Plausible constraint on Golevka's regolith from an accurate Yarkovsky/YORP effect model

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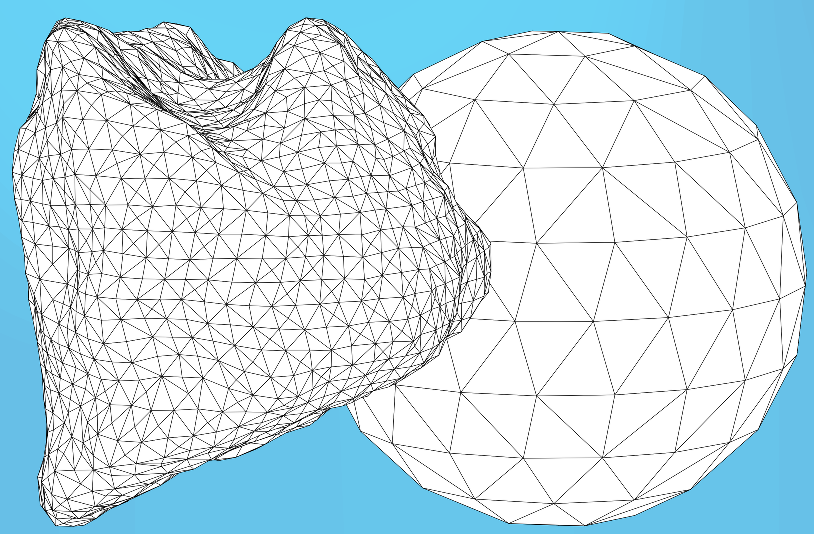
Abstract

The Yarkovsky effect, a recoil force due to thermal radiation, is an important perturbation in the dynamics of small Solar System bodies. In an attempt to determine the Yarkovsky force as accurately as possible we develop numerical model capable to remove most of simplifying assumptions of the analytic theories. A novel feature discussed here is a possibility to account for a multilayer surface structure. Assuming a high-conductivity core we are thus able to constrain thermal and geometric parameters of the surface lower-conductivity slab for the asteroid 6489 Golevka. With that we substantiate conclusions from Chesley et al. (2003) [1] who detected the Yarkovsky effect in its orbit.

The numerical model description

Shape model

The best available model of 6489 Golevka is a triangulated 4092 polyhedron derived from Arecibo radar ranging ([7]; see *http://echo.jpl.nasa.gov/links.html*). To speed the computations we also use an acceptable approximation with a uniform 248-hedron of the same volume as Golevka.



Physical parameters

Our working hypothesis assumes a low-conductivity (and density) particulated surface layer covering a high-conductivity core composed of a fresh basalt. Thus the thermal conductity of the core is set to be 2.5 W/m/K, while the surface layer has $K = A + BT^3$ with tested values A=0.001-0.1 W/m/K and B=2x10^{-11}W/m/K^4 (e.g. [2]). The core and the surface layer have assumed bulk densities of 2.5 g/cm^3 and 1.7 g/cm^3. The specific heat capacity C is also assumed temparature-dependent as given in the literature (e.g. [2]).

One-dimensional approximation for HDE

We use 1-D approximation of the heat diffusion problem. Thus the temperature T is computed separately for each of the surface elements and it depends on time t and depth z only. This is justified when neighboring elements do not thermally communicate enough. The size of the body D must be (much) larger than the penetration depth of the lowest frequency (seasonal) themal wave. For a basaltic body at ~ 2 AU heliocentric distance this turns out to constrain D > 50-100 m.

Crank-Nicholson scheme

used here is a unconditionally stable implicit solver of the diffusion problem. Temperature profile in the next timestep $T^{t+\Delta t}$ is determined by solving a set of linear equations (together with boundary conditions):

$$\boldsymbol{D}\ T^{t+\Delta t} = R,$$

where $\boldsymbol{D}$ is a tridiagonal matrix and R is a vector. The main problem here is, that $\boldsymbol{D}$, as well as R, depend on an unknown temperature $T^{t+\Delta t}$; this occurs because of temperature-depedence of the thermal parameters (see above). We solve this problem, as well as the non-linear surface boundary condition, iteratively, taking $T^{t+\Delta t} = T^t$ in the first step.

Boundary conditions

The first, usually linearized in analytic theories, follows from energy balance between incoming, conducted and re-radiated energy at the surface. The second is constant temperatute in the core (at large depth). Finally we assume that orientation of the body with respect to the Sun is periodic, thus repeats after some interval of time P (usually equal to the revolution period).

The space and time steps

We use constant timestep Δt=300s, and spatial step exponentially increasing according to $\Delta z_k = \Delta z_0 \exp(0.1\ k)$, where Δz_0=0.01mm.

Yarkovsky thermal force

When the temperature T of all surface elements has been computed, a recoil force due to thermal radiation is determined by

$$\boldsymbol{f} = \int d\boldsymbol{f}, \quad d\boldsymbol{f} = -2\sigma/(3c)T^4\boldsymbol{n}\ dS,$$

where c is speed of light, $\boldsymbol{n}$ is the unit vector normal to the surface and dS is the area of the surface element.

Introduction and motivation

The Yarkovsky effect is caused by the pressure of thermal radiation from a surface of an asteroid or meteoroid. A finite value of thermal inertia makes the maximum temperature (thus the thermal recoil force) to be tilted from the direction to the heating source (the Sun). This effect produces a nonzero transverse component of the total radiation force and results in a secular change of the orbital semimajor axis *a*.

Most of the analytical theories of the Yarkovsky effect require a large number of simplifying assumptions such as the spherical shape, thermal parameters constant, linearization of the heat diffusion problem, circular orbit etc. In spite of all this, their results are useful for problems when statistical behavior of a large sample of bodies is to be determined (e.g. [4]).

Predictions of the analytical theories are, however, unreliable when a high-accuracy computation of the Yarkovsky effect is needed (such as with the aim to detect it using orbit of one particular object). Numerical solution of the heat diffusion problem may relax most of the simplifications mentioned above at the expense of longer computing time. Models with different levels of sophistication are available today (e.g. [5], [6]).

Here we continue this effort by still improving our previous model to account for possible details of the surface composition. In particular, we allow the body to consist of several layers with different thermal properties, such as the high-conductivity core burried under a slab of low-conductivity surface layer (regolith of just fragmented/porous region). Previous models required constant thermal parameters.

We test implications of such an improved Yarkovsky force computation in the case of 6489 Golevka. Chesley et al. [3] succeeded to detect the Yarkovsky effect in the orbit of this small asteroid using precise radar astrometry data. Observationally, the effect amounted to ~ 15 km displacement from the Arecibo dish in May 2003 as compared to the standard (non-Yarkovsky) ephemerides. This effect fully stems from a non-zero secular drift of Golevka's semimajor axis of *(da/dt)* ~ -5.5 x 10^{-4} AU/My.

Results

We studied the influence of depth and thermal conductivity of the surface layer on the Yarkovsky semimajor axis drift *da/dt* for 6489 Golevka. Our results are summarized in the following two plots:

Figure 1 shows dependance of *da/dt* on the surface layer depth for three values of its conductivity parameter *A* (see the label).

Figure 2 describes dependance of *da/dt* on both the thermal conductivity parameter *A* and the depth of the surface layer. The thick solid line is a penetration depth of the diurnal temperation variations l_d and the dashed lines correspond to 1/4 l_d and 4 l_d. The value of *da/dt*=-5.5x10^{-4}AU/My, together with its 10% uncertainty interval, is marked by the thick contour and the dotted area respectively.

Results in Fig. 2 indicate that when the surface layer > 10 l_d, about an meter deep for all *A*, the value of *da/dt* is the same as it would correspond to the *A* conductivity value in a model with constant thermal parameters used previously (in either analytical [3] or numerical [1] approaches). Conversely, when the thicknes of the surface layer shinks to zero, *da/dt* becomes ~ -3x10^{-4}AU/My corresponding the *A*=2.5W/m/K uniform model.

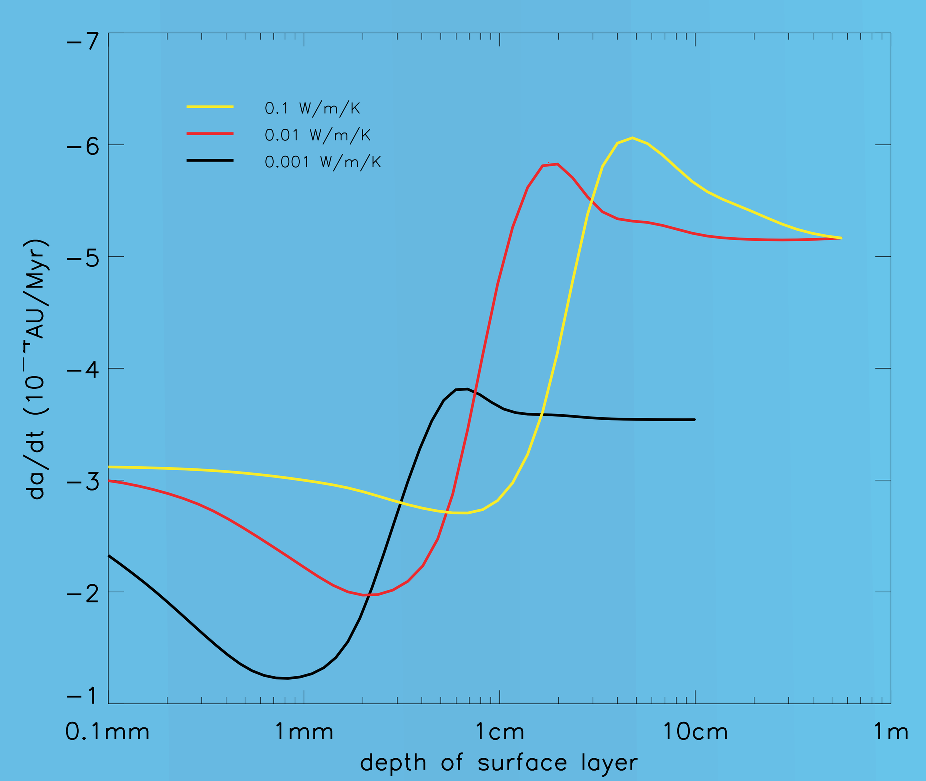


Figure 1: Yarkovsky semimajor axis drift as a function of the surface layer depth. See the text for details.

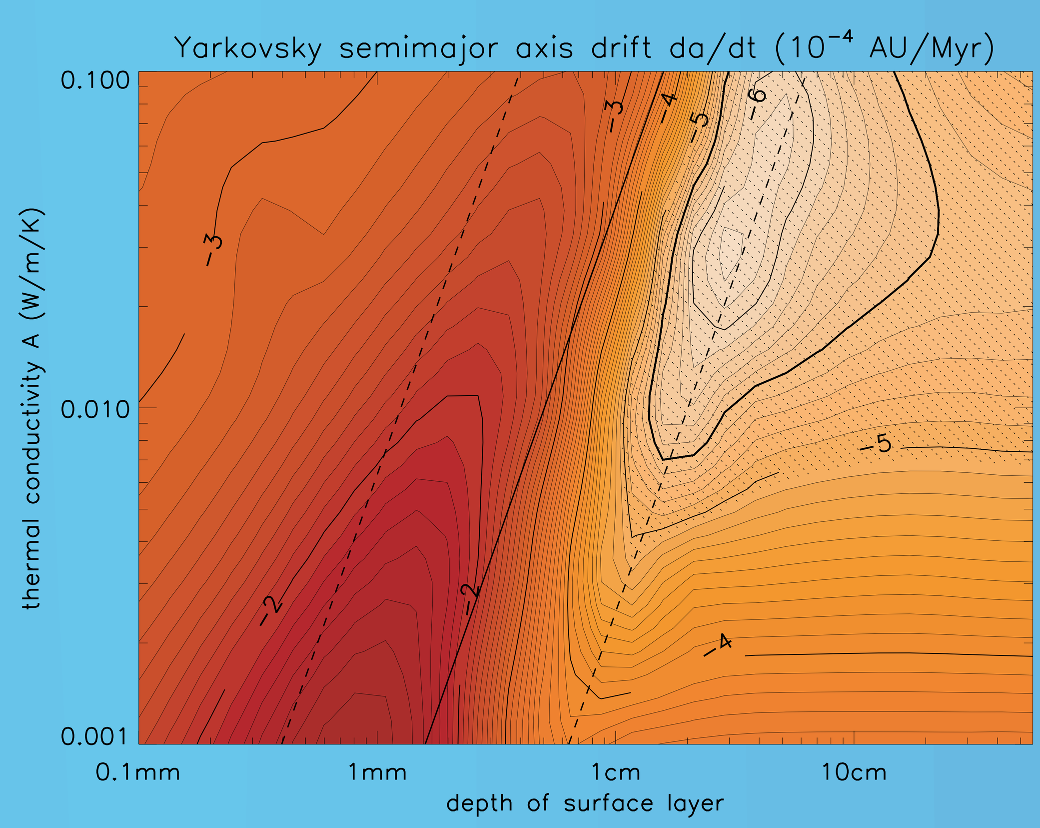


Figure 2: Yarkovsky semimajor axis drift as a function of the the surface layer depth and thermal conductivity parameter *A*. Labels are *da/dt* values in 10^{-4}AU/My. See the text for details.

These two limiting regimes are connected with a transition zone of a non-trivial *da/dt* behavior. The most steep variations occur when the depth of the surface layer is ~l_d (Fig. 2).

Figure 2 results may be used to a correlated determination of *A* and the surface layer depth *h* provided a certain value of *da/dt* is known. In the case of 6489 Golevka the region of admissible *(A,h)*-values is highlighted by the dotted area in Fig. 2.

Conclusions

- Our experiments indicate that the radiative term BT^3 in thermal conductivity K is not critical in evaluation of Golevka's semimajor axis drift *da/dt*. Droping this term from our analysis would significantly speed the computations.
- Low-conductivity surface layer may significantly change the resulting *da/dt* value if its depth is comparable to the penetration depth of the diurnal thermal wave (1-10 cm).
- If Golevka's interior is consistent with our assumption, high-conductivity basalt rock, our results constrain its surface parameters. In particular, its thermal parameter *A*>0.004 W/m/K and its depth larger than 1 cm. The infered *A*-value excludes a possibility of having regolith layer on Golevka, since its thermal conductivity would be still lower than our minimum value. The surface of Golevka is likely a highly porous rock.

References

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