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Susceptibility of exo-Earth to tidal dissipation, implications for habitability

M. Běhounková (1), G. Choblet (2), G. Tobie (2), O. Čadek (1)
(1) Charles University in Prague, Faculty of Mathematics and Physics, Department of Geophysics, Czech Republic (2) Université de Nantes, Nantes Atlantique Universités, CNRS, Laboratoire de Planétologie et Géodynamique, UMR 6112, France (marie.behounkova@mff.cuni.cz / Fax: +420 221 912 555)

Abstract

The detection of massive terrestrial planets outside the Solar System is now a real possibility. In light of recent discoveries, we study the influence of the tidal heating on the interior of Earth-like planets which will likely be detected around neighboring stars in the near future. By varying the parameters of the orbit (eccentricity, orbital period and the resonance type) and the internal properties (Rayleigh number and temperature dependence), we investigate the thermal stability of such planets. We look for such parameters for which the tidal dissipation could possibly lead to thermal runaways and thus has potential to globally melt the mantle. A possible impact on the habitability is studied in this context.

1 Introduction

We study here the influence of tidal dissipation on the thermal evolution within the mantle of an extrasolar Earth-like planet which is supposed to have a similar geometry as the Earth and as well as a liquid core. Since the rheological properties of long-term flow and tidal deformation are strongly temperature dependent, the thermal evolution and tidal deformation are solved simultaneously using a new method [1, 2].

For the viscous flow determining the thermal evolution, a Newtonian viscosity dependence on temperature is considered:

$$\eta = \eta_b \exp\left(-a_{\rm vis}\frac{T-T_b}{\Delta T}\right),$$

where η_b and T_b respectively denote the viscosity and the temperature at the base of the mantle, $a_{\rm vis}$ is a parameter describing the temperature dependence and ΔT is the temperature contrast across the spherical shell.

In order to model the visco-elastic response induced by the tidal forcing, we employ an incompressible Maxwell-like model where a purely formal definition of the effective viscosity $\hat{\eta}$ is proposed in order to reproduce an impossed dissipation factor Q^{-1}:

$$\hat{\eta}_b = \sqrt{Q_b^2 - 1}\,\frac{\mu}{\omega_{\rm E}},\ \hat{\eta} = \hat{\eta}_b \exp\left(-\hat{a}_{\rm vis}\frac{T-T_b}{\Delta T}\right)$$

where μ is the shear modulus and $\omega_{\rm E}$ is the excitation angular frequency. Note that parameters η_b and $\hat{\eta}_b$ as well as $a_{\rm vis}$ and $\hat{a}_{\rm vis}$ differ for periods lower than the Maxwell time. For sake of simplicity and in order to reduce number of parameters, we assume here $a_{\rm vis} = \hat{a}_{\rm vis}$. Additionally, model for the quality factor $Q = 350 - 5T_{\rm O}$, $T_{\rm O}$ being the orbital period, is used.

In order to study the sensitivity of an Earth-like planet to the tidal dissipation [1], we first compute a statistical steady state temperature field for a given model described by Rayleigh number, viscosity parameter and internal heating rate without any tidal dissipation. Then we investigate how the behavior of such a system changes when the tidal dissipation is considered. Specifically, we study the conditions under which a new equilibrium or a thermal runaway occurs (depending on the resonance, orbit period and eccentricity).

2 Results and scaling

For a given temperature field within the mantle, the following scaling for global tidal dissipation is derived

$$P_{\rm tide} = A Q_b^{-1} \exp\left(a_{\rm vis}\frac{T_e - T_b}{\Delta T}\right)(n^*)^5\,\zeta(e),$$

where A is a constant characterizing the size and physical properties of the planet and Q_b is the quality factor at the base of the mantle which together with $\hat{a}_{\rm vis}$ characterizes the rheological properties in our model. The temperature T_e corresponds to the geometrical mean of the temperature field weighted by the parameter

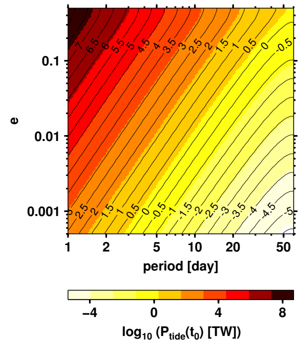

Figure 1: Power of tidal dissipation as a function of orbital period $T_{\rm O}$ and eccentricity e for 1:1 resonance and the statistical steady state temperature field (corresponding to $Ra = 10^8$, $a_{\rm vis} = 10$, radiogenic heating $P_{\rm rad} = 20\,{\rm TW}$).

$\hat{a}_{\rm vis}$. n^* is the mean motion. $\zeta(e)$ is a function of eccentricity e inherent to the resonance of the orbit which depends on the rheological description especially for a high eccentricity. An example of this scaling for synchronous eccentric orbit (1:1 resonance) is shown in Fig. 1.

Naturally, the presence of an extra source of energy changes both the mean temperature and the temperature pattern. Due to a positive feedback between the temperature and the tidal dissipation, a statistical steady state with the presence of tidal dissipation may not exist: a thermal runaway occurs if the heat transfer through out the upper boundary is not sufficient.

Generally, the following scaling for runaway time t_r may be derived:

$$\frac{1}{t_r} \propto \alpha + \beta P_{\rm tide}(t_r),$$

where α and β are scaling parameters depending on Rayleigh number, viscosity parameter and radiogenic heating.

As expected, the parameterized curve for $t_r = 5\,{\rm Gy}$ (see Fig. 2) shifts towards the higher orbital period or lower eccentricities with decreasing Rayleigh number Ra, increasing $a_{\rm vis}$ and increasing radiogenic heating $P_{\rm rad}$.

The impact of the tidal dissipation on habitability strongly depends not only on the rheological parameters describing the anelastic dissipation (Fig. 1) but also on rheological properties of the long term flow. Due to the tidally induced thermal runaway and the associated volcanism, the habitability around low-mass stars is limited for eccentricity higher than ~ 0.01 in the case of 1:1 resonance and Rayleigh number $Ra = 10^8$ (Fig. 2).

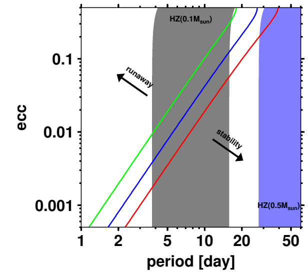

Figure 2: Phase diagram for the thermal runaways: red curve ($Ra = 10^8$, $a_{\rm vis} = 10$, $P_{\rm rad} = 20\,{\rm TW}$), blue curve ($Ra = 10^8$, $a_{\rm vis} = 10$, $P_{\rm rad} = 10\,{\rm TW}$), green curve ($Ra = 10^8$, $a_{\rm vis} = 5$, $P_{\rm rad} = 20\,{\rm TW}$). Habitability zone [3, 4] for 0.1 (grey area) and 0.5 (blue area) mass of the Sun.

3 Summary and Conclusions

We investigate the coupling between the long-term thermal evolution and the tidal dissipation. We observe a strong positive feedback which leads in some cases to thermal runaways. These runaways are strongly influenced by rheological properties of both the long-term flow and the anelastic dissipation. In the case of the short-period planets and low mass stars, occurence of tidally induced runaways is likely to restrict the habitability zone.

Acknowledgements

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