Setting a New Standard in the Analysis of Binary Stars
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PHOEBE 2.0 – TRIPLE AND MULTIPLE SYSTEMS

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Abstract. Some close binary formation theories require the presence of a third body so that the binary orbit can shrink over time. Tidal friction and Kozai cycles transfer energy from the binary to its companion, resulting in a close inner binary and a wide third body orbit. Spectroscopy and imaging studies have found 40% of binaries with periods less than 10 days, and 96% with periods less than 3 days, have a wide tertiary companion. With recent advancements in large photometric surveys, we are now beginning to detect many of these triple systems by observing tertiary eclipses or through the effect they have on the eclipse timing variations (ETVs) of the inner-binary. In the sample of 2600 Kepler EBs, we have detected the possible presence of a third body in ~20%, including several circumbinary planets. Some multiple systems are quite dynamical and feature disappearing and reappearing eclipses, apsidal motion, and large disruptions to the inner-binary. PHOEBE is a freely available binary modeling code which can dynamically model all of these systems, allowing us to better test formation theories and probe the physics of eclipsing binaries.

1 Introduction

Using transit timings and eclipse timings to find exoplanets is a well-known method (Schwarz *et al.* 2011). With *Kepler* data alone, Fabrycky (2012), Ford (2012), and

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Steffen (2012) have used transit timings to detect and study multiple planetary systems. *Kepler* 16 (Doyle *et al.* 2011), 34, and 35 (Welsh *et al.* 2012) were validated, in part, through their eclipse timing variations.

Furthermore, approximately 20% of *Kepler* eclipsing binaries have third-body candidates (Conroy *et al.* 2013; Rappaport *et al.* 2013; Gies *et al.* 2012; Orosz *et al.*, in preparation), most of which are likely stellar companions. Only a few of these have been confirmed with tertiary transits, as the third-body is often on a very wide orbit and must be perfectly aligned in order to observe eclipse events.

Modeling triple systems can often allow for greater precision in the resulting fundamental parameters than eclipsing binaries without companions. By modeling a large sample of multiple systems we can test theories of close binary formation and planetary migration caused by the presence of a third body, such as Kozai cycles and tidal friction (Bonnell 2001; Kiseleva *et al.* 1998).

2 Modeling ETVs

Borkovits *et al.* (2011) determined analytic functions for the "light time travel effect" (LTTE) component of the ETV signal. If the orbit of the third body is wide enough compared to the inner-binary, then dynamical effects can be ignored, leaving us with the following expression for the timings:

$$ETV_{\mathrm{LTTE}} = A_{\mathrm{LTTE}} \left[\left(1 - e_3^2\right)^{1/2} \sin E_3(t) \cos\omega_3 + \left(\cos E_3(t) - e_3\right) \sin\omega_3 \right] \quad (2.1)$$

where

$$E_3(t) = M_3(t) + e_3 \sin E_3(t) \quad (2.2)$$

$$M_3(t) = (t - t_0)\,\frac{2\pi}{P_3} \quad (2.3)$$

$$A_{\mathrm{LTTE}} = \frac{G^{1/3}}{c(2\pi)^{2/3}} \left[\frac{m_3}{m_{123}^{2/3}} \sin i_3 \right] P_3^{2/3} \quad (2.4)$$

where t_0 is a time offset, m_3 is the mass of the third body, m_{123} is the mass of the entire system, and P_3, i_3, e_3, ω_3, $E_3(t)$, and $M_3(t)$ are the period, inclination, eccentricity, argument of periastron, eccentric anomaly, and mean anomaly of the third body orbit, respectively.

Without any information on the inclination of the third body, we can fit A, e_3, P_3, and ω_3. Along with P_3, A includes $\frac{m_3}{m_{123}^{2/3}} \sin i_3$, but we cannot get the mass of the third body without both the inclination and mass of the inner-binary.

2.1 Modeling ETVs with tertiary eclipses

In cases where we observe the eclipse of the third body, we can constrain i_3 to be near 90°. This gives us $\frac{m_3}{m_{123}^{2/3}}$ as well as the mutual inclination between the two orbits. If the inner-binary is an ellipsoidal variable (perhaps not eclipsing but

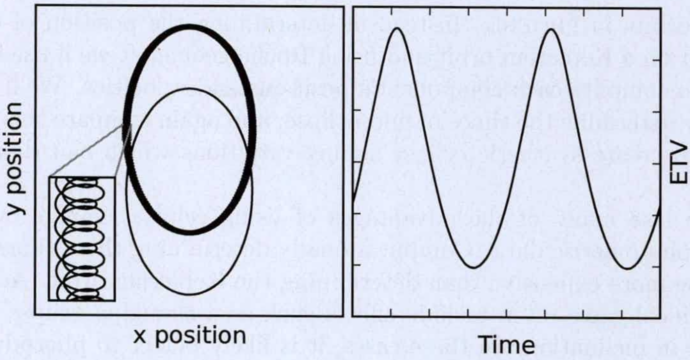

Fig. 1. Top-down view of a hierarchical orbit (*left*) with inset showing the orbit of the inner-binary. The companion causes the barycenter of the inner-binary to move, resulting in a light time delay in the observations of the eclipse times. The synthetic eclipse timing variations (*right*) can then be used to fit the orbit of a third body to data.

causing a sinusoidal like signal due to tidal distortion), then we can measure these large mutual inclinations and use these systems to test the predictions of Kozai cycles and tidal friction as a method of close binary formation.

3 Implementation in PHOEBE 2.0

3.1 Hierarchical

PHOEBE 2.0 allows for creating a hierarchical system, such that a component of a binary can be another binary itself. The orbital dynamics and lightcurve creation are treated the same as a traditional binary. If light time effects are enabled, eclipse times will be modeling including this delay effect.

Eclipse timing variations themselves can also be modeled and fit. We compute the Keplerian orbits of all components and determine the barycentric times at which each eclipse will occur. By comparing this to the linear ephemeris, we can simulate eclipse timing variations (Fig. 1).

Fitting to eclipse timing variations over the original photometric data can have several advantages. First, since this is all done analytically and does not require integrating over the mesh, this operation is much cheaper than synthetically creating the entire lightcurve and fitting each eclipse to the eclipse data. Secondly, especially in older datasets, often only eclipse times are reported. In these cases, modeling the eclipse times allows the model to extend to a much longer time baseline than would be the case if only using recent photometric data.

3.2 Dynamical

To deal with dynamical multiple systems in which the inner binary is actually perturbed by an outer body, we plan to implement an N-body alternative for computing orbits in PHOEBE. Instead of determining the position of each mesh by placing it on a Keplerian orbit and using Roche geometry, we'll use an N-body integrator to compute each component's positions and velocities. We'll then computationally determine the times of mid-eclipse, and again compare this to a linear ephemeris to create synthetic eclipse timing variations which can then be fit to data.

Here we lose many of the advantages of using eclipse timings over relying entirely on photometric data. Computationally determining these times of eclipse will likely be more expensive than determining the Keplerian orbit. Additionally, these dynamical cases often include effects such as a changing eclipse depth due to a change in inclination. In these cases, it is likely better to photodynamically model the entire lightcurve if possible.

4 Discussion

PHOEBE 2.0 introduces several new datatypes for modeling and fitting, including eclipse timing variations. We can now model and fit photometric, spectroscopic, radial velocity, and eclipse timing data simultaneously. Doing so will allow modeling these triple and multiple systems by utilizing information from tertiary eclipses, triple lined spectra, and variations in the eclipse timings due to the presence of additional bodies.

Modeling these systems in detail will help us to further constrain stellar parameters and test predictions of close binary formation theories.

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