OCEAN TIDES AND ROTATION RATES: APPLICATIONS TO VENUS AND EXOPLANETARY WORLDS.

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Introduction: Observations imply that Venus may have hosted an ocean in its deep past [1,2], and that it may have been habitable if its rotation rate was similar to today's [3]. This raises the prospect of a solar ocean tide, and an associated tidal drag that could have affected the planet's rotation rate, and thereby the early Venusian climate. We therefore simulate the potential solar tides in an ancient Venusian ocean using a dedicated numerical tidal model [4,5]. The simulations use topography from present day Venus [6] and from present day Earth since the ancient Venusian topography is hidden to us. Additionally we include a range of configurations to test the robustness of the results. A series of simulations with ocean depths varying between 330-4500m, rotational periods ranging from -243 to 64 sidereal Earth days. Simulations with and without vertical stratification in the Venusian ocean were used to calculate tidal energy dissipation rates, the resulting tidal torque, and the associated deceleration of Venus' rotation rate. The dissipation was computed from

$$D = W - \nabla \cdot \mathbf{P} \qquad (1)$$

where W is the work done by the tide-generating force and **P** is the energy flux vector, respectively. They are in turn given by

$$W = g\rho \langle \mathbf{U} \cdot \nabla(\eta_{EQ} + \eta_{SAL}) \rangle \qquad (2)$$

and

$$\mathbf{P} = g\rho \langle \mathbf{U}\eta \rangle \qquad (3),$$

where the angular brackets mark time-averages over a tidal period, g is gravity, ρ is sea-water density, **U** is the tidal transport vector, η is the tidal amplitude, and η_{SAL} and η_{EQ} are the self-attraction and loading and the equilibrium tide, respectively. The associated tidal torque, τ, can be written as:

$$\tau = \frac{9}{2}\frac{kGm_v^2R_v^5}{r^6} = \sin 2\alpha \qquad (4)$$

Here, G is the gravitational constant, m_v is Venus' mass, R_v is Venus' radius, r is the Venus-Sun distance, and k is a Love number that takes the non-uniformity of the planet into account. Assuming that most of the tidal bulge is sea water, k = 0.19, or the ratio between Venus' average mass density and that of water [7]. sin(2α) is the lag angle between the tidal bulge and the planet-satellite axis, and it is computed as D/W. This also allows us to compute the tidal damping factor, Q, (i.e., the number of cycles to obtain an e-folding decay of the amplitude) from Q = W/D. Finally, we can compute the resulting spin-down of the planet's rotation, Ω, due to the tidal dissipation from

$$\frac{d\Omega}{dt} = \frac{45}{8}\frac{kGm_s^2R_v^3}{m_v r^6}\sin 2\alpha \qquad (5)$$

where m_s is the mass of the Sun.

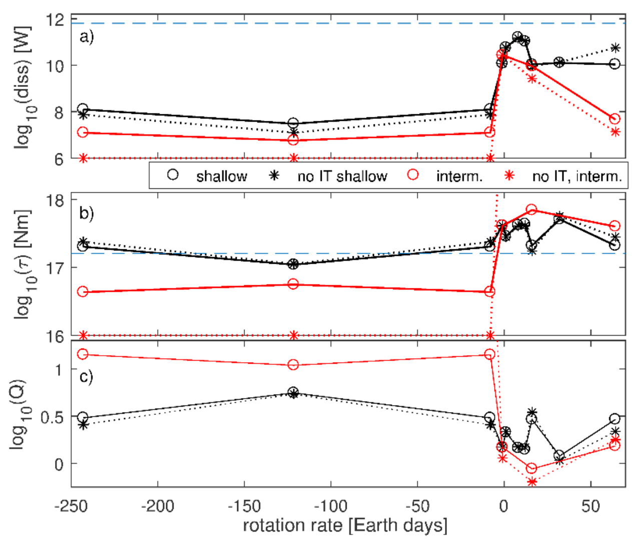

Figure 1a) Horizontally integrated dissipation rates for our simulations plotted against rotation rate. Note that the y-axis is logarithmic. "no IT" refers to simulations of a non-stratified oceans, whereas the other simulations have a vertical density gradient based on an average for present day Earth. "Shallow" denotes simulations with a mean depth of 330m, whereas the "intermediate" simulations had a mean depth of 830m.
b) As in a) but for the tidal torque.
c) As in a) but for the tidal damping factor, Q. Note that the no IT intermediate depth simulations with a retrograde rotation have a Q of about 2500 and is off the scale.

The results show that tidal dissipation rates on Venus could have varied over 3 orders of magnitude depending on rotational period and ocean depth (Figure 1). The most energetic simulations had a rotational period close to one Earth day and dissipated nearly as much tidal energy as the solar tide does in Earth's oceans today (~0.7TW). This occurs at all depth configurations regardless if the ocean was vertically stratified or not. The associated tidal torque in the most dissipative set-ups is large; it is of the same order of magnitude as today's total tidal torque on Earth, and only an order of magnitude below the atmospheric torque reported for present-day Venus [8]. This could have changed the day-length on the planet with up to 5 days per million years (cf. present day Earth, where the tides lead to a spin-down of about 20 s in a million years).

Consequently, an ocean tide on ancient Venus, albeit probably short-lived in geological terms, could have had significant effects on the rotational history of the planet if its rotation rate was faster than today. These calculations have important implications for the rotational periods of exoplanetary worlds and the location of the inner edge of the liquid water habitable zone.

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