EPSC Abstracts
Vol. 9, EPSC2014-83-2, 2014
European Planetary Science Congress 2014

Surface Temperature of Terrestrial Exoplanets

M. Káňová, M. Běhounková
Charles University in Prague, Faculty of Mathematics and Physics, Department of Geophysics, Czech Republic
(kanova@karel.troja.mff.cuni.cz)

Abstract

An increasing number of detected extrasolar planets with known orbital parameters provides a unique statistical set that may improve our knowledge about long-term planetary evolution. The length of semi-major axis, orbit eccentricity and stellar luminosity, together with thermal parameters of the planetary surface, determine the distribution of surface temperature which imposes constrains on inner dynamical processes. Here, we evaluate the effect of various orbital and thermal parameters on maximum surface temperature and temperature contrast on close-in terrestrial exoplanets without atmosphere.

1. Model

The surface temperature T as a function of time and depth in a spherical shell is obtained as the solution of heat diffusion equation

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \, , \tag{1}$$

where ρ is density, c_p is specific heat and k is the thermal conductivity of surface material. Insolation pattern on tidally locked planets is determined by their orbital elements (eccentricity and longitude of the periapsis) as well as by rotational characteristics (obliquity and the type of spin-orbit resonance) [3]. Magnitude of irradiance, or the "extrasolar constant" $S_* = \frac{L_*}{4\pi a^2}$, is controlled by the length of semimajor axis a and the luminosity of a host star L_*. Insolation of the planetary surface $S(\vartheta, \varphi)$ enters the heat diffusion equation in the form of upper boundary condition, given by the total energy conservation

$$S(1-A) = \varepsilon \sigma T^4 - k \frac{\partial T}{\partial r} \, , \tag{2}$$

where A and ε are dimensionless albedo and emissivity, respectively, and σ is the Stefan-Boltzman constant.

In order to solve the heat diffusion equation in the surface layer, we employ a finite difference scheme with staggered grid in either one or three dimensions. Due to the nonlinearity of upper boundary condition and the temperature dependence of k and c_p, the heat equation is solved iteratively in each time step. As the lower boundary condition we prescribe the heat flux density $\vec{q}$.

A study of long-term planetary evolution requires consideration of time-dependent orbital parameters, as they are secularly affected by tidal interactions or gravitational disturbances caused by other bodies in a planetary system. For a simple case of one planet orbiting its host star on eccentric orbit, we compute temperature changes during circularisation of the orbit using a constant time-lag tidal model [2].

2. Results

For the evaluation of parameter dependence of surface temperature we consider a terrestrial planet with both constant and temperature-dependent thermal parameters k, c_p. For all model planets we set $A = 0.1$, $\varepsilon = 0.9$, radius $R_p = R_{\mathrm{Earth}}$ and mass $M_p = M_{\mathrm{Earth}}$. The mean temperature is computed in different depths at a point of planetary surface with maximum or minimum insolation during one period (one orbital period for 1:1 resonance, two orbital periods for 3:2 resonance). In the following text, this average temperature is shortly referred to as the maximum or minimum surface temperature. We vary orbital parameters and thermal inertia $I = \sqrt{k \rho c_p}$ in a range of realistic values and observe following features:

Mean surface temperature during an insolation cycle is systematically lower than a steady-state temperature computed for the average insolation. The difference, influenced by the cooling of the night side, is significant especially in the case of higher spin-orbit resonance, while for a synchronously rotating planet with $e \sim 0$ and $\beta \sim 0°$ it tends to zero.

In the case of 1:1 spin-orbit resonance the maximum surface temperature for given extrasolar constant slightly increases with increasing thermal inertia and decreases with increasing orbit eccentricity or obliquity. It stays almost unaffected by variations of longitude of the periastron. The minimum surface temperature, or the temperature in the regions of "eternal night", is controlled solely by the heat flux density from below. The temperature contrast between the day and night side may rise up to hundreds or thousands of kelvins for different values of extrasolar constant.

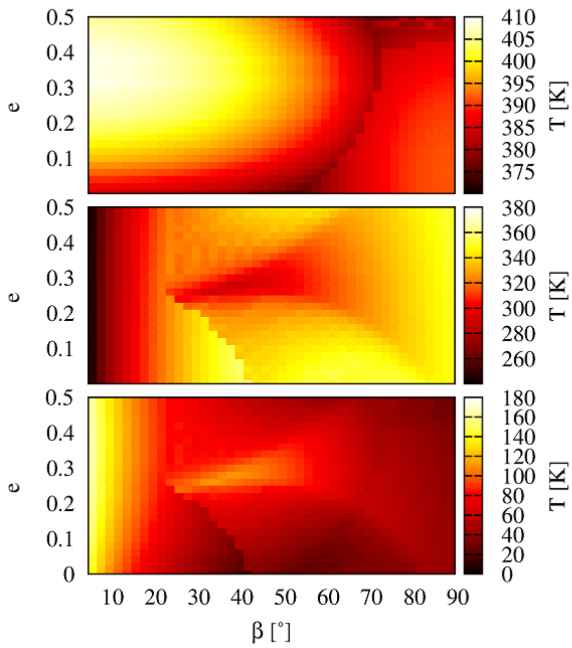

Figure 1: Mean temperature at the point of planetary surface with maximum (upper figure) and minimum (middle figure) insolation and their difference (lower figure). Temperature is plotted as a function of obliquity β and orbit eccentricity e in the case of 3:2 spin-orbit resonance with following constant parameters: $S_* = 9090\,\mathrm{Wm^{-2}}$, $k = 1\,\mathrm{Wm^{-1}K^{-1}}$, $\rho = 2700\,\mathrm{kg\ m^{-3}}$, $c_p = 800\,\mathrm{JK^{-1}kg^{-1}}$.

In the case of 3:2 spin-orbit resonance there are no areas of eternal night on the planetary surface, therefore the temperature contrast becomes less extreme. The parameter dependence of maximum and minimum surface temperature is not as simple as for the planet on a synchronous orbit. An example may be seen on Fig. 1. For low to intermediate values of obliquity the maximum temperature increases with increasing orbit eccentricity (as opposed to the 1:1 resonance), culminates at $e = 0.35$ and then starts to decrease. Variations of longitude of the periastron may affect the minimum temperature on the scale of tens of kelvins, if the orbit eccentricity is sufficiently high ($e > 0.2$).

3. Summary and Conclusions

We have studied parameter dependence of surface temperatures on terrestrial exoplanets without atmosphere in the case of two different spin-orbit resonances. The mean temperature that was computed using the heat diffusion equation (1) is always lower than the steady-state temperature for average insolation. This difference may rise up to hundreds of kelvins for higher spin-orbit resonance and should be considered in further models of inner dynamical evolution [1].

Acknowledgements

This work was supported by the Grant Agency of Charles University (project No. 338214) and the Czech Science Foundation (project No. 14-04145S).

References

[1] Běhounková, M. and Čadek, O.: Tidal dissipation in heterogeneous bodies: Maxwell vs Andrade rheology, EPSC, 2014.

[2] Correia, A.C.M. and Laskar, J.: Tidal Evolution of Exoplanets, arXiv:1009.1352, 2010.

[3] Dobrovolskis, A.R.: Insolation on exoplanets with eccentricity and obliquity, Icarus 204, pp. 760-776, 2013.