the perfect monoperiodic timing of transits can be detected in *O–C* curves

A. E. Simon · Gy. M. Szabó (✉) · K. Szatmáry
Department Experimental Physics and Astronomical Observatory, University of Szeged,
Dóm tér 9, 6720 Szeged, Hungary
e-mail: szgy@titan.physx.u-szeged.hu

A. E. Simon
e-mail: asimon@titan.physx.u-szeged.hu

K. Szatmáry
e-mail: k.szatmary@physx.u-szeged.hu

(Sterken 2005) and might suggest the presence of a moon (Díaz et al. 2008), perturbing planets (Agol et al. 2005) or suggest periastron precession (Pál and Kocsis 2008).

These methods require extremely high precision measurements, and all are based on the deep understanding of physical effects due to a satellite. Therefore, we developed a new code (Labview environment, NI 2008, http://www.ni.com/labview) for visualization and precise calculations of arbitrary transiting systems with a satellite. We simulate transit light curves and radial velocity curves for exoplanet–exomoon systems with adjustable masses, radii, orbit periods, eccentricities, inclinations and ascending node longitudes. This simulator generates light curve and radial velocity curves with Rossiter–McLaughlin effects for arbitrary planet–satellite systems with a handful adjustable parameters. We soon plan to publish the program after the current developing of the peripherals (such as improving the GU interface, enabling more input parameters, developing fitting algorithms etc.) will have been made ready, too.

Thanks to the recent improvements in spectroscopic design and instrumentation developments, one can expect reaching the ~1 cm/s velocimetric accuracy in a foreseeable future (e.g., utilizing laser frequency combs, Li et al. 2008). Therefore, we included the calculation of r_v curves into the code, and simulated the Rossiter–McLaughlin effects of the moon. This facility is one of the main features supported by our code, and enables to compare the light curves and radial velocity curves simultaneously.

2 Simulations

Our program offers a menu selection of four animated simulation windows (or GUIs). These show (i) a distant view of the orbit of the planet and the satellite; (ii) a zoom into the transit geometry (see an example in Fig. 1); (iii) the surface of the star behind the transiting objects and (iv) the light curves and radial velocity curves, respectively. In both GUIs, the transit parameters can be adjusted. The output files contain the light curve and the radial velocity curve with a header.

In Fig. 2, we show four sample simulations highlighting the most prominent observable light curve and r_v curve effects. The first is a modeled remote observation of our

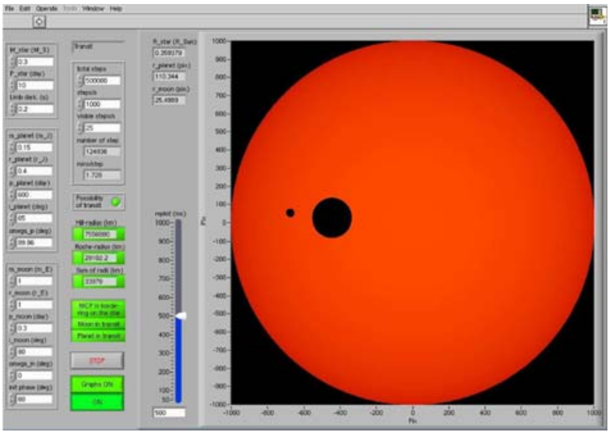

Fig. 1 The main GU interface of the simulator (in its present state) shows the configuration of the transit

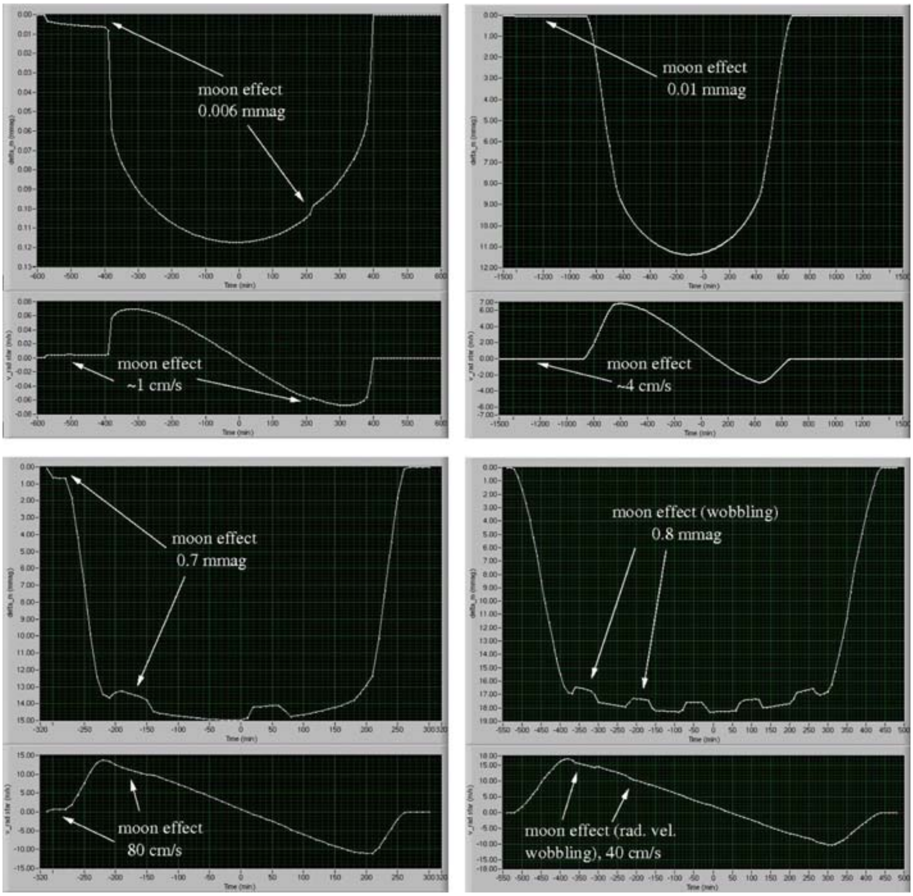

Fig. 2 Sample screenshots of simulations (data file GUIs). The four panels show the light curves in the upper part, and the velocity curves below. *Top left*: the Earth–Moon system; *top right*: the Jupiter–Ganymede system; *bottom left*: Simulation 3; *bottom right*: Simulation 4. See Table 1 for the parameters. The simulation is for a $0.3\,M_{\odot}$ star

Sun–Earth–Moon system, while the second one shows a system consisting of Jupiter and Ganymede orbiting the Sun, also observed remotely. Two hypothetical systems were designed up with a slowly (Simulation 3) and a rapidly (the moon orbits more times during the transit, Simulation 4) orbiting satellite. The most prominent observable effects are marked and quantified on the screenshots. For the hypothetical configurations, we summarized the sets of system parameters in Table 1.

3 Conclusions

For a *direct detection* of the moon in the photometric light curves, a large moon and a relatively small (thus low-mass) star is required. There is more chance for indirect detections with *Transit Timing Variation*. There is a possibility for the direct detection of a moon: a little transient shift of the radial velocity right before (or after) the transit, due to

Table 1 Input data of the simulations

Star mass		0.3 M_{Sun}
Star radius		0.36 R_{Sun}
Star rot. period		10 days
Limb darkening		0.5
	Planet	Satellite
Simulation 3		
Mass	0.15 $M_{Jupiter}$	1 M_{Earth}
Radius	0.40 $R_{Jupiter}$	1 R_{Earth}
Period	600 days	0.3 days
Inclination	65°	80°
Asc. node	0.04°	0°
Simulation 4		
Mass	0.15 $M_{Jupiter}$	1 M_{Earth}
Radius	0.45 $R_{Jupiter}$	1 R_{Earth}
Period	4,300 days	0.2 days
Inclination	70°	80°
Asc. node	0.04°	0°

the Rossiter–McLaughlin effect of the moon itself (Fig. 2 upper panels). Note that the RM amplitudes of the Moon and Ganymede are 0.8 cm/s and 4 cm/s, this latter is not apparent on this scaling (Sim. 2). If the moon is so close that during one transit it orbits the planet more times, this can lead to marked waves (wobbling) in the RM curve (Fig. 2 lower panels) that can have an amplitude of 10–100 cm/s.

An important observational constraint is the jitter that the planet-hosting star displays. It will be an error source in detecting any low-mass planets and their companions orbiting the star. Currently, there is very little available RV data with precisions better than 1 m/s, and so there is still not sufficient data. The current view is that the jitter level depends on the mass, activity and age of the star. Old, inactive G and K dwarfs typically offer the best planet-detection performance: few stars are known to have <1 m/s jitter, while they typically have jitter levels in the 1–5 m/s regime (Saar 2003; Wright 2005; O'Toole et al. 2008). The Geneva group with HARPS demonstrated that chromospherically quiet M dwarfs have a jitter level ≈ 1 m/s, mostly due to longer time-scale phenomena such as granulation noise (Mayor et al. 2009). Earlier-type stars generally have jitters in the 4+ m/s range, while active stars often exceed 10 m/s. Younger stars have far higher jitters increasing to 700 m/s at 12 Myr age (Paulson and Yelda 2006).

The lowest jitter levels are comparable to the RM effects due to a hypothetical satellite in the favorable cases, especially for late inactive dwarfs. Planet detection and precise orbit modeling is also easier for these stars because of their low mass. This means that nowadays telescopes perform nearly the precision required by a positive detections of exomoons, while the competent instrument for this observation will be the Extremely Large Telescope.

The main conclusions can be summarized as follows.

(1) Combining photometry and radial velocity measurements, there will be more chance for detecting exomoons. The moon's effect in the RM curve was modeled for an

Earth–Moon-like and Jupiter–Ganymede-like systems. The similar extrasolar systems may be detected in the future.

(2) For a direct detection in photometric curves, a large moon and a relatively small (i.e., low-mass) star is required. There is more chance for indirect detections with Transit Timing Variation (see Simon et al. 2007) from photometry.

(3) The radial velocity measurements can manifest the moon by its own RM effect superimposed on the RM curve.

(4) We suggest the analysis of the radial velocity measurements and photometric data together looking for signs of hosted satellites.

Acknowledgements This work has been supported by the OTKA K76816 Grant and the Bolyai János Research Fellowship of the Hungarian Academy of Sciences. The traveling and living expenses were financed by the National Office for Research and Technology, Hungary (Mecenatura Grant), the "Lendület Fiatal Kutatói Program" of the Hungarian Academy of Sciences and a funding provided by the Conference LOC.

References

E. Agol, J. Steffen, R. Sari, W. Clarkson, MNRAS. **359**, 567 (2005)
H.J. Deeg, IAUS. **253**, 388 (2009)
R.F. Díaz et al., Astrophys. J. **682**, 49 (2008)
D.M. Kipping, MNRAS. **389**, 1383 (2008)
D.M. Kipping, MNRAS. **396**, 1797 (2009)
M. Mayor et al., Astron. Astrophys. arXiv:0906.2780 (2009, accepted)
K.M. Lewis, P.D. Sackett, R.A. Mardling, Astrophys. J. **685**, 153 (2008)
C.-H. Li et al., Nature. **452**, 610 (2008)
S.J. O'Toole et al., MNRAS. **386**, 516 (2008)
A. Pál, B.Kocsis, MNRAS. **389**, 191 (2008)
D.B. Paulson, S.Yelda, PASP. **118**, 706 (2006)
S.H. Saar, The Future of Cool-Star Astrophysics: 12th Cambridge Workshop on Cool Stars, ed. by A. Brown, G.M. Harper, T.R. Ayres (University of Colorado, Colorado, 2003), p. 694
P. Sartoretti, J. Schneider, Astron. Astrophys. Suppl. Ser. **134**, 553 (1999)
A.E. Simon, K. Szatmáry, Gy. M. Szabó, Astron. Astrophys. **470**, 727 (2007)
C. Sterken, in *The Light-Time Effect in Astrophysics*, ed. by C. Sterken, ASP Conference Series vol. 335 (Astronomical Society of the Pacific, San Francisco, 2005), pp. 25–36.
Gy.M. Szabó, K. Szatmáry, Zs. Divéki, A. Simon, Astron. Astrophys. **450**, 395 (2006)
J.T. Wright, PASP. **117**, 657 (2005)