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The thermal forces and torques changing the orbits and spins of small asteroids

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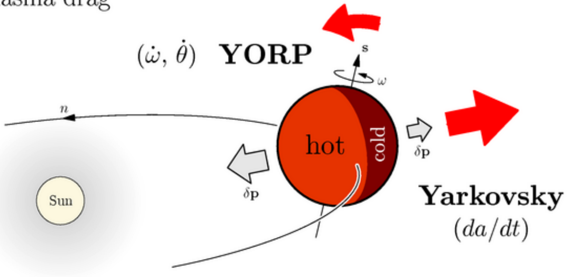
Accelerations in the size-range:

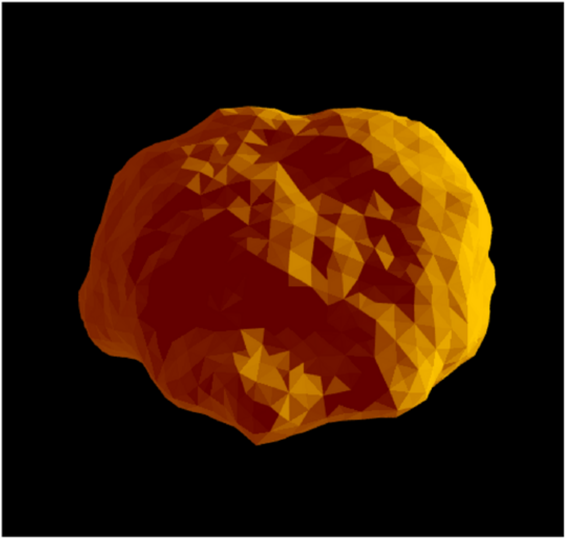
10 cm to 10 km

0. gravity	$GM_{\odot} \simeq 1$	$GM_{\rm pl} \simeq 10^{-3}$, $GM_{\rm ast} \lesssim 10^{-9}$
1. Yarkovsky/YORP effect	10^{-7} to 10^{-11}	
2. radiation pressure	10^{-6} to 10^{-11}	
3. Poynting-Robertson drag	10^{-10} to 10^{-15}	
4. solar wind	"too small"	
5. Lorentz force	⋮	
6. plasma drag		



- radial pressure vs. drag & long-term accumulated effect

What do we need to calculate Yarkovsky/YORP?

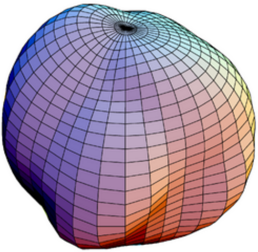


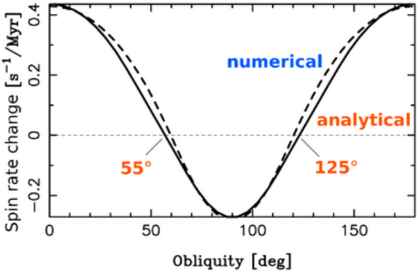
- orbit, size and shape, spin axis orientation and period, mass, density of surface layers, albedo, conductivity, ...
- often: thermal parameters as free & collective studies

Yarkovsky/YORP — state-of-the-art theory

- analytical spherical linearised solution of the HDE
- numerical 1-dimensional non-linearised approximation for irregular shapes ← not valid for small meteoroids!
- recent developments: analytical calculation of YORP for shapes slightly different from spheres (Nesvorný & Vokrouhlický, submitted)

1998 KY$_{26}$





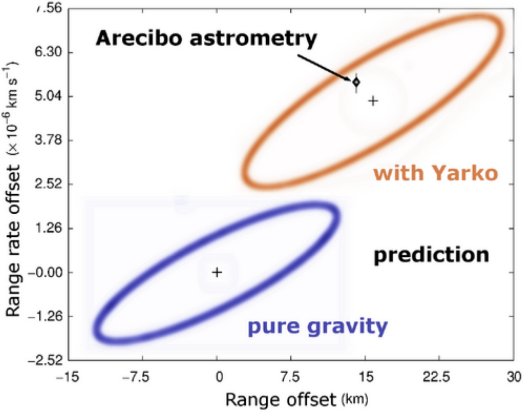
also Scheeres (2007, in press): semianalytic YORP theory

- future: full numerical 3-D solution of the HDE ⇒ YORP on small bodies, statistics for ≈ 100 shapes

PART 1

Direct measurement of Yarkovsky (Chesley *et al.*, 2003):

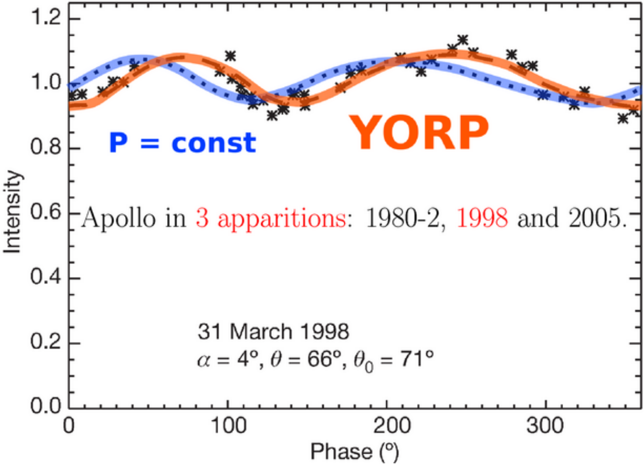
- radar ranging to (6489) Golevka ⇒ semimajor axis drift



- thermal conductivity 0.01 W/K/m ← in agreement with infrared photometry (Delbó *et al.* 2003)
- another case: long arc of 1992 BF (Chesley *et al.*, 2006)

Direct measurement of YORP:

- lightcurves (or radar) ⇒ rotational phase shift
- Lowry *et al.* (2007), Taylor *et al.* (2007): (54509) YORP = 2000 PH_5, radar shape, size 100 m → 1 ms/yr
- Kaasalainen *et al.* (2007): (1862) Apollo, shape from LC inversion, size 1.4 km → period change 4 miliseconds/yr



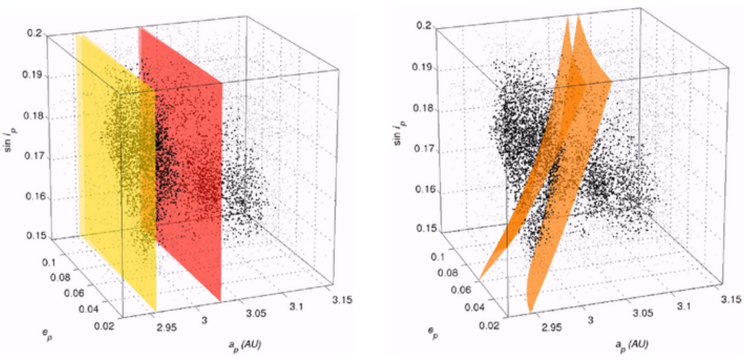
PART 3

Asteroid families:

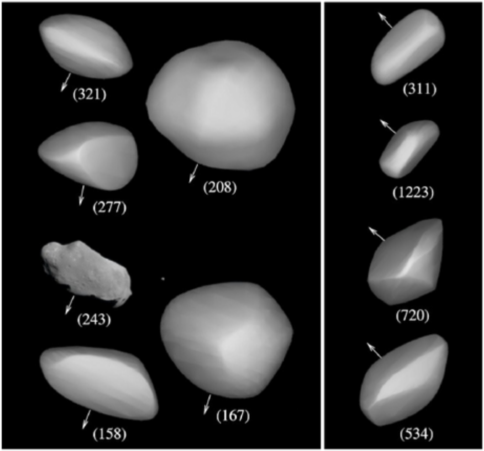
(Bottke *et al.*, 2001; Vokrouhlický *et al.*, 2006)

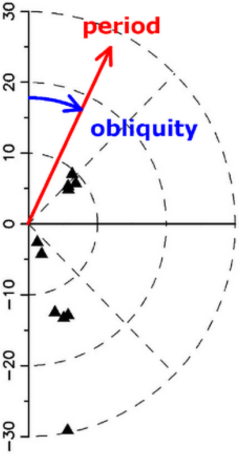
- "Bracketing" by resonances
- "Crossing" weaker MMRs
- "Trapping" in secular resonances

→ Eos family as an example



Bimodal obliquity distribution in Koronis family **(Slivan** *et al.*, **2003):**



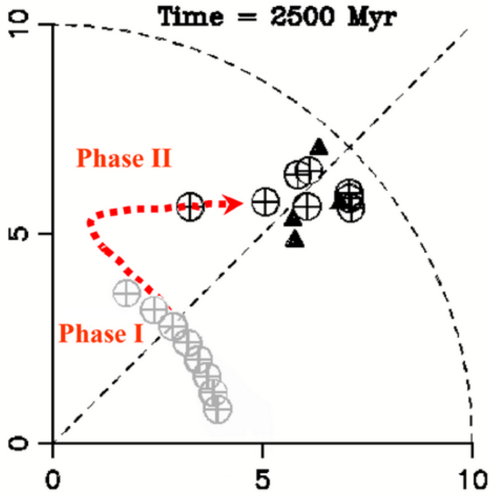


- prograde group: periods 7.5–9.5 h, obliquities 42°–50° and similar ecliptic longitudes within 40°
- retrograde group: $P < 5\,\mathrm{h}$ or $> 13\,\mathrm{h}$, $\gamma \in (154°, 169°)$

  $\Rightarrow$ collisions cannot produce this!

Spin state model (Vokrouhlický *et al.*, 2003):

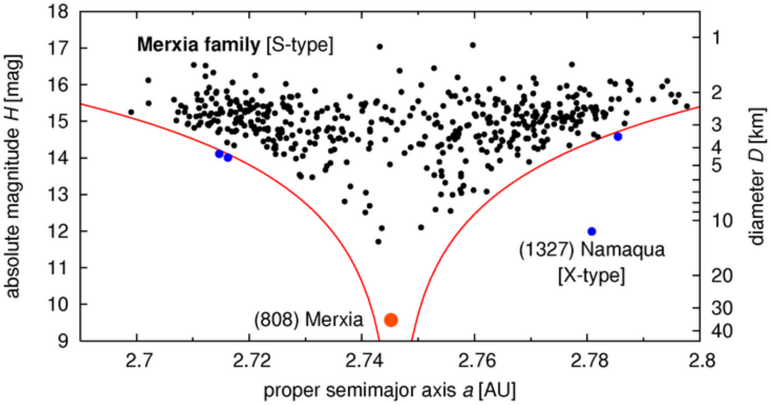
- solar torques & YORP thermal torque



- prograde group: (I) YORP driven evolution to asymptotic state & (II) capture in spin-orbit resonance s_6 (precession rate $\simeq 26''/\mathrm{y} = -s_6$) $\Rightarrow$ paralelism in space

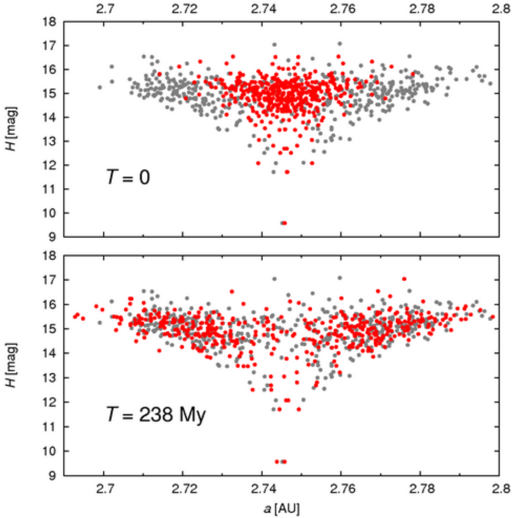
"Eared" families (Vokrouhlický *et al.*, 2006):

- 'V'-shape in the (a, H) plane
- outliers ⇔ probable interlopers



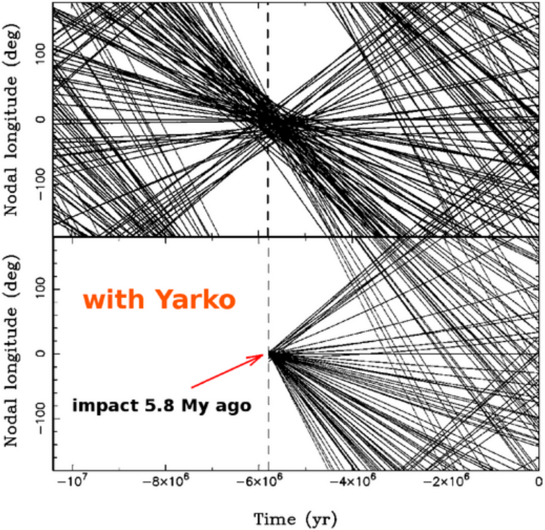
- problem: unknown *initial* spread
- "eared family" (overdensity of small members at extreme values of the semimajor axis) ⇐ YORP effect fingerprint!

- best-fit family evolution model:
- initial dispersion $\sim 1/2$ of observed



- $V = 24^{+6}_{-12}$ m/s $\Rightarrow$ small ejection velocity
- $c_{\rm YORP} = 0.6^{+1.4}_{-0.4}$ $\Rightarrow$ YORP important
- $T = 238^{+52}_{-23}$ My $\Rightarrow$ young age
- $K = 0.005$ W/m/K $\Rightarrow$ regolith

Convergence of angles in Karin cluster
(Nesvorný & Bottke, 2004):

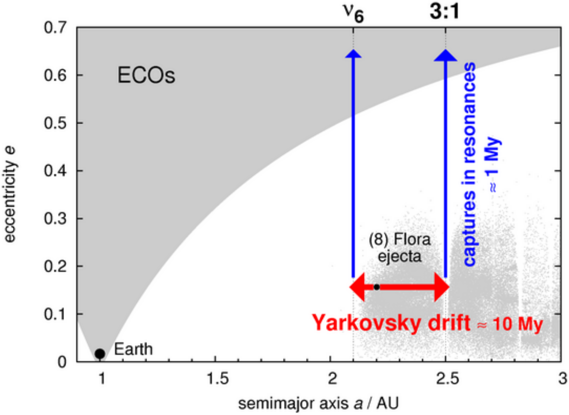


- both Ω, ϖ converge much better with Yarkovsky!
- another case: Veritas family 8.2 Myr ago → dust bands and ^{3}He in sea-floor sediments (Farley *et al.* 2006)

PART 3

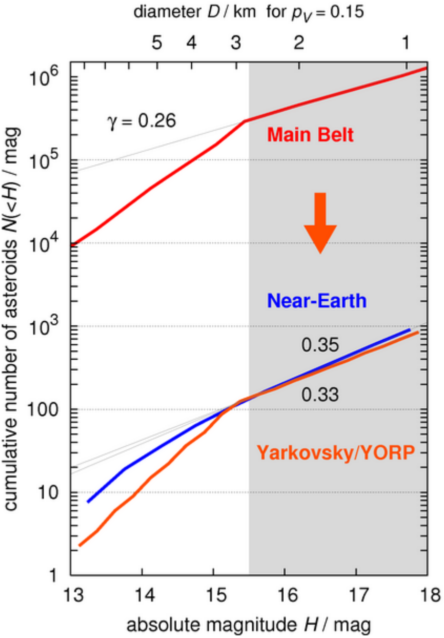
Meteorite transport from the Main Belt:

(Farinella *et al.*, 1998; Vokrouhlický & Farinella, 2000; Bottke *et al.*, 2000) ← no YORP here!



- long Cosmic Ray Exposure ages of meteorites
- CRE's of iron meteorites 10× longer than of stones

Delivery of Near-Earth Asteroids (Morbidelli & Vokrouhlický, 2003):



- observations of NEAs:

1. removal rate: $\sim$200 bodies ($>$1 km) per My
2. H distribution

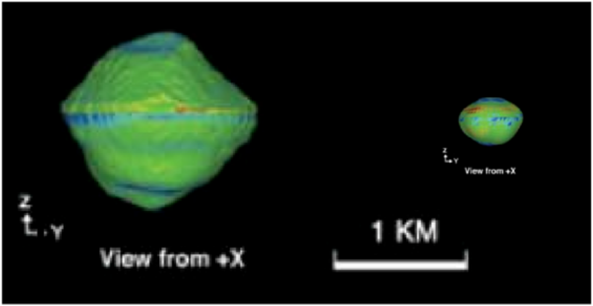
- the same basic scenario as for meteorites:

1. Yarko/YORP flux into the resonances: 150–200 My^{-1}
2. slope change

- La Spina *et al.* (2004): excess of retrograde NEAs
  ← consistent with Yarkovsky-driven transport
  from the MB via ν_6 and J3/1 resonances

Binaries and YORP?

- Ostro *et al.* (2006): radar imaging of (66391) 1999 KW_4

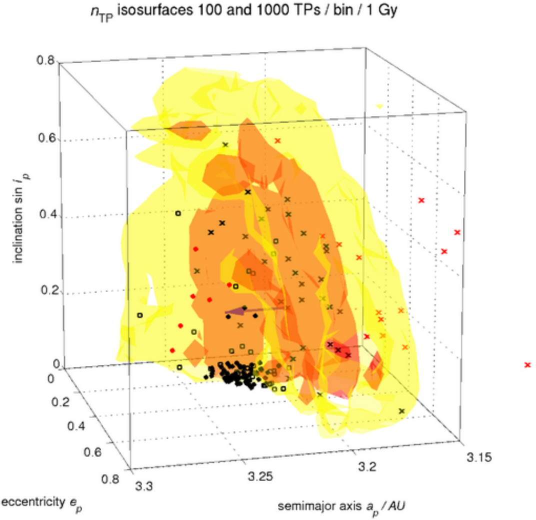


- equatoreal hill ← mass shedding?
- Kaasalainen *et al.* (2007): (1862) Apollo will reach critical $P \simeq 2$ hours within few Myr (maybe it already did in the past ⇒ its small moon)
- Pravec & Harris (2006): MB binaries are similar to NEAs ⇒ YORP induced fission (and not tidal encounters)?

Unstable resonant asteroids in the J2/1:

(Brož *et al.*, 2005; Roig *et al.*, 2002)

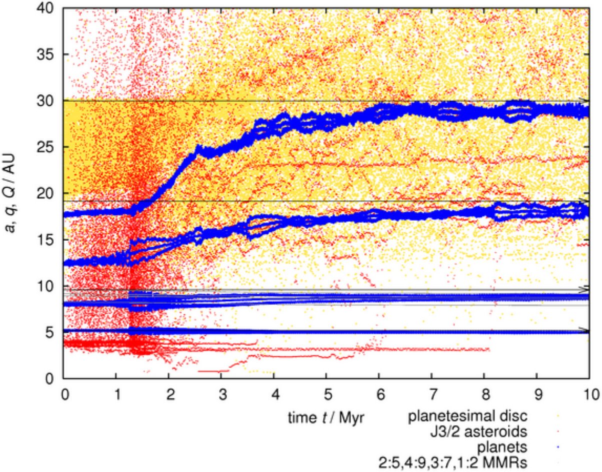
- short-lived ($\sim$10 Myr) $\leftarrow$ neighbouring MB asteroids pushed by Yarkovsky towards the resonance:



- confirmed by orbital evolution, lifetimes and SFDs

Stable resonant asteroids in the J2/1 and J3/2:

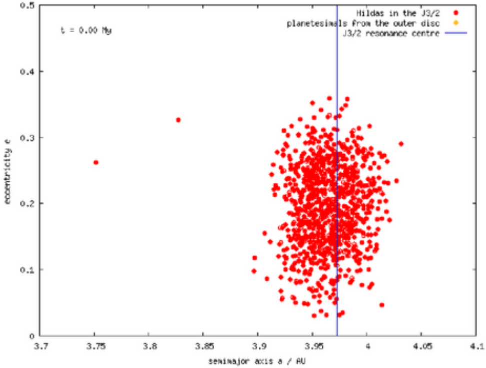
- simple Yarkovsky injection from the MB does not work
  $\Rightarrow$ more complex evolution with migration of planets due to planetesimal disc 30–50 $M_\oplus$ similar to the 'Nice model' (Morbidelli *et al.*, 2005)



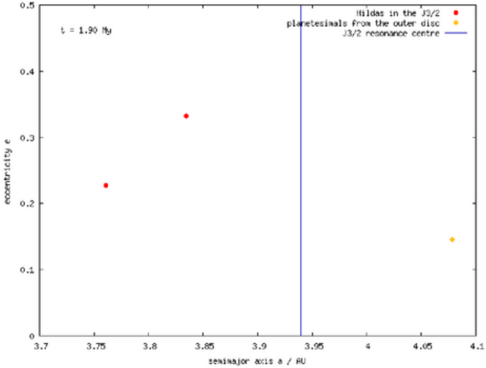
- $\sim$ half of J2/1 orbits survive $\Rightarrow$ might be primordial, but...

- almost no Hildas in the J3/2 survive Jupiter–Saturn 1:2 resonance crossing $\Rightarrow$ must had been captured during the crossing or after (by resonance sweeping)

original population



final population



- Yarkovsky does not significantly destabilise the orbits during the following 4 Gyr evolution

Future work:

- routine Yarkovsky/YORP detection
- systematic ages of all asteroid families, including extremely young (like Datura) and old ones (like Koronis)
- calculation of YORP on small meteoroids
  $\rightarrow$ corresponding update of transport models

- measurement of thermal-related parameters (masses, sizes, shapes, albedos, conductivity)
- modelling of several subsequent YORP cycles