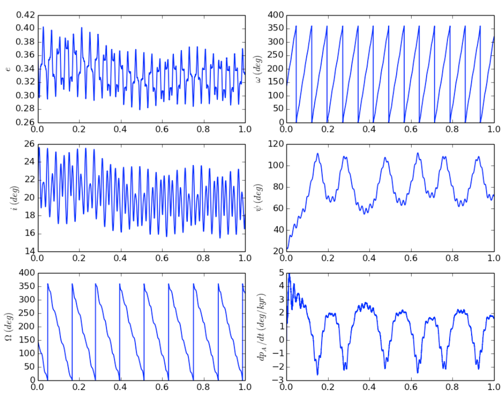
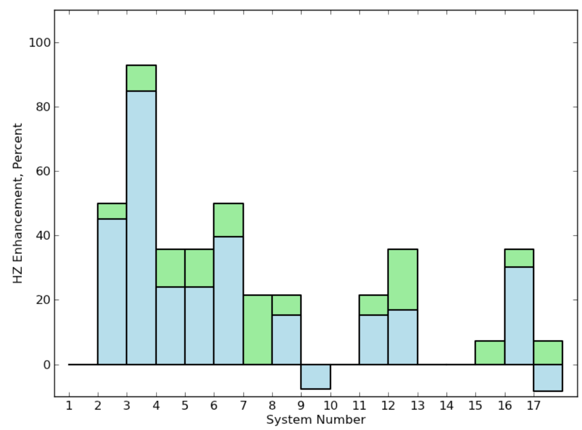
EFFECTS OF EXTREME OBLIQUITY VARIATIONS ON THE HABITABILITY OF EXOPLANETS. J. C. Armstrong[1], R. Barnes[2], S. Domagal-Goldman[3], J. Briener[2], T. R. Quinn[2], and V. S. Meadows[2]. [1]Weber State University (jcarmstrong@weber.edu), [2]University of Washington, [3]NASA Goddard.

Introduction: We explore the impact of obliquity variations on planetary habitability in hypothetical systems with high mutual inclination [1]. We show that large amplitude, high frequency obliquity oscillations on Earth-like exoplanets can suppress the ice-albedo feedback, increasing the outer edge of the habitable zone. We restricted our exploration to hypothetical systems consisting of a solar-mass star, an Earth-mass planet at 1 AU, and 1 or 2 larger planets. We verified that these systems are stable for 10^8 years with N-body simulations and calculated the obliquity variations induced by the orbital evolution of the Earth-mass planet and a torque from the host star. We ran a simplified energy balance model on the terrestrial planet to assess surface temperature and ice coverage on the planet's surface, and we calculated differences in the outer edge of the habitable zone for planets with rapid obliquity variations. For each hypothetical system, we calculated the outer edge of habitability for two conditions: 1) the full evolution of the planetary spin and orbit, and 2) the eccentricity and obliquity fixed at their average values. We recovered previous results (e.g. [2]) that higher values of fixed obliquity and eccentricity expand the habitable zone, but also found that obliquity oscillations further expand habitable orbits in all cases. Terrestrial planets near the outer edge of the habitable zone may be more likely to support life in systems that induce rapid obliquity oscillations as opposed to fixed-spin planets. Such planets may be the easiest to characterize due to their larger planet-star separation.



Orbital and Obliquity Models: Our theoretical systems were selected after careful consideration of orbital stability. We numerically integrated each case for 100 Myr in "hybrid" mode with Mercury [3] and confirmed that the evolution of every orbital element appeared periodic. Energy was conserved to better than 1 part in 10^6, which is sufficient for numerical accuracy [4]. We rotated each system such that the reference plane corresponded to the fundamental plane. For those systems with super-Jupiter planets, this conversion can change some orbital elements significantly. We reran each case at very high resolution for ~1 Myr, conserving orbital angular momentum to 1 part in 10^{12}. We are confident that no numerical inaccuracies are propagated into the rotational calculations. We employed an obliquity model [5] as used in previous orbit coupled modeling [6]. In the figure above, from left to right and top to bottom: eccentricity, argument of perihelion, inclination, obliquity, ascending node, and precession rate, illustrates a typical result.



Climate and Habitability: With the orbital variations and obliquity calculations in hand, we assessed the surface conditions using a simplified energy balance model [6]. In the figure above, the height of the bar is equal to the increase in the outer edge of the habitable zone for each system. The green portion of the bar indicates the percentage of the increase that is due to the variability alone. In all but two cases, the outer edge of the habitable zone increased or stayed the same. In two cases with obliquities smaller than 23.5 degrees, removing the time variations in the obliquity and eccentricity caused the habitable zone to shrink.

References: [1] Armstrong et al. (2014) *Astrobiology, 14, 4,* 277-291. [2] Spiegel, D. S. et al. *ApJ, 721*:1308–1318. [3] Chambers, J. E. (1999). *MNRAS, 304*:793–799. [4] Barnes, R. and Quinn, T. (2004). *ApJ, 611*:494–516. [5] Laskar, J. (1986). *A&A, 157*:59–70. [6] Armstrong, J. C. et al. (2004). *Icarus, 171*:255–271