An investigation of small-body shapes and spins reveal a preferred state of maximum surface stability

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Motivation:

Comet Hartley 2 as imaged by the Deep Impact spacecraft's Medium Resolution Imager (MRI) near the point of closest approach (695 km) as part of the EPOXI mission on November 4, 2010.
Potential variance minimization plot for comet Hartley 2, where the global and selected regional scale curves are quite similar in minima values. The dips mark the ‘optimum’ density at which potential variance, elevation variance, and surface slopes are minimized, ~200 (global) and ~220 (regional) kg/m$^3$. 
Potential variance minimization plot for 433 Eros, where the global and selected regional scale curves are within 14% of the measured density of 2670 +/- 30 kg/m³. The dips mark the ‘optimum’ density at which potential variance, elevation variance, and surface slopes are minimized, ~2200 (global) and ~2300 (regional) kg/m³.
Hypothesis:

A region exists for each small body wherein the surface gravity and spin state combine to produce a minimum with respect to topographic variation, slope magnitudes, and erosion rates.
On many asteroids, the rotation rate can have a significant effect on local slopes. Vectors $F$ mark the local accelerations due to gravity $g$ and rotation $\omega$, while lines $P$ mark the resulting equi-potential surface (horizon), which lies perpendicular to the combined local $F$ vector.
Erosion rates vary non-linearly with slope

A plot of the globally experienced, **downslope regolith movement** resulting from the seismic shaking produced by a single 10 m impactor striking the surface of asteroid 433 Eros at 5 km/s, **plotted as a function of slope** on an infinite plane, computed using the methods described in Richardson et al. (2005).
On many asteroids, the rotation rate can have a significant effect on local slopes. Vectors $F$ mark the local accelerations due to gravity $g$ and rotation $\omega$, while lines $P$ mark the resulting equi-potential surface (horizon), which lies perpendicular to the combined local $F$ vector.
In the case of 433 Eros, either increasing or decreasing the body’s rotation rate will cause an increase in the body’s average surface slope and erosion rates.
Gravity and Rotation combine to significantly effect asteroid topography

(A) High topography on the ends of an elongated body indicates slow rotation and gravity dominated slopes.

(B) Mixed topography over the surface of the asteroid is indicative of a body in an optimum spin state.

(C) Low topography on the ends of an elongated body indicates fast rotation and spin dominated slopes.
Conditions for “Erosional Minimum” Behavior:

1. The mean rotational force is a significant fraction of the mean gravitational force, and can therefore have a significant effect on local slopes.
2. A sufficiently thick, low-cohesion, mobile regolith layer exists over most of the body’s surface.
3. A downslope flow disturbance source is present, such as thermal cycling, volatile activity on comets, or impact-produced seismic shaking.
4. A sufficient amount of time has occurred since the body’s last major surface alteration or significant change in spin state.
Asteroid shape-model study: 30 objects

- 8 models from spacecraft observations
- 22 models from radar and optical observations
Quantitative Measure Used:

Normalized variance in total surface potential (gravity + rotation) across the surface of the body

**Independent of Body Size** (shape, density, & rotation dependent only)

Proportional to: (Holsapple, 2004)

Rotational Potential

Gravitational Potential

(Holsapple, 2004)
Group A: 1998 ML14 (1.1 km, 15.0 hrs)
density ~ 2000-2500
Group A: 2100 Ra-Shalom (2.3 km, 19.8 hrs)
density ~ 1500-2000

Spectral Class: C
Group A: 4660 Nereus (0.51 km, 15.1 hrs)
density $\sim$ 2500-3000

Spectral Class: E
Group B: 1998 WT24 (0.47 km, 3.7 hrs) 
density ~ 5000 (3000-8000)*

Spectral Class: E
Group B: 1580 Betulia (6.6 km, 6.1 hrs)
density ~ 1100 (700-2600)*

Spectral Class: C
Group B: 216 Kleopatra (217 km, 5.4 hrs) 
density = 4270 ± 860

Spectral Class: M
Group C: 101955 Bennu (0.49 km, 4.3 hrs) density ~ 1000-1500

Spectral Class: C
Group C: 1999 KW4 Alpha (1.5 km, 2.8 hrs)
density = 1970 ± 240

Spectral Class: S
Group C: 54509 YORP (0.11 km, 0.2 hrs) density ~ 2500-3500
General Properties:

Slopes and Erosion Rates
Typical shape model slope distributions:
Mean surface erosion rates:

Asteroid “Erosion Index” is a measure of the mean downslope regolith flow rate, relative body with a mean slope of 10°, and assuming transport-limited material flow (not weathering-limited).
Transport Limited vs. Weathering Limited Regolith Flow (A,B) vs. Weathering Limited Regolith Flow (C)

1998 WT24
470 m

1999 KW4
1.5 km

1994 CC
690 m

433 Eros
34.4 km
General Properties:

The zone of

Maximum Surface Stability
A (10 bodies): B (13 bodies); C (7 bodies)

Group A

Group B

Group C

$\omega$

$g + \omega$

$g$
Standard Shapes Study
(45 prolate models, 25 oblate models)

Prolate bodies

- $c/a = 0.25$
- $c/a = 0.50$
- $c/a = 0.75$

Oblate bodies

- $c/a = 0.25$
- $c/a = 0.50$
- $c/a = 0.75$
Topographic Variation for Standard Prolate Spheroids as a function of Scaled Spin and Aspect Ratio

(Blue) Zone of maximum surface stability: 1%-4% variation
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Contour of Topographic Variation for Prolate Spheroids

On small asteroids, YORP dominates!

(Blue) Zone of maximum surface stability: 1%-4% variation
Comparison to Holsapple (2004, 2007)

Asteroid surface stability coincides with low internal stresses
50% of 30 shape models & 75% of 1300 lightcurve data points lie within < 0.04 topographic variation curves.
Conclusions

- A scaled-spin zone of “maximum surface stability” (MSS) exists for each asteroid shape, wherein surface potentials, topography, and slopes are minimized.

- This MSS zone is self-correcting in that deviations from it will tend to push the surface back towards stability.

- Highly elongated bodies are more prone to migrate towards this zone, and remain there.

- On small bodies (<~8 km), YORP effects tend to outweigh erosional effects, particular where there is little loose regolith and weathering limited downslope flow prevails.