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Accurate model for the Yarkovsky effect

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Abstract. Yarkovsky effect (YE), a tiny nongravitational force due to radiative recoil of the anisotropic thermal emission, is known to secularly affect the orbital semimajor axis. Therefore, angular phases such as longitude in orbit or proper longitude of node undergo a quadratic perturbation. This is fast enough to allow direct detection of the YE. The first positive case was obtained for (6489) Golevka in 2003 and prospects are very good for many more detections in the near future. To make productive scientific use of the YE detections, we need to accurately compute its strength for a given body. Simple models, available so far, will likely not be adequate in many of the forthcoming YE detection possibilities. We thus developed a complex numerical approach capable of treating most of them. Here we illustrate its power by discussing the cases of: (i) Toutatis, with a tumbling (non-principal-axis) rotation state, and (ii) 2000 DP107, a binary system.

Keywords. Minor planets, asteroids: individual (Toutatis, 2000 DP107).

1. Introduction

The Yarkovsky effect (YE), and its consequences for planetary science, has attracted a considerable attention during the past decade (e.g. Bottke *et al.* 2003; Vokrouhlický *et al.*, this volume). It became a vital part of models for meteorite and asteroid delivery to the planet-crossing region (e.g. Farinella *et al.* 1998; Farinella & Vokrouhlický 1999; Vokrouhlický & Farinella 2000; Morbidelli & Vokrouhlický 2003), dynamical aging of the asteroid families (e.g. Bottke *et al.* 2001; Vokrouhlický *et al.* 2002; Nesvorný & Bottke 2004) or populating metastable asteroidal orbits (e.g. Vokrouhlický *et al.* 2001; Tsiganis *et al.* 2003; Brož *et al.*, this volume). Though important, these applications assume large samples of bodies and do not allow direct detection of the YE (with the unusual exception of the Karin family; Nesvorný & Bottke 2004).

Since the YE continues to perturb accurately known orbits of the planet-crossing asteroids, Vokrouhlický *et al.* (2000) suggested a direct detection can follow from their precise tracking (see also Vokrouhlický & Milani (2000) who discuss effects of other radiative forces on the motion of planet-crossing asteroids). This is because the YE makes a steady perturbation of the orbital semimajor axis, producing a quadratic advance along the orbit; in a number of cases the resulting displacement exceeds ephemerides uncertainty and allows YE detection. With that goal, Chesley *et al.* (2003) conducted a successful experiment by radar ranging to the near-Earth asteroid (6489) Golevka. Their analysis also proved the YE detection contains a significant scientific information, most importantly it has the capability to constrain an asteroid's mass. Vokrouhlický *et al.* (2004a,b) recently reviewed future possibilities for YE detection and noted about a dozen cases might be obtained in the next decade, with more possibly later on. Several of these candidate objects present unforseen difficulties in terms of the YE computation.

This situation motivated us to develop dedicated software for accurate YE computation: the purpose of this paper is to discuss its properties. Our goal is to tackle most of the "real-world" cases, including bodies of unusual shape, orbit and/or rotation state. Here we discuss two spectacular objects: (i) 4179 Toutatis, a body with the most accurately known tumbling state, and (ii) 2000 DP107, a binary system. If the YE is detected in the Toutatis' motion in October 2004 (see Vokrouhlický *et al.* 2004a), Toutatis might become a landmark case in several respects: (i) this will be the first multi-kilometre asteroid for which YE would be detected, and (ii) with further observation possibilities till 2012 this might be the first case for which the YE will be repeatedly measured. Similarly, if YE signal is too weak for 1998 RO1, the system 2000 DP107 might be the first binary for which YE will be detected (see also Vokrouhlický *et al.* 2004b).

2. Numerical model

Analytical expression of the Yarkovsky force components have been obtained so far for a spherical body residing on a low-eccentricity orbit (e.g. Vokrouhlický 1998, 1999; Vokrouhlický & Farinella 1999); moreover, these results assume linearization of the boundary condition (2.2). Though largely simplified, this formulation was successfully used by Vokrouhlický *et. al.* (2000) for low-accuracy, but reliable, predictions and is available at `http://newton.dm.unipi.it/` as a Fortran source within the `OrbFit` software package.

Apart from a non-linear nature of the heat diffusion problem (HDP), computation of the Yarkovsky force for near-Earth asteroids (NEAs) frequently brings some, or a combination, of the following complexities: (i) large orbital eccentricity, (ii) highly irregular shape (such as a part of the surface may cast shadow on another part), (iii) temperature-dependent thermal constants and/or (iv) unusual rotation state (including free motion of the rotation axis in the body, i.e. the "tumbling state"). Moreover, a fair fraction of NEAs are not solitary but compose binary systems (e.g. Merline *et al.* 2003). All these factors could invalidate the very simplified analytical approach and need to be considered for a high-accuracy YE computation.

Formulation of the heat diffusion problem.– In general, a fully 3D formulation of the HDP is needed to characterize the temperature inside and on the surface of a body. However, since we assume external energy sources only (such as impinging sunlight), in the most relevant situations the body consists of an isothermal core with temperature variations occurring in a thin surface slab. In that case, one can adopt a simplified, 1D approach with temperature $T(t, z)$ dependent on the depth z below the surface and time t (for an early formulation see Wesselink 1948). This is justified when the penetration depth of the most important thermal wave (diurnal or seasonal) is significantly smaller than the size of the body. Bodies larger than $\simeq 20$ m generally meet this condition, unless a very high thermal inertia†. The HDP is thus solved for each of the (infinitesimal) surface elements separately, as if there were no thermal communication between them through latitudinal thermal gradients.

The heat diffusion equation now reads

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z}\right) , \tag{2.1}$$

where ρ is the density, C is the specific heat capacity and K is the thermal conductivity, all of which might be temperature dependent. If this effect is taken into account, we

† An exceptional group of very small NEAs, such as 1998 KY26 or 2003 YN107, may require a full-fledged 3D analysis as in Spitale & Greenberg (2000).

use empirical fits to laboratory and/or space measurements (e.g. Wechsler *et al.* 1972; Yomogida & Matsui 1983).

The system (2.1) must be supplemented with boundary conditions to make the solution unique. In the space coordinate this means (i) energy input on the surface, and (ii) constancy of the temperature at large depth; put in mathematics we have

$$\varepsilon\sigma T^4\left(t,0\right) = K\,\frac{\partial T}{\partial z}\left(t,0\right) + E\left(t\right)\ , \tag{2.2}$$

$$\frac{\partial T}{\partial z}\left(t,\infty\right) = 0\ , \tag{2.3}$$

where we explicitly made clear depth z of the boundary. Here ε is the surface infrared emissivity, σ the Stephan-Boltzmann constant and $E = (1-A)\Phi\left(\mathbf{n}\cdot\mathbf{n}_0\right)$ is the radiative energy flux through the surface element; A is the albedo value in optical, Φ the incident solar radiation flux, $\mathbf{n}$ is the external unitary normal vector to the surface facet and $\mathbf{n}_0$ is the local direction to the Sun. We note E is nil, when $\mathbf{n}\cdot\mathbf{n}_0 < 0$ and also when another part of the body casts a shadow onto the chosen surface element (see below).

In the time coordinate we impose periodicity after interval P, thus $T(t,z) = T(t+P,z)$ for all grid nodes. After the period P the body must be brought into the same conditions, namely experience the same exterior radiation field. In practice this means to be at the same phase of revolution about the Sun and to have the same orientation in space. Though most asteroids of interest are in the principal-axis rotation mode, their rotation and revolution periods are not necessarily commensurate. However, the rotation period $P_{\rm rot}$ is usually much shorter than the revolution period $P_{\rm rev}$ and it is without loss of accuracy in evaluation of the YE to slightly modify $P_{\rm rot}$ in order to become commensurate with $P_{\rm rev}$. Then $P = P_{\rm rev}$. A more tricky situation occurs for a special class of tumbling asteroids (e.g. Pravec *et al.*, 2004), for which their orientation in space might not repeat at any time. Luckily, near-repetitions are usually found and they could be made commensurate with $P_{\rm rev}$; see Sec. 3 for an example.

We note that scaled, rather than physical, variables are best suitable in our problem. Depth z is expressed in terms of the penetration depth $h_T = \sqrt{KP_{\rm rot}/2\pi\rho C}$ of the diurnal thermal wave, thus introducing $z' = z/h_T$. Time t is replaced with the mean anomaly ℓ of the orbital motion. The "isothermal-core" condition (2.3) is applied at typically $10-15$ penetration depths of the seasonal thermal wave ($= \sqrt{P_{\rm rev}/P_{\rm rot}}\,h_T$), and the solution is (multiply) 2π periodic in the ℓ variable. Standard discretization methods are used to represent the heat diffusion equation (2.1) and Spencer *et al.* (1989) scheme is used for the non-linear surface boundary condition (2.2). An isothermal initial seed in the whole mesh quickly converges to the desired solution, though faster convergence is achieved when analytical approximation are used (such as in Wesselink 1948). We stop iterations of the numerical solution when a fractional change in temperature of all surface elements between two successive iterations is smaller than 10^{-4}.

Rotation state.– The surface energy input function $E(t)$ in (2.2) is computed from the known position of the Sun with respect to the surface element and it is a function of the asteroid orbit and its orientation in space. The latter is expressed using a rotation matrix $\mathbf{R}$ that refers body-fixed frame to an inertial frame. In general $\mathbf{R}$ may be parametrized by three Euler angles; for principal-axis rotators those depend on pole position, rotation period and epoch of local meridian,† while for tumbling asteroids the Euler

† In fact the result only weakly depends on the phase of local meridian at a given time, so that this information may be waived and replaced with an arbitrary zero value.

equations are numerically integrated with given initial data (e.g. Landau and Lifschitz 1976; Kryszczyńska *et al.* 1999).

Shape/shadowing.– We use polyhedron representation of the asteroid shape with typically several thousands triangular surface elements. These models are mostly due to radar sensing analysis, to lesser extend due to direct satellite reconnaissance and/or lightcurve inversion (data are generally available at the PDS node `http://www.psi.edu/pds/archive/rshape.html`). Solution of the HDP is preceded with a preliminary analysis, where we store in computer memory all combinations of mutual shadowing effects of different parts of the asteroid. This information is used for evaluation of the energy source function $E(t)$ in (2.2).

Yarkovsky force.– Once the surface temperature is determined by the numerical analysis described above, we compute components of the Yarkovsky force. For an oriented surface facet $d\mathbf{S} = \mathbf{n}\, dS$ their infinitesimal values read (see e.g. Milani *et al.* 1987)

$$d\mathbf{f}(\ell) = -\frac{2}{3}\frac{\varepsilon\sigma T^4(\ell, 0)}{c}\,\mathbf{n}\, dS \;, \tag{2.4}$$

where the isotropic (Lambert) thermal emission is used. Total force† components are expressed as a sum of partial results for all surface elements and they are exported in an output file (with an appropriate header describing model parameters). In complex situations, like those discussed below, we export the resulting force components once every fraction of the diurnal cycle (typically $20 - 200$ times per asteroid rotation). In the case of solitary asteroids with principal-axis rotation, we further locally average over a diurnal cycle, making roughly $100 - 500$ normal points of the Yarkovsky force components per asteroid's revolution about the Sun. This procedure makes then the orbit determination faster.

Data and their availability.– Examples of our results are available through the `http://sirrah.troja.mff.cuni.cz/~davok/` web site where we also maintain a page coordinating efforts for the future YE detections.

3. Two examples

In what follows we briefly discuss results for two cases that require a high-accuracy YE computation. More details can be found in Vokrouhlický *et al.* (2004a,b).

Toutatis: a tumbling asteroid.– Toutatis was the first asteroid for which the non-principal-axis (tumbling) rotation state was discovered and accurately determined (Hudson & Ostro 1995). With the orbit residing near the 1/4 exterior mean motion resonance with the Earth, Toutatis undergoes frequent close Earth encounters during a couple of decades and this might permit YE to be detected (Vokrouhlický *et al.* 2004a). Accurate radar astrometry was acquired in 1992 and 1996 (Ostro *et al.* 1999), and a single Doppler measurement from 2000 is less useful but still makes a valuable constraint on the orbit. A spectacularly close encounter which occurs late September 2004 may give the first opportunity to detect YE (Vokrouhlický *et al.* 2004a), with further refinements during 2008 and 2012 encounters (all within the reach of the current radar systems; see `http://echo.jpl.nasa.gov/`).

As noted in Sec. 1, a productive use the YE measurement requires ability of a high

† We also standardly compute total thermal torque $d\mathbf{t} = \mathbf{r} \times d\mathbf{f}$ ($\mathbf{r}$ is the position vector of the surface element) affecting body's rotation, the so called YORP effect; e.g. Bottke *et al.* (2003). As an example, this has been used for prediction of the YORP observability in the case of asteroid (25143) Itokawa (Vokrouhlický *et al.* 2004c).

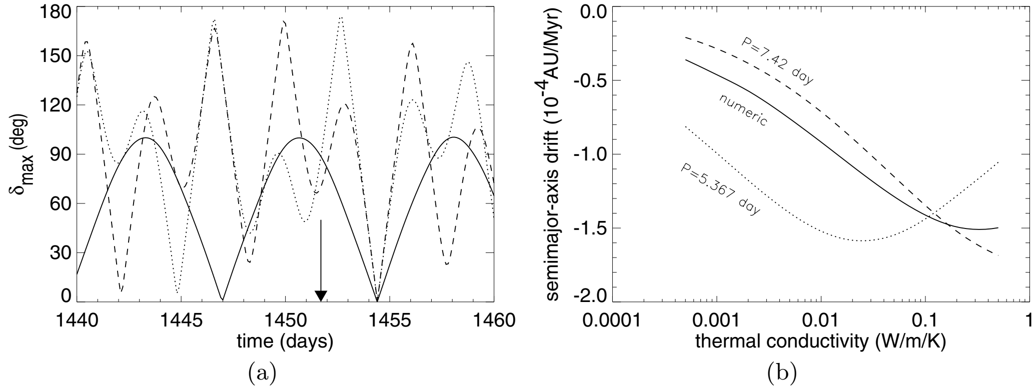

Figure 1. *Part a*: The angle between body principal axes at the initial epoch and time t (abscissa; in days): (i) solid for the longest axis, (ii) dotted for the middle axis, and (iii) dashed for the shortest axis. There is a sharp minimum in all angles at time $\simeq 1454.4$ d, meaning a near coincidence with the initial-epoch orientation (better than $0.5°$; initial epoch from Ostro *et al.* 1999). The arrow indicates orbital period. *Part b*: Estimated mean drift rate of the semimajor axis of Toutatis orbit due to the YE as a function of the surface thermal conductivity. Solid curve from the high-accuracy model, dashed and dotted curves from a simplified analytic approach assuming a spherical body with two characteristic periods: (i) 5.367 d (dotted), and (ii) 7.42 d (dashed); this model assumes spin axis along the total angular momentum of Toutatis.

accuracy Yarkovsky force computation. This appears non-trivial for elongated and tumbling Toutatis. The particular trouble for this body is its non-axial rotation: spin vector wobbles around the longest body axis in 5.367 d (in the body-fixed frame) and the longest body axis precesses around the nearly conserved total angular momentum in 7.42 d (in the inertial frame). Both motions are slow, which means the diurnal thermal lag is small and this strengthens requirements on accurate prediction of the YE magnitude. As for the boundary condition issue we note Toutatis undergoes a near repetition of its space orientation in $\simeq 1454.4$ d, remarkably close to the orbital period $P_{\rm rev} \simeq 1451.7$ d (Fig. 1a). Except an unlikely case of random coincidence, we do not have explanation for this interesting commensurability that may warrant future theoretical work. It appears important for our work, since we can take $P = P_{\rm rev}$ for the periodicity of the temperature solution.

We use a high-quality polyhedral model with 12 796 triangular facets adopted from `http://www.psi.edu/pds/archive/rshape.html`. Surface parameters are as follows: the mean density $\rho = 2\,{\rm g/cm}^3$, the mean specific thermal capacity $C = 800\,{\rm J/kg/K}$, the surface albedo $A = 0.1$ and the mean thermal conductivity varied in the interval $K = 0.0005 - 0.5$ W/m/K (though we consider $\simeq 0.01$ W/m/K the most likely value, compatible with the estimated thermal inertia reported by Howell *et al.* (1994)). When converting the Yarkovsky force to acceleration components, we adopt a bulk density $\rho_b = 2.6\,{\rm g/cm}^3$, slightly higher than ρ (presumably affected by surface microporosity).

Figure 1b shows the resulting mean rate of change of Toutatis' semimajor axis due to the YE as a function of the poorly constrained surface conductivity K. Because of the slow rotation the YE strength drops for small values of K. For interest, we also show prediction of the linearized analytical theory that would assume an equivalent spherical body uniformly rotating about the direction of Toutatis angular momentum with two characteristic periods. Interestingly, the 7.42 d period does a fairly good job, especially for high conductivity values. Adopting $K = 0.01$ W/m/K we predict the YE displacement should exceed during the early October 2004 a 3σ formal orbit-determination error due to uncertainty in observations, thus being possibly detectable at a statistically significant level (more details in Vokrouhlický *et al.* (2004a)). It is, however, yet to be verified that

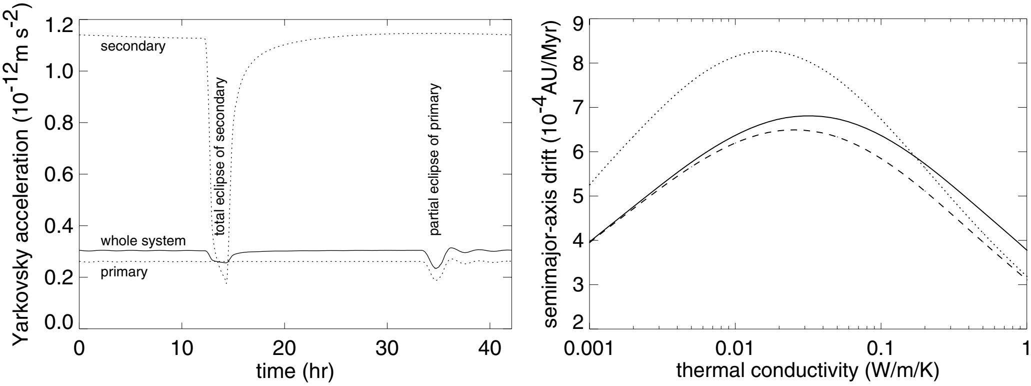

Figure 2. *Part a*: The effect of mutual eclipses between components of 2000 DP107 system: amplitude of the Yarkovsky acceleration during one revolution about their common center of mass. Eclipses produce dips in the signal; smooth variation during the shadow/eclipse entry and exit is due to a finite value of the surface thermal inertia (note the different effects for the fast rotating primary and the slowly rotating secondary asteroid). Solid curve is the effective Yarkovsky acceleration as it appears in the translational motion of the center of mass about the Sun. *Part b*: Drift rate of the orbital semimajor axis of the 2000 DP107 system due to the YE as a function of surface thermal conductivity K: (i) solid curve is for the whole system, (ii) dashed curve is for the primary component only, as if it were a solitary asteroid (no eclipses), and (iii) the dotted curve is for the primary component only and with the analytic formulation of the YE. A fair agreement indicates the effect of the secondary is minor, except for large value of K.

the orbit uncertainty due to gravitational perturbation by asteroids does not prevent the YE detection. This concern is mainly because of a low inclination of Toutatis' orbit (0.44°), thus leading to frequent encounters with many asteroids in the main belt. Assuming the encounter probability scales inversely proportinally with inclination (e.g. Öpik 1951, 1976), we might expect about 5 times larger orbit-uncertainty due to gravitational effects of asteroids than in the case of (6489) Golevka. This latter has been estimated to be about 15 μs in delay measurement (Chesley *et al.* 2003; note the predicted delay displacement due to the YE is in between $15 - 30\,\mu$s in October 2004).

2000 DP107: a binary system.– 2000 DP107 belongs to the $10 - 15\%$ population of binary asteroids among NEAs (e.g. Margot *et al.* 2002; Merline *et al.* 2003). It consists of two components, a primary with estimated size of $\simeq 800$ m and a secondary of $\simeq 300$ m. The primary component exhibits a fast rotation with $P_1 \simeq 2.775$ h, while the secondary component is likely orbit-synchronous with a period of $P_2 \simeq 1.755$ d (in our model we slightly tweaked these values to become commensurable with the orbital period of the system about the Sun, namely P_1 be 1/5034 and P_2 be 1/332 part of that value). The mutual orbit of the two asteroids is quasi-circular with radius of $\simeq 1310$ m. Current data do not allow shape resolution, so that we use spherical models for both components, represented in our model by 1004-facet polyhedra, with spin axes perpendicular to their mutual orbital plane (all data from Margot *et al.* (2002)).

In compact binaries, such as 2000 DP107, mutual eclipses produced by the two asteroids play important role and must be taken into account (Fig. 2a). We accordingly adapted our software to compute simultaneously Yarkovsky force for both asteroids in the system. The C-type classification for the primary component and tracking of mutual motion of the two components suggest lower density of $1.7\,\mathrm{g/cm^3}$ (Margot *et al.* 2002; we assume this value for both surface and bulk density). The specific thermal capacity is taken to be

$\simeq 800\,\mathrm{J/kg/K}$, the surface optical albedo $A = 0.1$, while we again let the surface thermal conductivity to change in a broad range of values $0.001 - 1$ W/m/K.

Figure 2b shows the mean drift rate of the semimajor axis of the center of mass orbital motion about the Sun due to the Yarkovsky effect (one easily shows that the effective YE for the center of mass heliocentric motion is given by a mass-weighted mean of the YE on the two asteroids). We note the contribution of the secondary component is small, but not entirely negligible. Not shown here, however, is the role of the YE for motion of the two components about their common center of mass, where the effect on the secondary component plays determining role (see Vokrouhlický *et al.* (2004b) for detailed discussion). With that result, Vokrouhlický *et al.* (2004b) conclude the YE should be comfortably detected for this system during its close encounter in August 2016 provided accurate radar observations are acquired in September 2008.

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