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Surface temperature and tidal heating on close-in exoplanets

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Abstract

Close-in terrestrial exoplanets are subjected to strong stellar tides resulting in tidal dissipation and locking into spin-orbit resonances. The presence of significant tidal heating can lead to extensive temperature increase and possibly to thermal runaways within the planetary interior. Additionally, the planets locked in the spin-orbit resonance may exhibit large surface temperature contrasts which further influence the temperature pattern and heat transport. Here, we focus on the parameter dependence of both quantities—the surface temperature and the tidal heating—and discuss the significance of the spin-orbit resonances.

1. Model and Methods

In order to compute the surface temperature of a planet, we solve the heat diffusion equation along the orbit using a finite difference method with staggered grid for the spatial discretization and Crank-Nicolson scheme for the time discretization. The temperature field $T(r, \vartheta, \varphi)$ is computed in a thin subsurface layer (up to few meters) under the assumption that the planet possesses no atmosphere and its surface is covered by regolith. The upper boundary condition for the heat equation is given by the energy conservation law

$$S(1 - A) = \varepsilon\sigma T^4 - k\frac{\partial T}{\partial r}\,, \qquad (1)$$

where k is the thermal conductivity, A and ε are the albedo and the emissivity, respectively, and σ is the Stefan-Boltzman constant. The instantaneous insolation $S(\vartheta, \varphi)$ is a function of orbital and rotational parameters (semi-major axis, eccentricity of the orbit, obliquity, spin rate) [1].

Computation of the tidal heating requires knowledge of the rate of energy dissipation in the planetary mantle. Average power over a time interval T due to the heating may be obtained from the deviatoric part $\mathbf{D}$ of the Cauchy stress tensor and the strain rate tensor $\dot{\epsilon}$ as

$$P = \frac{1}{T}\int_V \int_t^{t+T} \dot{\epsilon}(\tau) : \mathbf{D}(\tau)\mathrm{d}\tau\mathrm{d}V\,. \qquad (2)$$

The tidal deformation of the planet is evaluated for the Maxwell or the Andrade viscoelastic rheology [2], using a staggered finite difference method in the radial direction and spherical harmonic decomposition in the lateral directions.

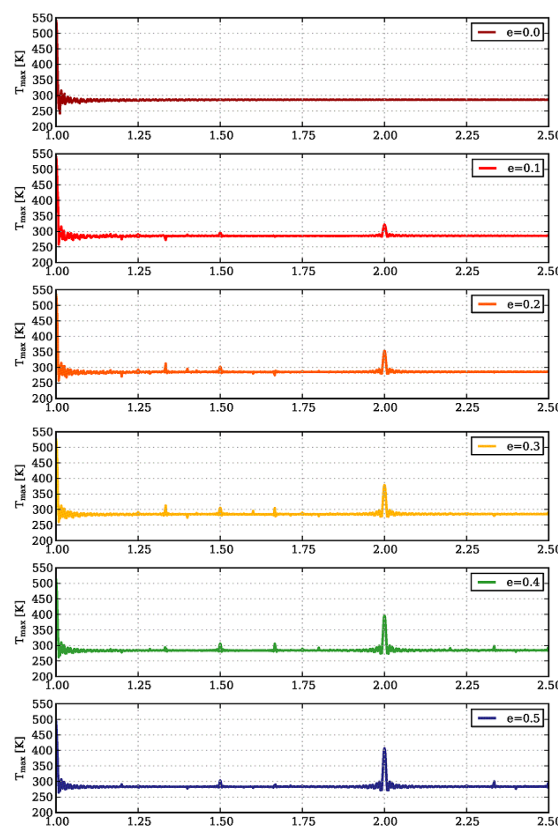

Figure 1: Mean temperature in a point of planetary surface with the maximum average insolation. Effect of the spin-orbit ratio (x-axis) and the eccentricity (colour).

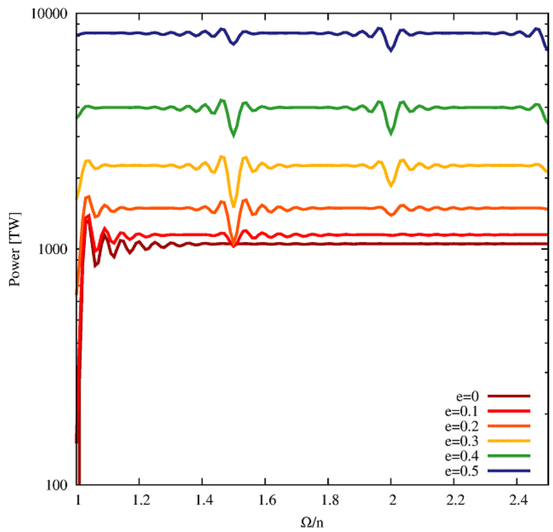

Figure 2: Average tidal heating as a function of the spin-orbit ratio and the eccentricity.

2. Results

Figure 1 and Figure 2 show results obtained for an Earth-like planet orbiting a host star with the mass $M_* = 0.5\,\mathrm{M_{Sun}}$ on the orbit with the semi-major axis $a = 0.1\,\mathrm{AU}$. The emissivity of the planetary surface is $\varepsilon = 0.9$, the albedo is $A = 0.1$ and the planet is considered to be a Maxwell body with the effective viscosity [2] $\eta = 10^{18}\,\mathrm{Pa.s}$ and the effective shear modulus $\mu = 2.10^{11}\,\mathrm{Pa}$.

The most prominent features in our parametric study of the surface temperature and the tidal heating are associated with the spin-orbit resonances. When the planet gets tidally locked and its rotational frequency is an integer multiple of the orbital frequency, the average temperature at the most irradiated location on the planetary surface increases abruptly in the order of hundreds of kelvins (Figure 1). Weaker effect is observed for other half-integer or third-integer multiples. The tidal heating of the planetary mantle (Figure 2), on the other hand, reaches a local minimum when the spin rate equals half-integer multiple of the orbital frequency, the deepest minimum being associated with the stable spin-orbit resonance for a given eccentricity, semi-major axis and the Maxwell time. Planets with lower eccentricity of the orbit are expected to be locked in a synchronous rotation state (1:1 spin-orbit resonance), while planets on the eccentric orbits prefer higher spin-orbit resonances [3].

3. Summary and Conclusions

We have studied the parameter dependence of the surface temperature and the tidal heating on terrestrial exoplanets without atmosphere. Both quantities undergo significant change when the planet falls into a spin-orbit resonance. This may have important consequences for the type of mantle convection as well as for possible habitability of the planet (if the atmosphere was considered), as it would be altered during the orbital evolution.

Acknowledgements

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