

Physical Oceanography in the Solar System and Beyond. R.K. Barnes¹, J.A.M. Green², B.W. Blackledge^{2,3}, M.J. Way⁴, G.D. Egbert⁵, and J. Sharples⁶. ¹Astronomy Department, University of Washington, Seattle, WA 98195, rory@astro.washington.edu, ²School of Ocean Sciences, Bangor University, Menai Bridge, UK, ³Environmental Futures & Big Data Impact Lab, University of Exeter, Exeter Science Park, EX5 2FS, UK, ⁴NASA Goddard Institute for Space Studies, ⁵College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, OR, USA, ⁶School of Environmental Sciences, University of Liverpool, Liverpool L69 3GP, UK

Introduction: A key controller of a planet’s rotational evolution, and hence habitability, is tidal dissipation, which on Earth occurs primarily in the oceans. As the discovery of habitable exoplanets is a primary objective of exoplanet research, it is imperative that we understand how “exo-oceans” behave. Despite this importance, little research has investigated the physical oceanography of worlds other than Earth. This oversight has occurred even though the Earth science community has studied tidal flows in Earth’s oceans for over a century and developed sophisticated models that exquisitely match satellite altimetry data, e.g. [1]. Here, we present a) models of tidal effects on exoplanets to motivate the problem [2], b) the application of a physical oceanography model to a putative ancient Venus ocean [3], and c) the application of that model to an ensemble of “alternative Earths” with a range of continental configurations and seafloor properties [4]. We find that oceanic tidal dissipation can span 5 orders of magnitude, revealing that simulating exo-oceans with Earth science tools will provide fundamental insight into exoplanet evolution and habitability.

Methods: To calculate tidal effects on exoplanets we use the “equilibrium tide” model, first derived in [5], which assumes that the line connecting two worlds’ centers of mass and the direction of the tidal bulge are not parallel. We consider two cases: one in which the offset is constant in phase (constant-phase-lag, CPL) or constant time in time (constant-time-lag, CTL). We model these tidal effects with the code *VPLANET* [6]. To calculate tidal dissipation in oceans, we use the OSU Tidal Inversion Software (OTIS) [7,8], which solves the shallow water equations and can simulate a range of bathymetries, continental shapes, and frequencies.

Exoplanets: Although the possibility of tides driving planetary rotation to synchronous rotation (“tidal locking”) is well known [9,10], we have explored a much broader range of assumptions and found that the range of planets that can be affected by tides is much larger than previously realized [2], see Fig. 1. This result assumes that planets can form with obliquities from 0 to π , and rotation rates from 8 hours to 10 days [11]. We find that planets with initially slow rotation periods may tidally lock in the habitable zones (HZs) of Sun-like stars within 10 Gyr, and therefore oceanic tidal effects could affect many habitable exoplanets, including those that will be targeted by direct imaging campaigns. These

simple models predict that exoplanets to the left of the dotted line are almost assuredly tidally locked, those to the left of the solid line may be tidally locked, and those to the right of the solid curve are almost assuredly not tidally locked.

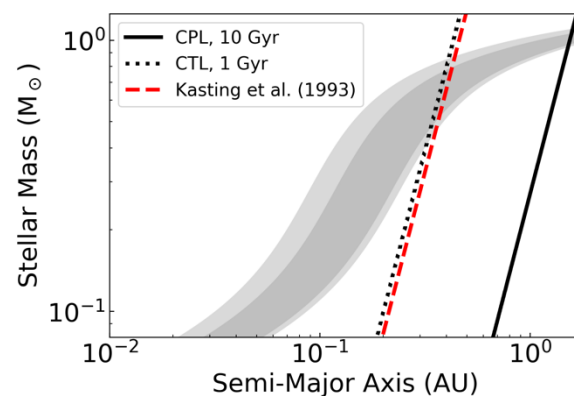


Fig. 1: Timescale to tidally lock as a function of stellar mass and semi-major axis, assuming circular orbits. The HZ from [12] is shown in grey, with light representing the “optimistic” limits and dark the “pessimistic” limits. The dotted line assumes a 0.1 Earth-mass planet, one-tenth of modern Earth’s tidal response, a tidal locking time of 1 Gyr, an initial rotation period of 8 hours, an initial obliquity of 60°, and the CTL model. The solid line assumes a 10 Earth-mass planet, modern Earth’s tidal response, a tidal locking time of 10 Gyr, an initial rotation period of 10 days, no obliquity, and the CPL model. The red curve is from [12] and assumes a 1 Earth-mass planet with no obliquity, an initial rotation period of 13.5 hours and the CPL model.

Ancient Venus: We next turn to directly modeling a hypothetical ocean on Venus [3]. Although Venus may not have had an ocean [13], it is a known planet with a well-studied surface and therefore serves as a useful fiducial in the quest to understand exo-oceans. We use the elevation data from [14], consider “shallow” (330 m mean depth) and “deep” (830 m mean depth) oceans, and explore a range of prograde and retrograde rotational frequencies. We also consider turbulent (“internal tides,” IT) and laminar (noIT) tidal flows. In Fig. 2 we plot the dissipation, torque, and tidal Q (the amount of energy available in the system divided by the energy dissipated in one cycle) of the simulations. These 3 quantities vary by over 4 orders of magnitude depending on assumptions.

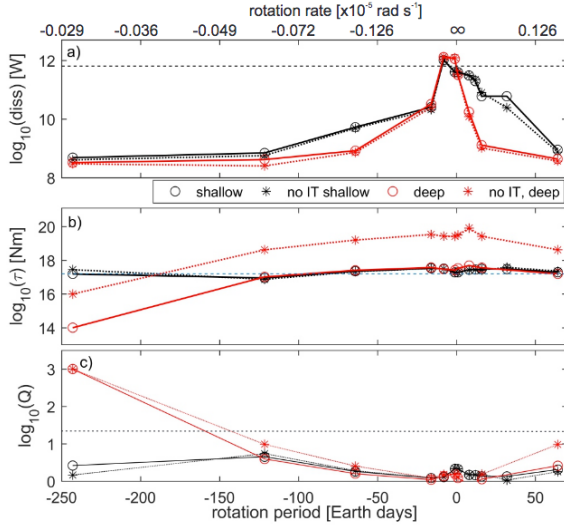


Fig. 2: Tidal effects in an ancient Venusian ocean. Negative rotation rate means retrograde rotation. Modern Earth's values are shown by dotted lines. *Top*: Global dissipation in Watts. *Middle*: Rotational torque induced by tides. *Bottom*: Tidal Q .

Alternative Earths: For our final experiment, we consider an Earth-like planet affected by the Sun and Moon, but for a range of continental shapes with fractal coastlines [15], bathymetric “roughness,” and rotational frequencies [4]. We considered 111 randomly generated continental configurations and 9 specific configurations designed to test specific scenarios.

In order to characterize the total effect of continent size, ocean basin size, and coastal complexity, we use the non-dimensional value $R = L_{\text{tot}}/(A_{\text{ocean}})^{0.5}$, where L_{tot} is the total coastline length and A_{ocean} is the ocean basin area. The results of these simulations are shown in Fig. 3 and reveal that, similar to ancient Venus, the dissipation can span 5 orders of magnitude.

Conclusions: Using simple models of tidal effects and a plausible range of initial rotational angular momentum, we find that planets in the HZs of stars up to the mass of the Sun may become tidally locked within 10 Gyr. However, we also find that the tidal locking limit is not well-defined, in part because we only extrapolated from Earth values. This uncertainty motivates the application of OTIS to non-Earth worlds to explore the range of tidal dissipation that is possible on exoplanets.

We found that dissipation in an ancient Venusian ocean as well as in an ensemble of Earth-like planets reveals a span of 5 orders of magnitude. Although these simulations greatly expand the number of worlds that have been modeled with modern physical oceanography methods, they still only address a narrow range of possibilities for exoplanets. In the HZs of M dwarf stars,

tidal forces and frequencies are orders of magnitude larger than on Earth or Venus due to their closer proximity to their host star. Future research that simulates oceans beyond the Solar System could provide critical insight into the search for life in the universe.

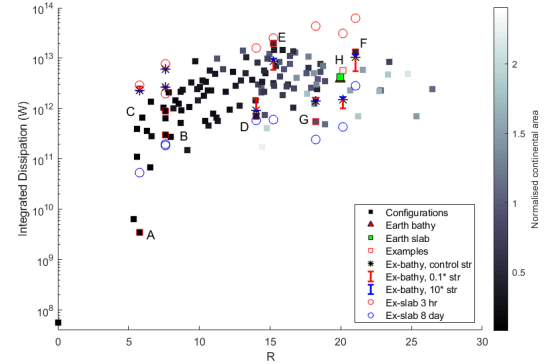


Fig. 3: Tidal dissipation for Earth, but with a range of continental configurations, bathymetries, and rotation periods. The shading corresponds to the amount of land relative to modern Earth. Runs labeled “bathy” include seafloor roughness, while “slab” does not. Squares denote 24 hour rotation period, red circles 3 hours, and blue circles 8 days. Letters denote continental configurations investigated in more detail because they span the parameter space.

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