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Multiple transiting extrasolar planetary systems – follow-up and Kepler discoveries

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Abstract

The Kepler Mission, dedicated to discover and characterize numerous transiting extrasolar planets has been in operation since 2009 [1]. Among the candidate planetary systems there are several ones with more than one (transiting) companions [2]. Transiting systems exhibiting multiple planets expected to show variations both in the transit timings and durations due to the mutual perturbations between the planets (these effects are known as transit timing variation, TTV and transit duration variation, TDV, respectively). The magnitude of this effect can efficiently be used to characterize the system, using multiple-body dynamical simulations in parallel with the analysis of the transit timing variations.

The magnitude of the actual variations in the timings can be even larger in the case of resonant systems. For instance, the two planets in the Kepler-9 system [2] orbit their star on a period of nearly 19 and 38 days, however, even on a time-base of one or two years, the deviance from a quadratic TTV fit is larger than a day. Although Kepler monitors continuously this system at this time, the lifetime of the mission is finite and in the case of further systems with such interesting and prominent dynamical features, additional observations (ground-based transit photometry) are required after the mission in order to have a more precise or accurate view of the system.

In addition, the uncertainties might also be large for future predictions in the case of such dynamically interacting systems. The uncertainty of these predictions are relevant in the case of scheduling ground-based follow-up observations (see e.g. Fig. 1). However, the estimation of these uncertainties requires both a combined method of regression analysis and dynamical modelling and a reasonable a priori assumption for the geometry of the system.

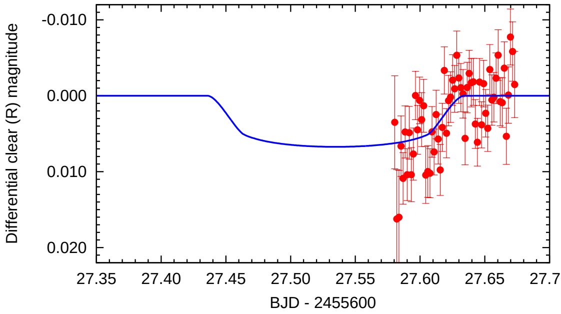

Figure 1: A partial ground-based observation of a transit of the planet Kepler-9c. Although the light curve is relatively noisy, the egress of the transit is clear. The transit occurred as it was predicted by the dynamical fit of the transit timing variations. However, it is not easy to estimate even the magnitude of uncertainties in such predictions.

In this work we present a method that can be used as a tool for investigating such planetary systems in the framework of classic regression analysis. The base of the method is the employment of the Lie-integration method [3] that provides the solution of the differential equations (that describe the interacting planetary dynamics) in the form of power series and therefore provides a way to exploit the properties of the integrator for further analytical computations, such as error propagation calculations. This analytical description is rather relevant in the cases of not-so-well constrained orbital elements (for instance, mutual inclination): letting these parameters be varied might yield an unexpectedly high correlation that affects badly the otherwise efficient alternative methods, such as Monte-Carlo estimations. This analytical treatment aids us to perform almost any kind of regression analysis method as simple as it would be in case of well-known and or other well-behaved functions.

Based on previously developed methods for similar types of analysis of radial velocity variations in multiple planetary systems [4], we present further possible applications discussing the above mentioned aspects of multiple transiting planetary systems. These applications include creating observation strategies for follow-up of Kepler discoveries after the mission, adaptive observation scheduling focusing on the more effective refinement of selected orbital parameters and of course, precise and accurate estimation of masses, orbital elements and their respective uncertainties.

References

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