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Comparative estimates of the heat generated by ocean tides on icy satellites in the outer Solar System

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ABSTRACT

This study illuminates scenarios whereby the heat produced by the dissipation of ocean tides is significant in the heat budgets maintaining liquid oceans on icy satellites in the outer Solar System. It has been shown in previous work that ocean tides, if resonantly forced, can supply heat at or exceeding the rates necessary for maintaining these oceans. It has also been shown that because of feedbacks these resonant configurations may be unavoidable under typical situations. This study extends from the previous work and seeks to examine the full set of dynamically-consistent ocean tidal solutions to describe the parameter dependencies that may cause one ocean to become trapped in such a vigorous ocean state while allowing another to freeze—why do some of these satellites have oceans, and others do not? It is found that even with no other sources of heat, a liquid ocean on many of these satellites would be maintained by ocean tidal heat because the process of freezing (which changes the thickness of the remaining liquid ocean and thereby the eigenmodes) would push the ocean into a resonant configuration, with the associated increase in heat production preventing further freezing and stabilizing the configuration. An ocean on Io or Mimas would suffer extreme tides (with heat generated exceeding 1 W/m^2) unless an implausibly large volume of water were present to lift the eigenmodes of the configuration out of resonance with the tidal forces. Europa can maintain a thick (~100 km) ocean due to an obliquity-forced tidal resonance, while parameters for most other satellites suggest eccentricity-driven resonance scenarios involving much thinner ocean thicknesses (1–10s km). But these thin ocean thickness in the latter scenarios will be altered by ice cover: as the ice cover damps the ocean tidal response, significant heat is still generated which would stall freezing but the ocean thicknesses are modified to larger values than would be expected without ice cover.

1. Introduction

1.1. Background

Within the general background for the topic of this study, an essential starting point is the evidence for liquid oceans on several of the icy satellites. While this has been discussed extensively in the literature, a brief summary of this evidence is included next. Following this, a review of the more specific research on the dynamic tidal response of these oceans is presented.

The most compelling cases for water oceans on the icy satellites have probably been made for Europa and Enceladus, with evidence also compiling for oceans on Ganymede, Callisto, and Titan. In the case of Europa (as well as Ganymede and Callisto), a strong source of evidence is the magnetic variations observed by Galileo during fly-bys, which implicate electromagnetic induction in a global electrically conductive layer near the surface (Kivelson et al., 1999, 2000, 2002; Zimmer et al., 2000; Schilling et al., 2004). The surprising observations of a geyser (Hansen et al., 2006, 2008; Porco, 2006; Manga and Wang, 2007; Matson et al., 2007; Halevy and Stewart, 2008; Saur et al., 2008) and high heat fluxes (Spencer et al., 2006; Abramov and Spencer, 2007, 2009) emitted from Enceladus' southern pole region are spectacular evidence of a lack of understanding of the internal dynamics of these satellites, and may also implicate a regional or global subsurface ocean (Collins and Goodman, 2007; Manga and Wang, 2007; Meyer and Wisdom, 2007; Matson et al., 2007; Nimmo et al., 2007; Halevy and Stewart, 2008; Roberts and Nimmo, 2008a,b; Tobie et al., 2008; Ingersoll et al., 2010; Lainey et al., 2012). Other observed features that have been used to infer subsurface oceans include a

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variety and range of associations. It is insightful to describe the basic categories of the physical processes proposed that implicate these oceans.

Liquid water with salts may have a conductivity ranging from a fraction of 1 S/m (relatively fresh water) to a maximum of several hundred S/m where the water becomes saturated with these salts (Hand and Chyba, 2007). For induction effects at the frequencies of rotation of the bodies and their parent stars, the oceans behave essentially as perfect electrical conductors surrounded by insulators (e.g. Tyler, 2011c). Inferences of oceans that draw on the magnetic measurements implicate a good conductor and by proxy (and perhaps in combination with other constraints on the density of the medium), a liquid ocean. Electric observations in Titan's atmosphere show resonance peaks that have been interpreted as the normal modes in a spherical waveguide requiring a global conducting shell (ocean) in the near subsurface (Beghin et al., 2007; Simoes et al., 2007). There is no requirement in this that there be ocean tidal flow, only an ocean. Other observations implicate a surface ice shell decoupled from the interior Baland et al. (2011), Bills and Nimmo (2011), Patthoff and Kattenhorn (2011), Iess et al. (2012), and an ocean provides this by essentially acting as a lubricant—again, no implication of tidal flow. Still, in other cases large tidal stresses of the ice shell are implicated in the observations, and when it is seen that a subsurface solid cannot provide a large enough tidal response, it is proposed that inclusion of a liquid layer can increase the surface response. Although both tides and ocean are involved in the latter, the ocean is again merely acting to decouple the surface ice layer and may be regarded again as a lubricant. In all of these cases, the dynamical response of the ocean to the tidal forces is ignored and any motion within the ocean simply complies with other dynamical activities in the surrounding solids, or is dynamically non-inertial.

The specific background for this contribution is provided in Tyler (2008), Bills (2009), Tyler (2009a,b, 2010, 2011a,b, 2012) and the study presented here may be regarded as an extension and consolidation of this previous work. These studies started from the observation that the assumption of an equilibrium tidal response in the applications of ocean-bearing satellites was not justified, and that a number of resonantly forced ocean tidal scenarios with flows much stronger than predicted from the equilibrium tidal response assumption were in fact allowed. The work was then extended to show that in some cases these resonant scenarios were also very plausible and perhaps even inevitable when feedbacks of the ocean tidal state on the ocean's parameters were considered. In (Tyler, 2008), it was proposed that one of these resonances involving an obliquity-forced Rossby wave might describe the scenario on Europa because it was demonstrated with analytical solutions that this resonantly forced tidal flow should be present and have an amplitude of perhaps ~10 cm/s, rather than the ~1 mm/s commensurate with the equilibrium-tide assumption. Estimates of the associated dissipation (heat generation) required extrapolation from formally non-dissipative analytical solutions. Two theoretical limits were used to contain these extrapolation errors and provide a minimum and maximum estimate for the dissipative heat (with, however, no indication of where the correct solution would fall between these limits). The values (e.g. for an assumption of 0.1° obliquity) was given as 6.5×10^{10} W ($2.1\ \mathrm{mW/m^2}$ when presented as a surface average) for the constraint on the minimum, and 7.9×10^{12} W ($255\ \mathrm{mW/m^2}$) for the constraint on the maximum. Following the original study, a semi-analytical method was developed to obtain solutions to the same governing equations but with dissipation terms explicitly included Tyler (2011b). The earlier estimates do indeed provide correct bounds on the dissipation amplitudes but, as can be verified in results below, the maximum amplitudes ($\sim 10\ \mathrm{mW/m^2}$) are closer to the lower bound and require that the ocean depth fall within a limited range near ~100 km. Understanding the control of dissipation parameters on the behavior of the solution space has become a very interesting element in the continuing work because new configurations in which an ocean can become trapped become apparent. The obliquity of 0.1° used in the calculations was taken from the study and represents a minimum (a forced component associated with the Cassini state (Bills, 2005)). If the obliquity is larger, the dissipation rates are larger, increasing simply with the square of the obliquity angle, as the obliquity affects the solution only through a scaling constant. It is clear, in any case, from these results that ocean tides must be included in the consideration of Europa's heat budget. It may even be the case that tidal dissipation of Europa occurs primarily in the ocean—just as for Earth.

An important result from the Tyler studies cited above is that ocean tidal heat must be considered as a potentially important source of heat in the ocean of the icy satellites. Chen et al. (2014), however, make quite the opposite claim in deciding that ocean tidal heat is not likely to be significant in the heat budgets of the icy satellites. The claim is, however, unsupported because they consider only a few solution scenarios using ad hoc input parameters and so do not adequately sample the larger space of solutions calculated and discussed in the Tyler studies. One of the ad hoc parameter assumptions is that the ocean thickness is 30 km for all satellite oceans considered. They provide little justification for this choice, despite that it is clear that the tidal solution state (including whether it is resonant) depends very sensitively on this choice (i.e. ocean thickness controls the eigenvalues of the underlying equations for the tidal response.) They ignore consideration of a number of other resonant states under the assumption that these will take place only for an unrealistically thin ocean. But such reasoning is valid only if the shallow ocean maintains a high value for the dissipation time scale *Q*. One shall see in the work here (see arguments related to the "separtrix" of the solution space) that such an assumption is invalid in all cases considered here, though a quite different argument can be used for excluding some of these resonant scenarios. The author has submitted an Icarus Commentary carefully reviewing both the Chen et al. and Tyler studies to identify the source of these quite different claims which arrive from examination of essentially the same equations and underlying model restrictions.

1.2. Setting up well-posed research goals

The etymology of the word "tide" is closely related to that of "time" and both have arrived from experiences of the regularity of natural cycles ultimately associated with the spin of the Earth with respect to the Sun and moon. One may appreciate that the precise regularity in the cycles of sea-level variations stems from the closely repeating celestial cycles of the tidal forces. One might say that the responding phenomena display a projection of the spatio-temporal behavior of the driving agent. Although this is a useful basis for associating a dynamical response with its driving force, a second consideration is required: the internal dynamics of the responding system is also important and may even be a predominant factor in determining the spatio-temporal behavior of the response (consider, for example, the spectrally characteristic response of a wind chime subject to spectrally-smooth broad-band wind forcing.) In approaching the study of an ocean's response to tidal forces, let us therefore start with the expectation that the ocean's response will show a spatio-temporal behavior that is always a conflation of the spatio-temporal behavior of the force and the spatio-temporal behavior of the internal dynamics of the ocean. Let us also recognize that the rules of this conflation are potentially resolvable through mathematical analyses. Therefore, given a partial set of the behavior and parameters describing the