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A novel analytical thermal model of asteroids at small thermal parameters, and its implications for the Yarkovsky effect

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The dynamics of asteroids is strongly affected by the Yarkovsky effect, a non-gravitational force caused by asymmetric thermal radiation from a rotating asteroid. The computation of the Yarkovsky effect requires thermal modeling of the asteroid and is usually done in the framework of a linearized heat conduction problem [1]. The major complication of the thermal model arises from the non-linear 4th-order term in the Stefan–Boltzmann law for heat emittance, which enters the boundary condition for the 1D heat equation. The linear model treats this complication by Taylor-expanding the boundary condition via a small deviation of the temperature from its mean value and only considering the linear terms. The higher-order terms can be neglected only when diurnal temperature changes are much smaller than the mean temperature. This holds when the so-called thermal parameter θ is much greater than 1, which is true if the asteroid has a sufficiently high heat conductivity, rotates sufficiently fast, and is situated sufficiently far away from the Sun. Still, analysis of the available observational data shows that most asteroids with estimated thermal parameters have $\theta \sim 1$, and it is assumed that many asteroids should have $\theta << 1$. This motivates the development of a modified thermal model for the case of not-so-large thermal parameters.

We start with creating a fully analytical thermal model at $\theta << 1$. As a 0th-order approximation, it uses the equilibrium temperature at each moment, determined by the incidence angle of the solar radiation. Then the 1st-order approximation is constructed iteratively using perturbation theory with θ serving as a small parameter [2]. A special care should be given to sunrise and sunset, when the 0th-order approximation for the temperature has an infinite derivative, which results into infinite temperatures in the 1st-order approximation. To avoid this problem, we correct the 0th-order approximation by assuming a non-zero night temperature. The resulting 1st-order solution is continuous and asymptotically converges to the correct solution at small θ. This new analytical solution for $\theta << 1$ is just as important as the classical solution for $\theta >> 1$. We use it to compute the corresponding asymptotics of the Yarkovsky effect of one flat surface element, but it can equally well be applied to compute the infrared asteroid radiation, the normal and tangential YORP effects, the Yarkovsky effect on meteoroids smaller than the heat penetration depth etc. (all in case $\theta << 1$). We use the two analytically solvable cases of the heat conduction problem ($\theta << 1$ and $\theta >> 1$) as two pillars to support our general theory for the Yarkovsky effect. We fill in the gap between these two limiting cases with the aid of numerical simulation, and fit a simple analytical expression to it that has correct asymptotics at $\theta << 1$ and $\theta >> 1$ and is accurate to within 0.2% throughout the range $0.001 < \theta < 1000$.

Further on, we integrate the derived expression for the Yarkovsky effect for one surface element over the surface of an asteroid. We devise a theory for asteroids of spherical shape, in which the Yarkovsky effect is well described by an equation similar to the one for an individual surface element, but with a slight modification of the coefficients. Additionally, we integrate the Yarkovsky force over the surface of asteroids that have the shape of either triaxial ellipsoids or polyhedra from

the DAMIT database [3], and on this basis we put forward an approximate expression for the Yarkovsky effect as a function of the asteroid shape. At last, we construct a simple approximation to account for the asteroid's obliquity and its orbit's eccentricity. Our final expression for the diurnal Yarkovsky effect presents it as a product of four terms that depend on the asteroid's thermal model, shape, obliquity, and the orbit eccentricity correspondingly. As a result, we obtain a new expression for the Yarkovsky orbital drift, which preserves the accuracy of the numerical simulation, but has the speed of the analytical formula. It is crucial in long-term orbital dynamics models or population studies, where the Yarkovsky effect needs to be computed multiple times. It also corrects the error arising from blind application of the linear model at $\theta < 1$, which can cause errors up to 50%.

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