OBLIQUITY EVOLUTION OF EARTH-LIKE EXOPLANETS AND ITS EFFECT ON HABITABILITY.
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Abstract: The obliquity of the Earth, which controls our seasons, varies by only ~2.5° over ~40,000 years [1, 2]. Nonetheless, this variation has been demonstrated to have influenced the Earth's ice ages [1]. The stability of the planet's spin axis is a result of the presence of a large satellite (the Moon) [2, 3]. In the absence of such a moon, the obliquity of a terrestrial planet can evolve chaotically and with large amplitude. Mars has experienced chaotic obliquity oscillations of ~60°, based on numerical calculations of its orbital history and images of its polar regions displaying alternating layers of dust and ice [4, 5]. The habitability of moonless Earth-like exoplanets has been explored and in many dynamical configurations these obliquity cycles extend the outer edge of the habitable zone by preventing runaway glacial formation (snowball states) [6].

In order to properly assess the potential for habitability and prioritize target selection for the characterization of exoplanets, we need to understand their orbital and rotational dynamics. It may be rare for rocky planets to have large moons and impossible to determine their existence anyway. Consequently, it is necessary to quantify the likelihood of a planet's having extreme obliquity cycles in the absence of a moon and to model the potential impact on the planet's climate.

We are following up these studies by exploring the obliquity evolution of known exoplanet systems that could contain Earth-like planets in the habitable zone, with a special focus on the dynamics of these systems. We use the obliquity model developed by Kinoshita [7] and Laskar [8], also used in [6] and a semi-analytical secular model for the orbital evolution

We find that in some known systems, planets' obliquity variations are minor and unlikely to have a major effect on climate, unless undetected planets are present. Systems with three or more planets are significantly more dynamically rich, with planets that undergo obliquity changes of ~10° over 50,000 years and >30° over a million years (see Figure 1).

The obliquity amplitude increases generally with a planet's initial eccentricity and mutual inclination, however, the dependence is highly nonlinear (see Figure 2). For a habitable zone planet in a three-planet system, we see a "strip" of parameter space in which the oscillation becomes large compared to the surrounding regions. This is a result of the complicated interactions between the stellar torque on the oblate planet and the slow variation of the planet's orbital plane. Nonlinear behavior of this kind should be expected for habitable zone exoplanets. Hence, in order to predict habitability, we must understand both the orbital and the rotational dynamics of multi-planet systems.

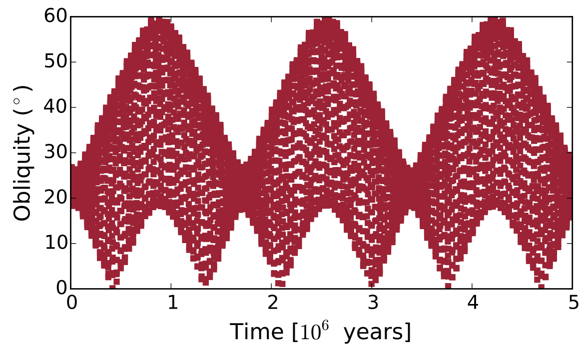

Figure 1: Obliquity evolution of a habitable zone planet in a three-planet system. **Over 1 Myr, the obliquity oscillates by ~60°.** This trial is taken from inside the "strip" in Figure 2.

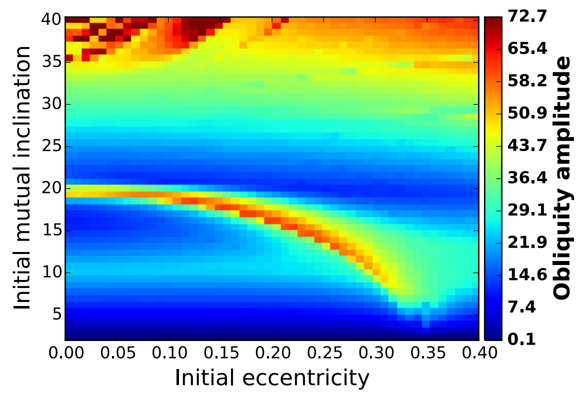

Figure 2: Amplitude of the obliquity cycle over 1 Myr for a habitable zone planet in a three-planet system, as a function of its initial eccentricity and mutual inclination. **The obliquity variation strongly depends on eccentricity and inclination, but the dependence is very nonlinear.** The red "strip" is a result of the interplay between the solar torque and the slow variation in the planet's orbit.

References: [1] Berger A. and Loutre M. F. (1991) *QScRv, 10,* 297-317. [2] Laskar J. et al. (1993) *A&A, 270,* 522-533. [3] Lissauer J. J. et al. (2012) *Icarus, 217,* 77-87. [4] Laskar J. and Robutel P. (1993) *Nature, 361,* 608-612. [5] Laskar J. et al. (2002) *Nature, 419,* 375-377. [6] Armstrong J. C. et al. (2014) *AsBio, 14,* 277-291. [7] Kinoshita H. (1977) *CeMec, 15,* 277-326. [8] Laskar J. (1986) *A&A, 157,* 59-70.