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Obliquity Variability of Terrestrial Planets in the Habitable Zone

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Abstract. Obliquity (axial tilt) and its variability could play an important role in the climate and habitability of a planet. We explore the spin-axis dynamics of two specific habitable zone exoplanets, Kepler-62f and Kepler-186f, using numerical and analytical techniques. Based on our current understanding of their orbital architecture, we find that, in contrast with the typical conditions in the Solar System, Kepler-62f and 186f should have low obliquity variations except in fine-tuned conditions. Extra undetected planetary companions and/or the existence of a satellite could either stabilize or destabilize obliquities at a variety of values.

Keywords. methods: analytical, methods: numerical, planetary systems, celestial mechanics

1. Introduction

The NASA *Kepler* mission has detected thousands of planetary candidates and identified terrestrial planets in the habitable zone (HZ) of their host stars (e.g., Barclay *et al.* 2013, Torres *et al.* 2015). Many of these planets reside in multiplanet systems, where dynamical interactions could affect their orbital and spin evolution, which are important considerations for assessing their habitability.

A planet's obliquity (or axial tilt) is the angle between its spin and orbital axes, which determines the latitudinal distribution of solar radiation on a planet's surface (e.g., Williams & Kasting 1997), therefore affects climate. Evolution in a planet's obliquity is governed by orbital perturbations from its companion planets, as well as torques from the host star and any moons acting on the planetary spin axis (e.g., Ward 1974; Laskar *et al.* 1993). The exact combination of system architecture and intrinsic planetary parameters could lead to a variety of outcomes. In particular, spin-orbit resonances can cause large obliquity variations. For example, without its Moon the Earth's axial tilt would fall into overlaps of resonances and be quite unstable, varying chaotically between 0° and 45° (Laskar *et al.* 1993; Lissauer *et al.* 2012; Li & Batygin 2014).

Exoplanets found in multiplanet systems must contend with possible dynamical instabilities, including obliquity variability. In this contribution, we study the short-timescale obliquity variation of Kepler-62f and Kepler-186f, which are likely rocky transiting planets in the HZ of stars less massive than the Sun (Borucki *et al.* 2013, Quintana *et al.* 2014). Each HZ planet co-inhabits its respective system with at least 4 other small transiting planets in a relatively compact configuration.

2. Obliquity Evolution: Numerical and Analytical Results

Using planetary system parameters from the literature (Borucki *et al.* 2013; Quintana *et al.* 2014; Torres *et al.* 2015) and radius-to-mass relations of Chen & Kipping (2017),

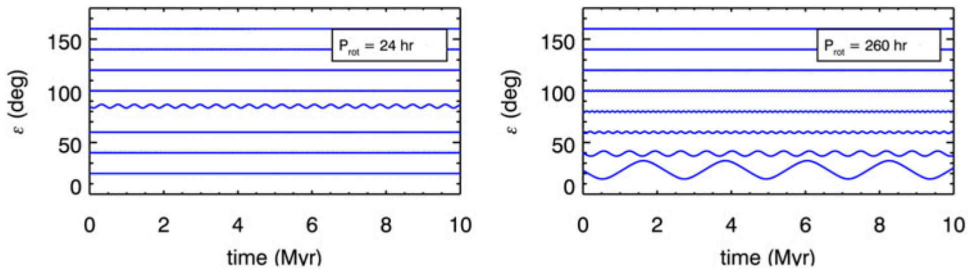

Figure 1. Evolution of obliquity over 10 Myr for range of initial obliquity values for Kepler-186f with spin period 24h (left) and 260h (right). Reproduced from Shan & Li (2018).

we run N-body simulations of each system to derive orbital elements over 10 Myr (Shan & Li 2018). These are in turn fed into the secular Hamiltonian of obliquity variation (e.g., Laskar *et al.* 1993). To determine the precession coefficient for the HZ planets of interest, we assume similar internal structure as the Earth such that we can scale the Earth's dynamical ellipticity. We examine the obliquity time series for a few representative spin periods, as shown in the Figure 1 for Kepler-186f. Retrograde obliquities ($\epsilon > 90°$) are always stable, whereas prograde ($\epsilon \leqslant 90°$) obliquities can undergo variations. Spin period affects the number and locations of the unstable zones. The baseline case – an Earthlike 24h-rotator – remains stable for all obliquities $\lesssim 80°$. The results for Kepler-62f are qualitatively similar.

The fundamental reason for obliquity variations is spin-orbit resonance (Laskar *et al.* 1993; Touma & Wisdom 1993; Lissauer *et al.* 2012). We use an analytic framework to compute the resonance locations as a function of rotation periods, moon properties and system architecture. We find that only one (two) dominant oscillation mode(s) exists for Kepler-186f (62f), making obliquity variations for these planets unlikely except under fine-tuned circumstances (i.e., at very specific rotation periods or within very limited range of obliquity values). The analytic frequencies allows us to characterize obliquity variability in a large parameter space. Using Monte Carlo trials, we also verify that our results are robust to measurement errors in stellar and planet masses. Additional undetected planets and moons in the system could modify the resonance structures, which could have either a stabilizing or destabilizing effect to existing obliquity.

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