Models of asteroids

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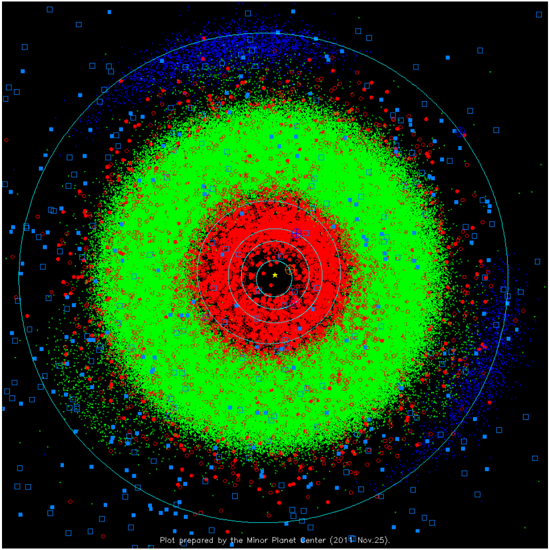
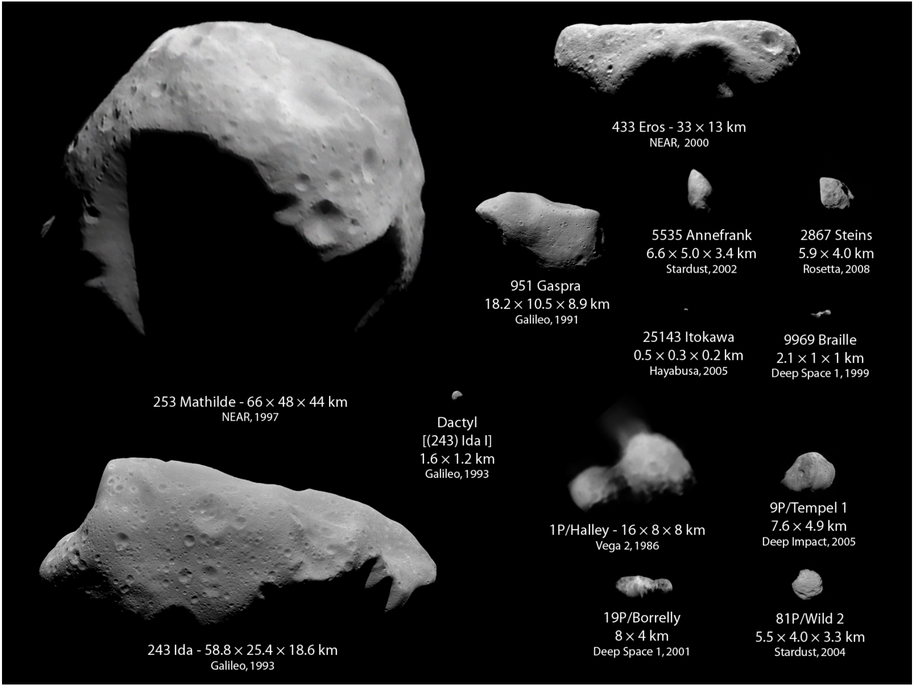
Contents

Asteroids in the solar system



- main belt
- near-Earth asteroids
- Trojans


433 Eros - 33 × 13 km
NEAR, 2000
951 Gaspra
18.2 × 10.5 × 8.9 km
Galileo, 1991
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993

What do we know

- $\sim$ 570 000 known asteroids
  - $\sim$ 300 000 numbered
  - $\sim$ 100 new discovered every day
  - we know the orbit in the solar system and the size (from the brightness, 10 m to 1000 km)
- for $\sim$ 5000 we known the rotation period (1 min to 100 d)
- for $\sim$ 200 we know the global shape (from the lightcurve inversion)
- for $\sim$ 20 we know the detailed shape (from space probes, radar,...)

Physical properties are known for a small fraction of the population
– we want to know more.

Motivation

- Basic research. Shape reconstruction is a nice example of the applied mathematics – nice inverse problem.
- The knowledge of asteroid physical properties is important for the understanding of the history and evolution of the solar system.
- Thermal emission from the surface affects the orbit – important for the prediction of the collision probability with the Earth. We have to know the shape and the spin.

How do they look like?

space probe
(433 Eros)

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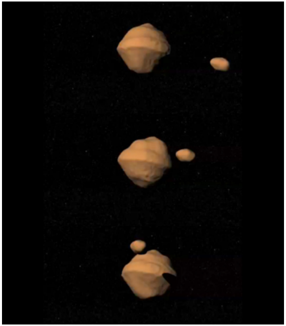
space probe
(433 Eros)

radar (1999 KW4)



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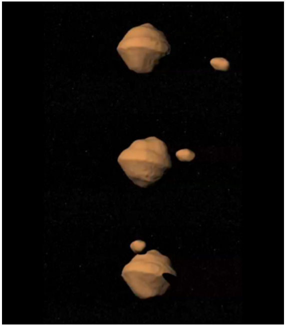
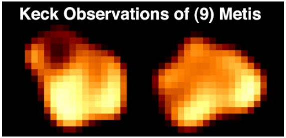


adaptive optics



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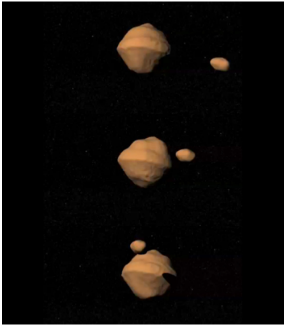

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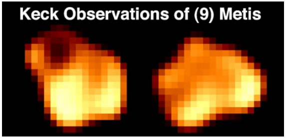

HST (4 Vesta)

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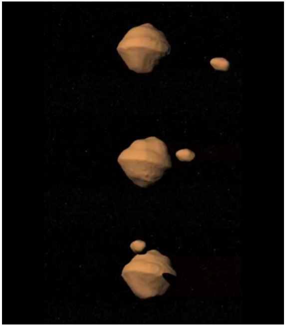

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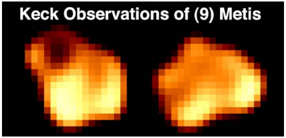
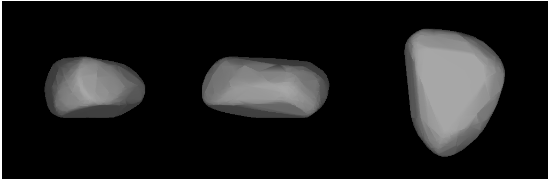


HST (4 Vesta)

lightcurve inversion



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Asteroid lightcurves

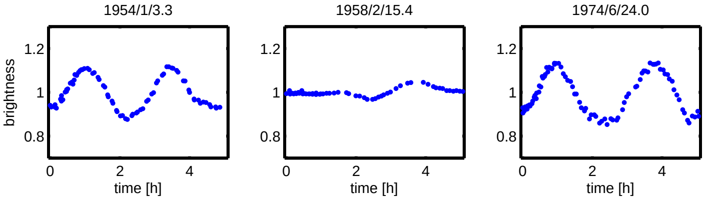
The apparent brightness depends on

- the distance from the Earth and the Sun (known)
- geometry Sun–asteroid–Earth (known)

and unknown parameters

- shape
- rotation state – spin axis direction, period of rotation
- surface properties (albedo, light-scattering behaviour)

Periodic change of brightness caused by rotation – lightcurve.
Periods from ~ 1 min to ~ 100 d, typically hours.
Amplitudes up to 1.5 mag, typically 0.3 mag.



Inverse problem

From the set of lightcurves (tens) observed under different viewing/illumination geometry (during several years) we can reconstruct shape, spin, period and other parameters – lightcurve inversion (Kaasalainen et al. 2001).

- the best fit model – least squares method
- when sufficiently many different geometries are available, we get a unique convex model
- homogeneous albedo distribution on the surface – no spots (usually good assumption)

Shape versus albedo

Lightcurves can be caused

- irregular shape
- nonuniform albedo distribution
- both

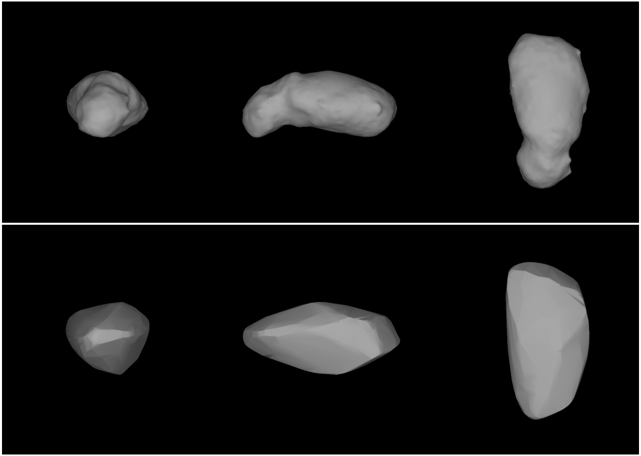
We cannot distinguish between shape/albedo effects, fortunately asteroids are mostly uniform – variations are caused by the shape.

Contents

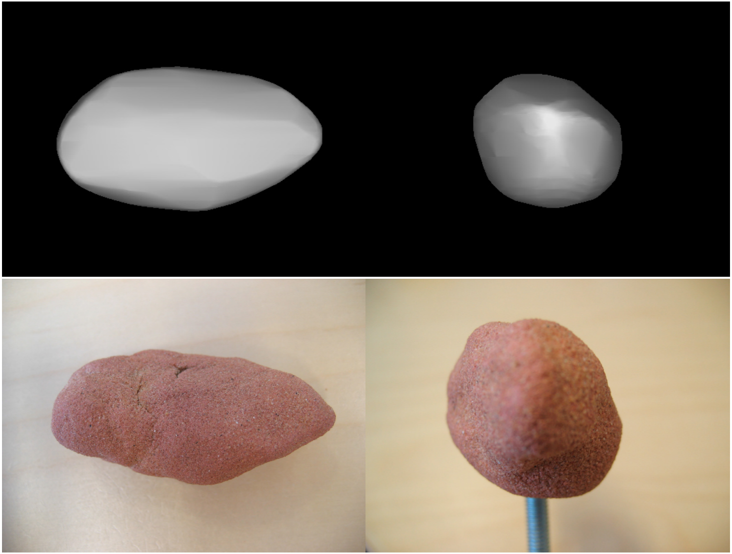
Comparison with the reality

Good approximation, convex models are good for global shape characteristics, spin axis $\pm 5^\circ$, accurate rotation period ± 0.01 s.

(25143) Itokawa



Laboratory model of an asteroid

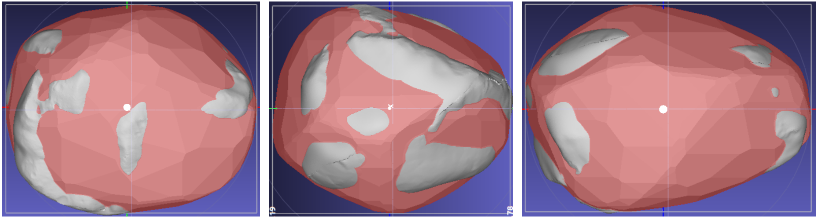


Kaasalainen at al. (2005)

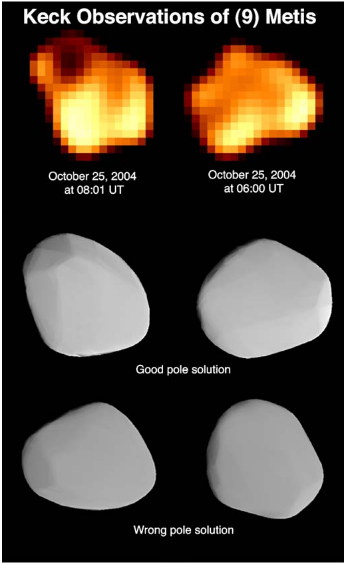
(21) Lutetia – model versus reality

size ∼ 100 km, Rosetta fly-by – reconstruction of the real shape

comparison of the real shape with the model (±5 km)



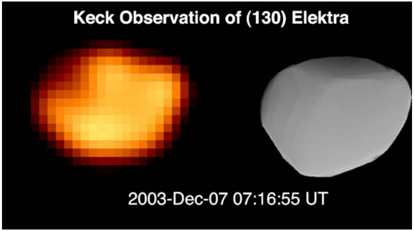
Adaptive optics

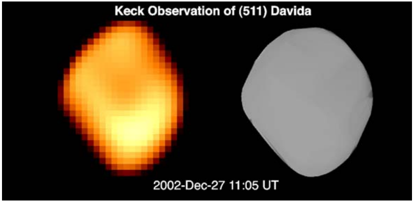


Marchis et al. (2006)

we can derive

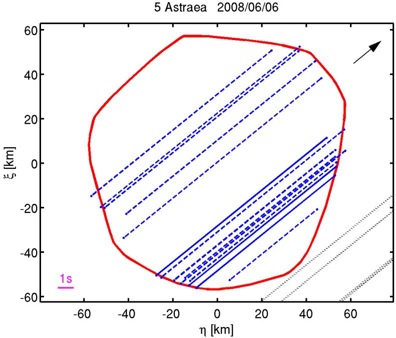
- unambiguous pole
- size
- nonconvex details





Occultations of stars by asteroids

Asteroids are moving on the stellar background – sometimes they occult a star. The star 'disappears' for a couple of seconds. If there are more observers, we can reconstruct the profile (and compare it with the model).



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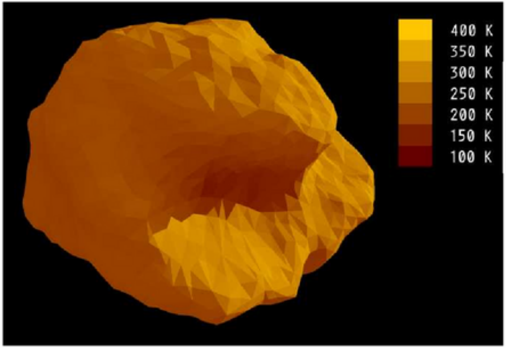
Thermal effects on asteroids

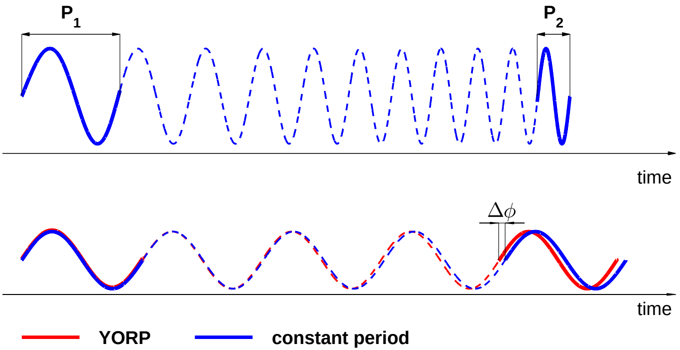
Yarkovsky effect – anisotropic thermal emission causes non-zero net force
$\rightarrow$ measurable change of the orbit.
Yarkovsky-O'Keefe-Radzievskii-Paddack effect – non-zero net torque
$\rightarrow$ measurable change of the rotation period.

$$\mathrm{d}\vec{f} = -\frac{2}{3}\frac{\epsilon\sigma T^4}{c}\,\mathrm{d}\vec{S} \qquad \vec{f} = \int_S \mathrm{d}\vec{f} \qquad \vec{T} = \int_S \vec{r} \times \mathrm{d}\vec{f}$$



Brož et al. (2005)

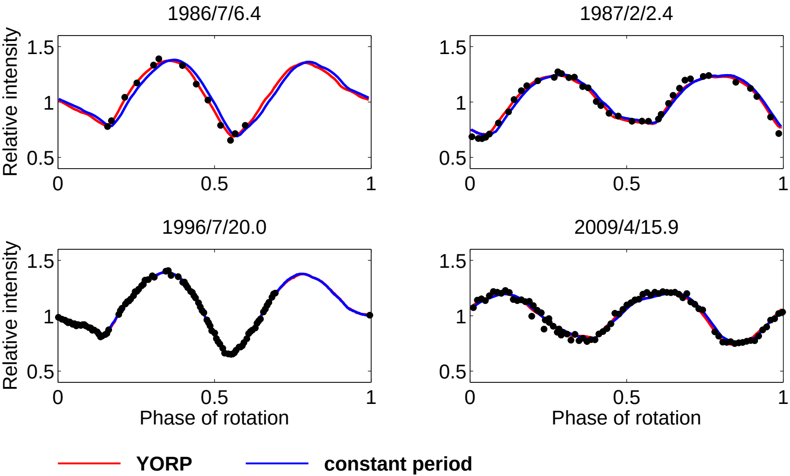
YORP detection from the change of the phase



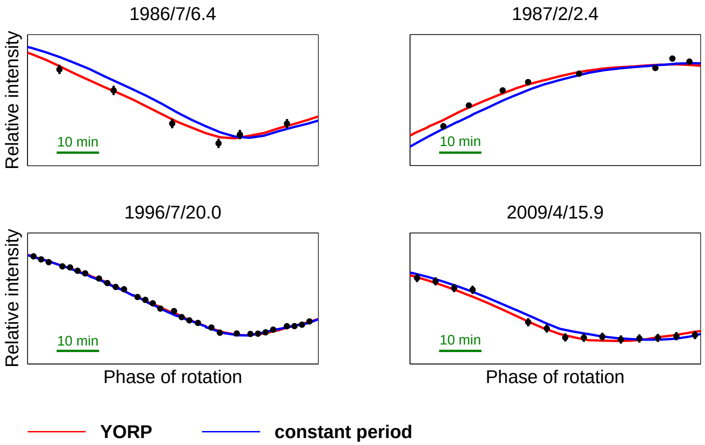
If the rotation rate changes $\omega = 2\pi/P$ linearly in time, then $|\Delta\phi|$ changes quadratically in time $\Delta\phi \sim t^2$.

Small changes of the order of 0.1 s can be detected – during decades the phase difference is $> 10^\circ$.

Asteroid (3103) Eger – models versus data



Model versus data – detail

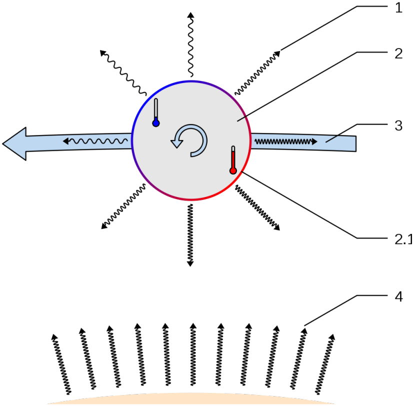


Measured value $(9 \pm 6) \times 10^{-9}\,\mathrm{rad/d^2}$ (the change of the period 2.7 ms/yr, $P \sim 5.71\,\mathrm{h}$) agrees with the theoretical value.

YORP is a natural explanation of the observed spin-up.

Yarkovsky effect

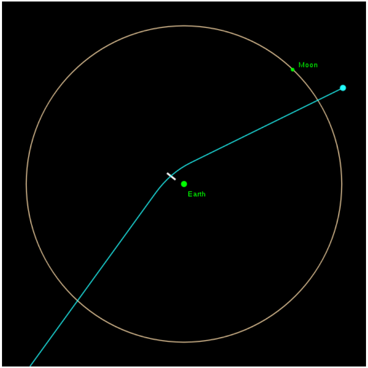
Thermal inertia causes that the maximum of the temperature is not at the 'noon', but shifted.
The net force in the direction of the velocity vector changes the orbit.



- prograde rotation enlarges the orbit
- retrograde shrinks
- important for the evolution of the solar system – asteroids migrate significantly
- important for the ephemeris prediction

Yarkovsky effect – importance for the humankind

Asteroid (99942) Apophis close encounter with the Earth April 13, 2029 with the distance $\sim 30\,000$ km from the Earth, which will significantly change its orbit. For an accurate prediction of its next encounter in 2036 the accuracy of ~ 100 m is needed– Yarkovsky effect plays an important role (can shift the asteroid of some km), thus the shape and spin, thus model! Radar observations in 2013 will solve it.



Conclusions

- The lightcurve inversion methods provides reliable results – will be used to invert data from big surveys Pan-STARRS, Gaia, LSST – $\sim 10\,000$ models.
- See DAMIT – Database of Asteroid Models from Inversion Techniques – for more info http://sirrah.troja.mff.cuni.cz/projects/asteroids3D
- Further development of the tools – multi data inversion, automatic processing, ...
- ASTEROIDS@HOME – distributed computation – to solve time-consuming inversion problem for hundreds of thousands of asteroids.