Non-gravitational Forces in the Orbital and Rotational Motion of Small NEAs

Tomasz Kwiatkowski
Astronomical Observatory of A. Mickiewicz University
Poznań, Poland

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Shapes of asteroids

- Diameters from 963 km (Ceres) to 1 meter
Itokawa

Image from the Hayabusa spacecraft (500 × 300 × 200 m)
Itokawa’s surface
Thermal inertia of regolith and boulders
Asteroid rotation

- $\omega$ – angular velocity
- $F_g$ – gravitational force
- $F_s$ – strength
- $F_c$ – centrifugal force

$F_c > F_g + F_s \Rightarrow$ rotational brake-up
Itokawa’s composition: gravitational aggregate
Yarkovsky effect

- Requires non-zero thermal inertia
- Changes all orbital elements
- Most important secular change of semimajor axis $a$
Yarkovsky effect. Simplified analytical formulation

**Assumptions:** spherical body, principal axis rotation, circular orbit about the Sun

**Orbit-averaged changes of }delta a:}

\[
\left( \frac{da}{dt} \right)_{\text{diurnal}} = -\frac{8}{9} \frac{\alpha \Phi}{n} W(R_\omega, \Theta_\omega) \cos \gamma
\]

\[
\left( \frac{da}{dt} \right)_{\text{seasonal}} = -\frac{4}{9} \frac{\alpha \Phi}{n} W(R_n, \Theta_n) \sin^2 \gamma
\]

- \( \alpha = 1 - A, \gamma - \) obliquity, \( n - \) mean motion
- \( \Phi = \pi R^2 F/(mc) \) (\( R - \) radius, \( F - \) solar flux, \( m - \) mass, \( c - \) velocity of light)
- \( R_\omega, R_n, \Theta_\omega, \Theta_n - \) non-dimensional parameters

**Note:** since \( m \sim R^3, \Phi \sim R^{-1} \) and Yarkovsky is greater for smaller bodies
Yarkovsky effect detection for (6489) Golevka

The image shows a graph with two ellipses. The x-axis represents the range offset (km) and the y-axis represents the range rate offset (mm s\(^{-1}\)). The ellipses are labeled "with Yarko" and "pure gravity." The point labeled "Arecibo" lies outside the "pure gravity" ellipse, indicating a deviation from gravitational forces due to the Yarkovsky effect.
Yarkovsky effect detection for 1992 BF
Density of (101955) Bennu

![Graph showing the bulk density of (101955) Bennu as a function of thermal inertia. The graph compares rough and smooth surfaces, with error bars indicating uncertainty.](image-url)
1950 DA impact hazard assessment
1950 DA impact hazard dependance on phys. model

Impact probability in 2880 ($\times 10^{-4}$)

\[
D = 1.5 \text{ km} \pm 10\% \\
D = 0.8 \text{ km} \pm 10\% \\
d_0 = 200 \pm 45 \text{ J m}^{-2} \text{ s}^{-0.5} \text{ K}^{-1} \\
d_0 = 400 \pm 45 \text{ J m}^{-2} \text{ s}^{-0.5} \text{ K}^{-1} \\
\rho = 2.5 \pm 0.87 \text{ g/cm}^3 \\
\rho = 4.5 \pm 0.87 \text{ g/cm}^3
\]
Surface of asteroid 1950 DA (Rozitis et al, 2014)

With bulk density obtained from Yarkovsky effect, ambient gravitation acceleration can be computed.
Impact mitigation of 1950 DA

- 1950 DA has nominally 1 in 20000 chance of impacting the Earth
- It is a rubble pile held together by weak cohesive forces
- If spun up by YORP, it would brake up into many pieces
- The same may happen if a wrong deflection technique is used (e.g. a kinetic impactor)
YORP effect

- Rotational counterpart of Yarkovsky
- Two torques:
  1. changes angular velocity $\omega$
  2. changes spin axis obliquity $\gamma$
Yorp effect. Zero order approximation

Assumptions:
- zero surface thermal inertia (no time lag)
- Lambertian scattering and thermal re-emission

Changes of $\omega$ and $\gamma$:

$$\frac{d\omega}{dt} = \frac{\Lambda}{C} \sum_{n \geq 1} A_n P_{2n}(\cos \gamma), \quad \frac{d\gamma}{dt} = \frac{\Lambda}{C\omega} \sum_{n \geq 1} B_n P_{2n}^1(\cos \gamma)$$

- $\Lambda = \frac{2F}{3c} R^3$
- $C$ — moment of inertia corresponding to rotation axis
- $P_{2n}(\cos \gamma)$ — Legendre polynomials of even orders
- $P_{2n}^1(\cos \gamma)$ — associated Legendre functions

Note: since $\Lambda \sim R^3$ and $C \sim R^5$, $\dot{\omega} \sim R^{-2}$ and $\dot{\gamma} \sim R^{-2}$
YORP effect detection for (54509) YORP

Days since July 27, 2001

Additional sidereal phase \( \Delta \phi \) (deg)

2001 2002 2003 2004 2005

0 90 180
YORP effect detection for Itokawa (Lowry et al, 2014)

Itokawa
Phase Offset Change in 10 yrs ~12 deg

Phase Offset (degrees)

Year
Itokawa centre of mass displacement
Explanation of the centre of mass position
Internal structure of Itokawa

- Body: 1750 kg m⁻³
- Head: 2850 kg m⁻³
YORP effect from Itokawa’s boulders (Sevecek et al, 2015)

- surface features of sizes comparable to the thermal skin depth can have significant influence on the total YORP effect
- YORP torque caused by the asymmetry of emission from the eastern and western sides of the boulder
- thermal inertia different for the regolith and the boulder
Total YORP torque due to boulders

- size distribution of boulders obtained from Hayabusa images
- random location and orientation of boulders on the surface
- total YORP torque due to the boulders comparable to the torque due to the Itokawa’s global shape
Meteoroid impacts onto asteroids (Wiegert, 2015)

- Impact of a small meteoroid onto an asteroid surface transfers kinetic energy and momentum to the larger body.
- Direct impact negligible compared to Yarkovsky effect.
- Ejecta production amplifies the effect of impacts:
  - Into regolith by an order of magnitude,
  - Into bare rock by up to two orders of magnitude.
- Net drag produced by the meteoroids exceeds Yarkovsky effect at sizes below one meter (for bare rock).
- It can also change YORP effect below sizes of tens of meters.