HEAT MODELS OF ASTEROIDS AND THE YORP EFFECT

O.Golubov[1, 2, 3]

[1] Institute of Astronomy of V. N. Karazin Kharkiv National University, 35 Sumska Str., 61022, Kharkiv, Ukraine, *golubov@astron.kharkov.ua*

[2] School of Physics and Technology, V. N. Karazin Kharkiv National University, Svobody Sq. 4, 61022, Kharkiv, Ukraine

[3] Department of Aerospace Engineering Sciences, University of Colorado at Boulder, 429 UCB, Boulder, CO, 80309, USA.

ABSTRACT. The Yarkovsky–O'Keefe–Radzievski–Paddack (YORP) effect is a torque of light pressure recoil forces acting on an asteroid. We show how this torque can be expressed as an integral of a universal function over the surface of an asteroid, and discuss generalizations of this expression for the case of non-Lambert's scattering laws, non-convex shapes of asteroids, and non-zero heat conductivity. Then we discuss tangential YORP (TYORP), which appears due to uneven heat conductivity in stones lying on the surface of an asteroid. TYORP manifests itself as a drag, which pulls the surface in the tangential direction. Finally, we discuss relation and interplay between the normal YORP and the tangential YORP.

Keywords: Asteroids: dynamics – Galaxy: abundances – stars: late-type

1. Introduction

The YORP effect was first introduced by Rubincam (2000) as the torque experienced by an asymmetric asteroid due the recoil forces created by the scattered or re-emitted light.

It was soon recognized to be the major factor causing evolution of rotation state of kilometre-sized asteroids. The YORP torque alters the distribution of asteroids over rotation periods and rotational axis orientations. Via centrifugal forces it alters shapes, and for most rapidly rotating asteroids YORP creates binaries via rotational fission. Via changing period and rotation axis orientation, YORP also changes Yarkovsky effect experienced by an asteroid (Bottke, 2006). YORP effect already turns to be necessary for precise light-curve fitting, and has thus been detected for 5 asteroids.

2. YORP as Surface Integral

The YORP torque can be conveniently represented as an integral over the asteroid's shape of a universal function $f(\psi,\varepsilon)$, which determines the average YORP torque created by a surface element located at latitude ψ of an asteroid with obliquity ε. This approach was first presented in Golubov & Krugly (2010) and Steinberg & Sari (2011). Their analysis had some important limitations due to the assumptions used in the model, the most important of which were:

1. Lambert's scattering law;
2. Convex shapes of asteroids;
3. Zero heat conductivity.

Our current analysis shows, that abandoning Lambert's scattering law does not substantially change the results. Substituting Lambert's law with Lommel-Seeliger law causes no substantial change in $f(\psi,\varepsilon)$.

Applying this treatment to non-convex asteroids shows results close to the ones obtained via rigorous ray tracing, if only the concavity of the asteroid is not too extreme. Thus convexity is also not a crucial assumption.

Finally, this treatment can be generalized for non-zero heat conductivity, if heat propagation is considered in a semispace under the surface. This model leads to the same expressions with only the universal function f depending not on 2, but on 3 parameters, the third one being thermal parameter of the soil θ.

Still, this model does not exhaust all possible physics of the process. It turns out, that if non-flat surface is considered, a qualitatively new effect turns in, which we call tangential YORP or TYORP, to distinguish it from normal YORP or NYORP introduced by Rubincam (2000).

3. Tangential YORP

Tangential YORP is due to heat conductivity fluxes going through centimetre- to metre-sized structures on the surface of the asteroid, such as stones or grooves. Under some conditions, it turns out that western slopes of structures are on average slightly warmer than their eastern slopes, which causes the preferential emission of light in the western direction, and the accelerated rotation of the asteroid. These additional forces produced by the fine structure of the surface are directed tangentially to the global gross-scale surface of the asteroid.

TYORP was first studied by Golubov & Krugly (2012) in the simplest model, with stones approximated via vertical walls on the surface of an asteroid. Although the model allowed to give a rough order-of-magnitude estimate of TYORP, it used numerous assumptions, the most limiting of which were

1. One-dimensional geometry of the wall.
2. Mirror reflection of light from regolith to account for self-illumination.
3. Zero obliquity.
4. Circular orbit of the asteroid.

Golubov & Krugly (2014) could get rid of the first two assumptions. They considered spherical stones lying in regolith on the surface of the asteroid. Ray tracing technique was used to account for multiple scattering of light by the stones and the regolith. The model included more free parameters, which made parametric study of the effect more complicated, but the general result was consistent with the estimate of the effect given by Golubov & Krugly (2012).

TYORP is substantial only in a relatively narrow area, where the size of the stone is of the order of the thermal wavelength, and the thermal parametre is of the order of unity. TYORP rapidly vanishes as one goes away from this area. It means, that only stones within some size range substantially contribute to the TYORP force. Moreover, this size range changes with changing rotation rate of the asteroid.

Incorporating non-zero obliquities and non-zero eccentricities into the theory of TYORP still remains an important problem to solve.

4. Conclusions

The YORP effect has two components: the normal YORP is caused by scattering and emission of light normally to the overall asteroid's surface, while tangential YORP is caused by preferential emission of light by small structures on the surface westward rather than eastward.

For each surface element the NYORP force is much bigger than the TYORP. But after integration over a symmetric surface NYORP torque vanishes, so that only asymmetry of the asteroid contributes to the total torque. In contrast, TYORP can produce torque even for a symmetric asteroid. As most asteroids are only moderately asymmetric, NYORP and TYORP torques can be comparable.

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