The long-term maintenance of liquid-water oceans by self-tuned ocean tidal resonance

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Introduction: Liquid water oceans in the universe may be far more stable, long-lived, and abundant than previously thought. This conjecture is not simply an extrapolation from surprising recent discoveries in our Solar System. Rather, it comes from considerations of the internal fluid dynamical response of a generic ocean to tidal forces, and feedbacks from this response that stabilize ocean parameters against secular trends. Relatively basic dynamical arguments are combined to show that attempting to freeze or stratify an ocean pushes it toward a resonant state, with an increase in dissipative heating and mixing that counters these trends and stabilizes the ocean over long periods of time. The aim of this presentation is to provide a short and simple description and demonstration of this important dynamical effect for the broad community currently developing a path forward in the investigation of ocean worlds. Availability of a sophisticated software package TROPF (Tidal Response of Planetary Fluids) developed by the author will also be described.

Illustration of ocean/ice tidal evolution: To illustrate the self-tuning effect, we first integrate (using an explicit Runge-Kutta method) over non-dimensional time t' a simple ice-growth model of the form $\frac{d\tilde{h}_I}{dt'} = k_1\tilde{P}_{radio} + k_2\tilde{c}_e^2\tilde{P}_{tidal} \text{-} k_3\tilde{P}_{cool}$, where $\tilde{P}_{radio} = e^{-t'}$ is an exponentially decaying (e.g. radiogenic or solid-tidal) heat source, $\tilde{P}_{cool} = 1/\tilde{h}_I$ represents a simple (e.g. conductive) cooling, and $\tilde{P}_{tidal}$ is the non-dimensional ocean tidal power calculated using the TROPF software package. The dimensionalization of time as well as the choice of coefficients $k_{i=1,2,3}$ depend on the specific case and are chosen here arbitrarily for generic demonstration. (The basic points we wish to illustrate will be robust provided the dimensionalized tidal power is strong enough to counterbalance the dimensionalized cooling and that the time span is long enough for the $\tilde{P}_{radio}$ source to decay below these levels.) One may view the terms $\tilde{P}$ as representing average power density per volume, with the factors k_1, k_2 incorporating the constant radial integration factors. The tidal term, however, has the additional factor $\tilde{c}_e^2$ (as discussed next) to account for the variation with time of the ocean depth over which this source is integrated.

The tidal power $\tilde{P}_{tidal}$ depends on the tidal force, but also the parameters controlling the ocean's tidal response. We consider first the simplest case for forcing which is the situation of the ocean spinning rapidly relative to the orbit of a tide raising body in a circular, equatorial orbit. In this case, the force is represented by simply one propagating spherical harmonic term (a degree-two spherical harmonic propagating across the ocean in the retrograde sense with twice the ocean's rotation frequency. We assume in this case that the ocean's response is governed by the Laplace Tidal Equations, with dissipation proportional to the kinetic energy density, and varies with two parameters $\tilde{T}$, $\tilde{c}_e^2$, where $\tilde{T}$ is the ratio of dissipation and tidal-period time scales, and $\tilde{c}_e$ is the ratio of ocean wave speed to twice the equatorial rotation speed.

We then illustrate several extensions to this illustrated example that include recent developments by this author and others. These extensions consider other tidal forces (notably the obliquity/eccentricity components of a synchronous orbit), other dissipation-process assumptions, and most importantly the dynamical effects of the coupled ice layer on the ocean/ice tidal response. The ice layer creates both a damping effect but also can change the effective wave speeds involved in the tidal response. In terms of the governing equations, these alter the imaginary and real components of the eigenvalues, respectively, and can also make the wave speeds dispersive (i.e. dependent on wavelength).

Conclusion: When considering the preponderance and stability of liquid water oceans in the Solar System and beyond, and for constructing an efficient research path forward for ocean worlds, self-tuned tidal resonance should be included and closely examined. Basic dynamics as well as the demonstration provided here suggest that oceans in systems with even weak tidal forces are remarkably hard to freeze. This has a large impact on our starting assumptions for ocean worlds on icy satellites in the Solar System, as well on exoplanets and interstellar nomads.