Modeling the Mutual Inclinations of Exoplanets

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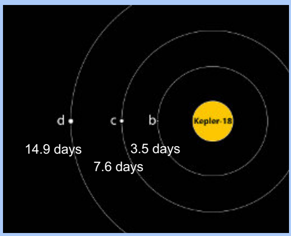
Introduction

As analyzing the architecture of exoplanets has become a more popular area in astronomy, many researchers have worked to estimate the mutual inclinations of Kepler systems. However, many models neglect mutual inclinations when they could be used to create a more accurate representation of the system. Our research utilizes information-rich Transit Duration Variations (TDVs) to determine mutual inclinations. This is done using our photodynamical model PhoDyMM (see below) to measure mutual inclinations from the present lightcurve data. Most of our research thus far has been with simulated lightcurves of the Kepler-18 system to determine the accuracy and precision of mutual inclination measurements with PhoDyMM.

Kepler-18

Kepler-18 is a three-planet system where the two outer planets show strong TTVs, allowing us to get good mass measurements for both planets (Cochran et al. 2011, Hadden & Lithwick 2018) and with 18c showing significant TDVs (Holczer et al. 2016).

Figure 1



Credit: Tim Jones/McDonald Obs./UT-Austin

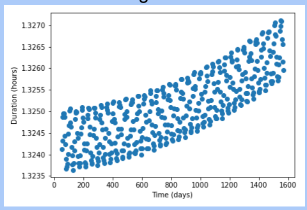
Evaluating a system's TDVs

Transit Durations are controlled primarily by the eccentricity and inclination of transiting planets. Transit Duration Variations (TDVs) are typically caused as planet-planet gravitational interactions subtly alter the path of a planet as it transits its parent star. The strength of TDVs depends on the mutual inclination, masses, and orbital configuration. Most systems do not exhibit large enough TDVs to be detected even by Kepler's four-year-long precise photometry. Kane et al. 2019 used transit duration measurements from Holczer et al. 2016 and identified ~25 cases with significant TDVs, most of which have not been studied in any detail. While the period distribution of these planets is similar to the overall population, most planets with significant TDVs are large (median of 7.5 Earth radii) where durations are easiest to measure. Ten of these are in multi-transiting systems, but only one planet in the system shows significant TDVs except for Kepler-9 (see Freudenthal et al. 2018). Some of these are accompanied by significant Transit Timing Variations and others are not.

Photodynamical Modeling

PhoDyMM is the PhotoDynamical Multi-planet Model we use that is capable of analyzing TDVs and complex systems as a whole. It is an n-body integrator directly connected to the light curve that is able to explore parameter space and determine the best log likelihoods of a given system's architecture. In our project, we used PhoDyMM to produce synthetic lightcurves of Kepler-18 with various known solutions with set mutual inclinations. Kepler-18 was chosen because Kepler-18c and d have very strong TTVs and Kepler-18c has significant TDVs (see figure 2).

Figure 2

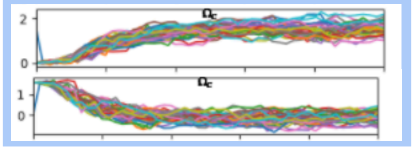


Using Differential Evolution Markov Chain Monte Carlo (DEMCMC), we strived to understand how well PhoDyMM recovers mutual inclination with a variety of architectures, fixed parameters, and starting guesses. Typically in Kepler lightcurve modeling, even with advanced photodynamical models, mutual inclinations are ignored (by setting all longitudes of ascending node equal to 0, so that the mutual inclination is assumed to be the difference of the traditional inclinations). This is done primarily with the concern that adding more parameters would complicate the fits. However, we found that in the case of the Kepler-18 synthetic lightcurves, the parameters were not adversely affected by allowing for mutual inclinations in the model.

Results

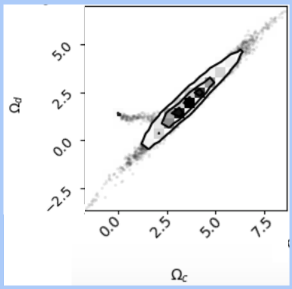
Our modeling of the real system resulted in what we believe to be the most precise model of the Kepler-18 system yet in terms of likelihood; this included a mutual inclination of Kepler-18c and d of 1.57 degrees. We were able to consistently measure the mutual inclination between Kepler-18c and d in our models, even when given different starting guesses. In two different models where the starting guess was offset by 1.57 degrees, PhoDyMM was able to recover the mutual inclination in the lightcurve in 4000 steps to within ~0.25 degrees of the true value (see figures 3 and 4). PhoDyMM can quickly find the best fit in a variety of models and guesses.

Figure 3



We were also able to constrain the mutual inclination to Kepler-18d even though this planet didn't have TTVs or TDVs, showing that information regarding mutual inclinations can be applied to planets without transit variations. As the model shifted through different mutual inclinations to Kepler-18b, the mutual inclination between c and d was preserved and can be seen in the corner plot (see figure 4).

Figure 4



Mutual inclinations for transiting planets are approximately equal to the difference in longitudes of ascending node (Omega). Here we have a run on a synthetic light curve with Omega_b = 0, Omega_c = 1.57, and Omega_d = 0. In the fit, Omega_b is held fixed at 0 (as usual since there is no information about the overall orientation of the system relative to astronomical North), but all other parameters were allowed to float. The tight correlation between Omega_c and Omega_d shows that the mutual inclination between these planets (approximately Omega_d-Omega_c) is measured very precisely and accurately (about 1.6 +/- 0.3 degrees). This solution also shows that even though planet b is not measured precisely enough to show significant TTVs or TDVs, we can still constrain its mutual inclination relative to planet c (Omega_c - Omega_b = Omega_c) to be about 3.5+/-1.4 degrees, consistent with the true known value of Omega_c = 1.57. Thus, the three-dimensional orientation of orbits in the Kepler-18 system can be accurately and precisely determined.

We measure a precise mutual inclination for the Kepler-18 system!

Conclusion

As can be seen by DEMCMC analysis in PhoDyMM, if there are mutual inclinations in light curve data (at least with strong TDVs), these mutual inclinations can be determined. Through more study and testing, a method may be determined to use PhoDyMM and DEMCMC analysis to determine the true mutual inclinations for many more systems.