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Orbital and internal evolution of low-mass exoplanets in biplanetary systems

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Abstract

More than two decades of exoplanetary science have unveiled an abundance of planetary bodies, many of which are expected to reside in environments much harsher than experienced at the orbit of planet Mercury. Besides being constrained by the surface conditions, which are related to the planet's distance from the host star, the inner life of close-in bodies is profoundly shaped by tidal heating, which depends on the elements of planetary orbit.

The semi-major axis as well as the eccentricity of the orbit can be altered particularly by the two following secular mechanisms: tidally induced orbital evolution due to the host star and third-body perturbations due to another planets in the system. Our goal is to include both of these effects into a self-consistent model of coupled thermal-orbital evolution and explore its implications for the secular dynamics of low-mass exoplanets.

1. Model and methods

The model consists of four subproblems: 1) calculating the planet's tidal Love number, given its internal structure; 2) solving the evolution equations for planet's spin and orbit; 3) calculating radially dependent tidal heating, given the strain and stress under the actual external potential; and 4) finding the mantle viscosity (and thickness of the lithosphere) consistent with the obtained tidal heating and estimated radiogenic heating in a 1D parametrized model of mantle convection.

We approximate the planet by a layered sphere whose reaction to the external loading is characterized by either the Maxwell or the Andrade viscoelastic rheology and calculate its frequency-dependent complex Love numbers $\tilde{k}_l(\omega_{lmpq}) = k_l\, e^{i\varepsilon_{lmpq}}$ by means of the normal mode theory [1]. Complex Love numbers describe the magnitude of the disturbing potential induced by tidal deformations of the planetary surface, together with the lagging of this deformation due to attenuation inside the body. The disturbing potential can then be expressed as a serie [2]

$$\delta\mathcal{U}^{\rm tide} = \sum_{lmpq} k_l R^{2l+1} \mathcal{B}^*_{lm} \mathcal{C}^*_{lmpq} \sum_{hj} \mathcal{C}_{lmhj} \times \\ \times \cos\left[\nu^*_{lmpq} - \varepsilon_{lmpq} - m\theta^* - (\nu_{lmhj} - m\theta)\right], \tag{1}$$

where $\mathcal{B}_{lm}$ includes algebraic prefactors and mass of the perturber, $\mathcal{C}_{lmpq}$ characterizes shape and inclination of the orbit, R is the outer radius of the studied planet, θ the sidereal time and ν_{lmpq} is a combination of angular variables. Asterisk signifies that some variables are defined with respect to the perturber and the others with respect to the body whose motion is disturbed due to the tidally deformed planet (see [2] for details).

Similarly, for the sake of consistency, we describe the third-body perturbations by a disturbing function expanded into a Fourier serie,

$$\delta\mathcal{U}^{\rm third} = \mathcal{G} m_B \sum_{\rm indices} \frac{a^n_<}{a^{n+1}_>} \mathcal{D}_{I_0}(i_B) \mathcal{G}_{I_1}(e_A)\, \mathcal{G}_{I_2}(e_B) \times \\ \times \cos\Big[(n-2p_1+q_1)\, M_A + (n-2p_2+q_2)\, M_B + \\ + (n-2p_2)\,\omega_B + (-n+2p_1)\,\Omega_B\Big] \tag{2}$$

with m_B being the mass of the perturber, i_B, ω_B and Ω_B are angular Keplerian elements of the perturber's orbit with respect to the studied planet's orbit, a and e are the semi-major axes and eccentricities of the two planets (A and B) and M are the respective mean anomalies at the time of the computation. Function $\mathcal{D}_{I_0}$ is defined in analogy with Kaula's functions of inclination, $\mathcal{G}_{I_{1,2}}$ are Kaula's functions of eccentricity and $I_{0,1,2}$ symbolize the appropriate multiindices.

Both of the disturbing functions (1) and (2) drive the

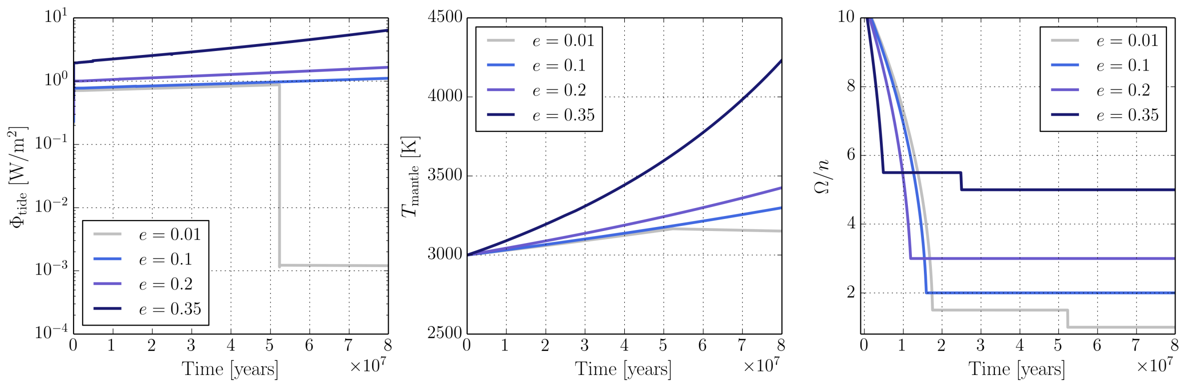

Figure 1: Long-term evolution of the tidal heat flux (*left*), the average mantle temperature (*centre*) and the spin rate (*right*) for a model of low-mass exoplanet Proxima Centauri b. Different shades of blue indicate different orbital eccentricities, which are almost constant on the presented time scales. The initial effective tidal viscosity of the mantle, governed by the Maxwell rheology, was set to $5 \times 10^{19}\,\mathrm{Pa\,s}$.

long-term evolution of the two planetary orbits, whose exact form is obtained from the Lagrange planetary equations (e.g., [3]). Additionaly, the change in each planet's spin rate is derived as a consequence of the conservation of total angular momentum.

Together with its contribution to the orbital evolution of close-in exoplanets, tidal interaction with the primary is also an important source of their internal heating. Radial dependence of the average tidal heating is calculated using an expanded version of the method described in [4], which is applicable to bodies with arbitrary orbital eccentricity and spin rate. Note that this method is also derived using the normal mode theory of [1].

Finally, the secular cooling of the planet is described by a 1D parametrized model of subsolidus convection in a mantle heated both volumetrically and from below. For the mantle viscosity, a parameter influencing vigour of the convection as well as the rate of orbital evolution, we prescribe temperature dependence of the form (e.g., [5])

$$\eta = \eta_0 \exp\left(\frac{E^*}{R_{\rm G}}\frac{(T_{\rm ref}-T)}{T_{\rm ref}T}\right) \tag{3}$$

with $\eta_0 = \eta(T_{\rm ref})$, where $T_{\rm ref} = 1600\,\mathrm{K}$ is the reference temperature, E^* is the activation energy for viscous deformation and $R_{\rm G}$ is the universal gas constant.

2. Preliminary results

Calculations performed for a single-planet system indicate, that depending on the initial mantle viscosity and the orbital eccentricity, the long-term coupled thermal-orbital evolution leads the planet either to gradual cooling down and stiffening of its mantle, or towards a thermal runaway, which can transform the planet into a magma world. Evolution of the interior then affects also the stable spin state of the planet. An example of this effect is shown in Figure 1, which presents the eccentricity-dependent tidal heating and consequential despinning of a model planet inspired by Proxima Centauri b.

Acknowledgements

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