TIDALLY HEATED EXOMOONS AROUND COLD EXOPLANETS

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Introduction:

In the last decades more than four thousand exoplanets have been discovered. As is the case in our solar system, it is sensible to expect that some of these exoplanets host moons. Although the search and study of exomoons is in its infancy (only one exomoon has been detected to date [1]) it is expected that more discoveries will follow [e.g., 2,3].

In contrast to close-in exoplanets, where the role of tidal dissipation is limited by the high solar irradiation and the large distance separating exoplanet and star [4], tidal heat production can play a dominant role in exomoons orbiting giant planets [5]. Missions to the outer Solar System have revealed that tides can power vigorous endogenic activity resulting in the formation of subsurface oceans [6-8] or widespread volcanism [9,10]. Tidal heat production in exomoons can similarly extend the habitable zone [e.g., 5,11] and result in highly volcanic bodies.

Here we consider tidally-heated exomoons around cold exoplanets. Using the Jovian system as an analogue, we aim to tackle two questions: (1) how common are icy moons with sub-subsurface oceans? And (2) can super hot Ios exist around exoplanets? The first question has important implications for extending our current understanding of the habitable zone, the second might lead to new approaches for observing exomoons [e.g., 12].

Methods: To answer the previous questions we consider thermal equilibrium models of exomoons and compute mantle temperature and ice shell thickness for different orbital configurations.

We consider a simplified spherically symmetric body consisting of three layers: a metallic liquid core, a silicate layer and a water layer that might be partially molten. Layers of high pressure ice are not presently considered. We compute heat transfer through the different layers. Depending on ice shell thickness and mantle temperature, heat transfer through the ice shell and silicate mantle can occur via conduction or convection. If convecting, we use a parametrisation for heat transfer in the ice and silicate layer [e.g., 4,11,13], otherwise heat transfer is computed using Fourier's law. We do not consider heat transfer via heat piping.

We compute tidal dissipation using the viscoelastic theory for self-gravitating incompressible bodies [e.g., 15,16]. We consider Maxwell rheology as well as Andrade rheology for both the ice shell and the silicate mantle. Viscosity is approximated using Arrhenius' law. Partial melt in the mantle is accounted for by an exponential decrease of viscosity and shear modulus with melt fraction when the pressure dependent solidus temperature is reached [e.g., 4].

For different combinations of orbital frequency and orbital eccentricity we compute equilibrium configurations for which the amount of heat generated in the interior (radiogenic plus tidal dissipation) equals the amount of heat transferred through the silicate mantle and ice shell (see Figure 1).

We consider a rocky body with Io's radius with a liquid core of 30% of its radius and covered by a 100 km ice layer that can be partially molten. To study the effect of moon size in our results, we additionally consider a body with twice and half the previous radius.

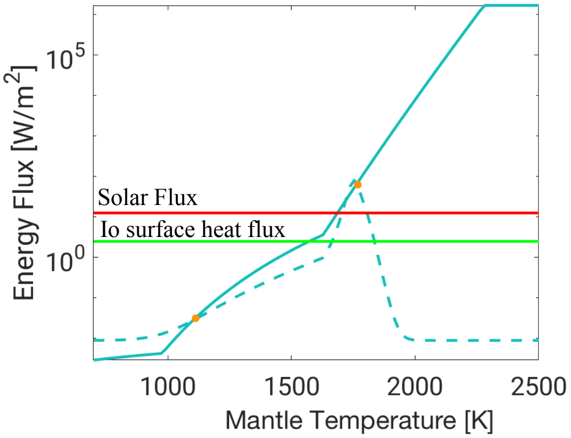

Figure 1: Surface heat flux (solid line) and internal heat (dashed line) for a rocky, Io sized body with Io like orbital parameters. The two stable equilibrium points are indicated in orange. Andrade rheology is used in this case.

Results:

Icy Moons with Subsurface Oceans: For the three different body sizes we obtain the range of orbital distances and eccentricities for which subsurface oceans can persist in thermal equilibrium in the Jovian system (Figure 2). As expected, we observe that the subset of orbital parameters for which this occurs decreases with decreasing radius.

We extend the previous results to exoplanets where temperature allows for the existence of icy exomoons and find combinations of orbital periods and eccentricities for which subsurface oceans are stable. For most of the exoplanets we find that these conditions are found within their Roche limit and Hill sphere which suggests that icy moons with subsurface oceans should be common in other planetary systems. Further constraints from moon formation theory and orbital evolution are needed to discern whereas exomoons with the required eccentricity and orbital frequency are expected in these systems.

Super hot Ios: We also explore the possibility of extreme tidal heating in exomoons. For high eccentricities and low orbital periods, equilibrium configurations where tidal heating exceeds solar irradiation can be found (Figure 1). Assuming blackbody radiation, we compute the new equilibrium surface temperature and find that tidal dissipation can boost surface temperature by more than 200K.

It has been argued that tidally heated exomoons can be observed by the *Spitzer Space Telescope* or by the future *James-Web Telescope* [12] provided their surface is hot enough (T>300K). Our preliminary results shows that indeed tidal dissipation can boost surface temperatures above these values. However, it remains to be seen if the high eccentricity needed to generate these high amounts of tidal heat can be maintained over geological timescales.

References:

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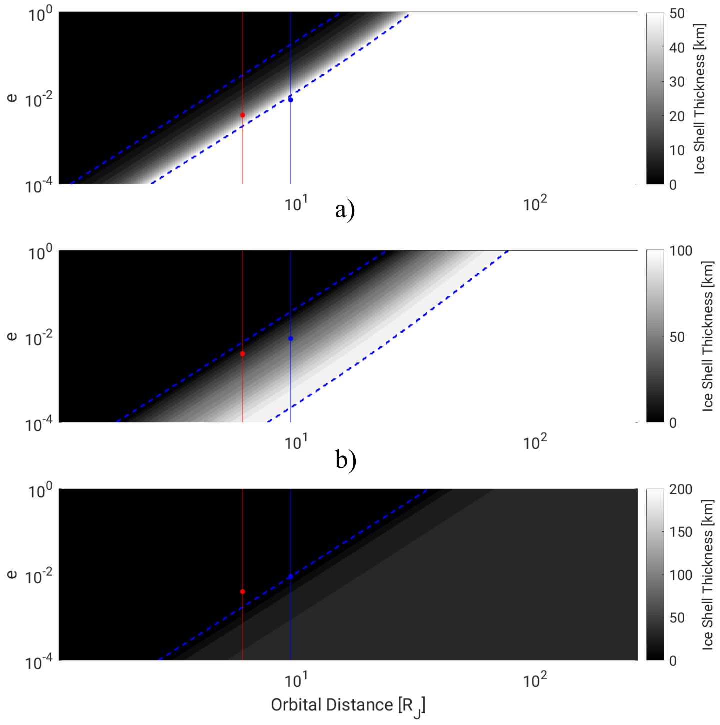

a)

b)

c)

Figure 2: Equilibrium ice shell thickness for moons of radius R,R/2 and 2R (a,b and c) for different combinations of distance to Jupiter and orbital eccentricity. Black regions are regions where tidal dissipation melts the outer ice shell while white regions correspond to cases with completely frozen ice layers. Europa and Io are indicated in blue and red, respectively.