

CHAOTIC EARTHS: ORBITAL AND ROTATIONAL EVOLUTION OF EARTH-LIKE EXOPLANETS IN MEAN MOTION RESONANCES. R. Deitrick^{1,2}, R. Barnes^{1,2}, R. Greenberg³, T. R. Quinn^{1,2}, and S. N. Raymond^{2,4}, ¹University of Washington, ²NASA Astrobiology Institute Virtual Planetary Laboratory, ³University of Arizona, ⁴Laboratoire de Bordeaux. (Contact Russell Deitrick: deitrr@uw.edu)

Mean motion resonances, in which two orbital frequencies are close to integer multiples of each other, are common throughout the Solar System and exoplanetary systems. We present N-body simulations of hypothetical exoplanets in resonance and with inclined orbits that reveal orbital eccentricities and inclinations can evolve chaotically for at least 10 Gyr [1]. A wide range of behavior is possible, ranging from fast, low amplitude variations, to a nearly complete sampling of all possible values, i.e. eccentricities reach 0.9999 and inclinations 179.9 degrees. While the orbital elements evolve chaotically, at least one resonant argument librates, the traditional metric for identifying resonant behavior. This chaotic evolution is possible in at least the 2:1 (see Fig. 1), 3:1 and 3:2 resonances, and for planetary masses from lunar- to Jupiter-mass. In some cases, orbital disruption occurs after several Gyr, implying the mechanism is not rigorously stable, just long-lived relative to the main sequence lifetimes of solar-type stars. We also re-examine simulations of planet-planet scattering [2] and find that they can produce planets in inclined resonances that evolve chaotically. The known systems HD 73526, HD 45364 and HD 60532 system may be in chaotically-evolving resonances. The GAIA spacecraft is capable of discovering giant planets in these types of orbits.

The chaotic, but long-lived, evolution of planets in inclined mean motion resonances suggests that potentially habitable planets may have dramatically different climatic evolution than Earth. We use the obliquity model of Kinoshita [3] and Laskar [4] to determine the evolution of a habitable zone planet's spin axis in these dynamical configurations.

In configurations in which eccentricities and inclinations stay below ~ 0.1 and $\sim 10^\circ$, respectively, obliquities oscillate quasi-periodically with moderate amplitudes. In more dynamically active configurations, in which eccentricities and inclinations evolve to $e > 0.3$ and $i > 15^\circ$, obliquities can extend from $\sim 0^\circ$ to well past 90° (see Fig. 2). The combined effects of chaotically evolving eccentricity and obliquity will have a significant influence on the climates and habitability of planets in even the milder configurations. These effects will need to be taken into account when diagnosing the potential habitability of exoplanets near mean motion resonances.

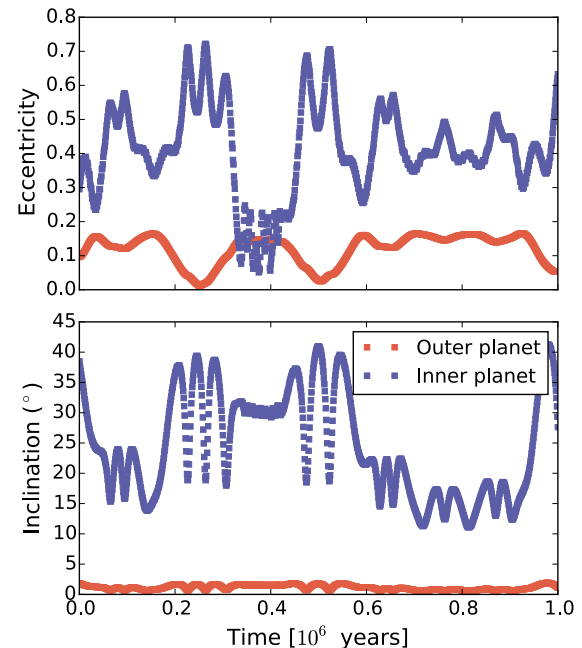


Figure 1: Eccentricity (upper) and inclination (lower) evolution for two planets in an inclined 2:1 resonance. **The inner planet's orbit changes wildly over 1 Myr but the system survives 10 Gyr with no collisions or ejections.**

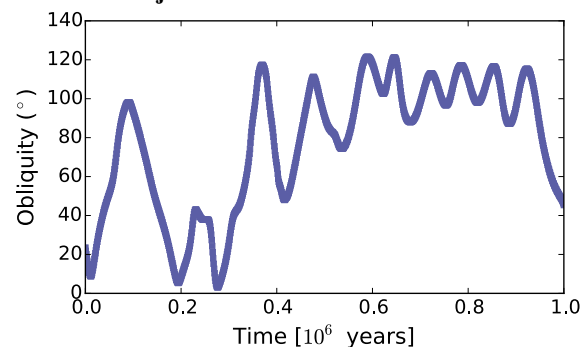


Figure 2: Obliquity evolution of an Earth-like planet in a chaotic 2:1 resonance. **The planet evolves from prograde to retrograde spin in < 1 Myr.**

References: [1] Barnes R. et al. (2015) *arXiv:1501.03231*. [2] Raymond S. N. et al. (2008), *ApJ*, 687, L107. [3] Kinoshita H. (1977) *CeMec*, 15, 277-326. [4] Laskar J. (1986) *A&A*, 157, 59-70.