The effects of YORP on the spin rate distribution of the Near Earth Objects

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Binary Asteroid Dynamics Workshop
Meudon, 19-22 May, 2008

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- To reproduce the observed spin distribution of the NEO starting from a plausible distribution for the Main Belt asteroids, by means of gravitational perturbations.

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- To reproduce the observed spin distribution of the NEO starting from a plausible distribution for the Main Belt asteroids, by means of gravitational and non-gravitational perturbations.

The model

- An initial population of 20 000 objects is evolved in a Monte Carlo model for 4.5×10^9 years.
- Distribution of dimensions: power law from Spacegurad Survey (Morrison *et al.*, 1999).
- Shapes distribution: the mean diameter from Morrison *et al.* is taken as the major semiaxis a of a triaxial ellipsoid with b and c given by Giblin *et al.* (Icarus, 1998).
- Initial spin distribution: Maxwellian distributions (Fulchignoni *et al.*, 1995; Donnison and Wiper, MNRAS, 1999).
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The model - Spin evolution: flyby

- Earth and Venus fly-bys:
  - collision probability from Gladman *et al.* (Icarus, 2000);
  - encounter distance distributed according an r^2 distribution (including gravitational focusing).
  - the NEO–planet relative velocity (the velocity at infinity) is evaluated, for each encounter, taking into account the actual orbital elements of the NEO;
  - the geometry of the approach is randomly chosen.
- The change in rotational angular momentum and kinetic energy after every encounter is analytically evaluated taking into account the gravitational interaction between the ellipsoidal body and the planet (Scheeres *et al.*, Icarus, 2000; Scheeres, Cel. Mech. Dyn. Astr.,2001).

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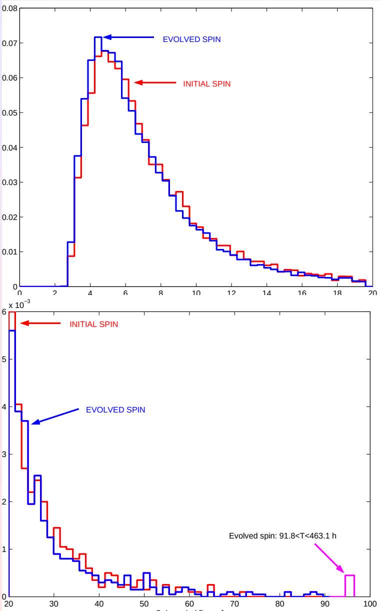
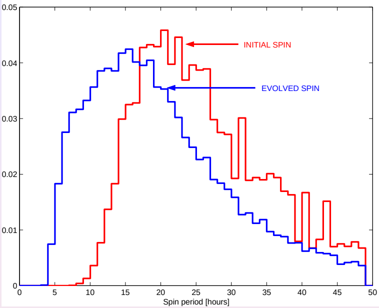
Planetary encounters

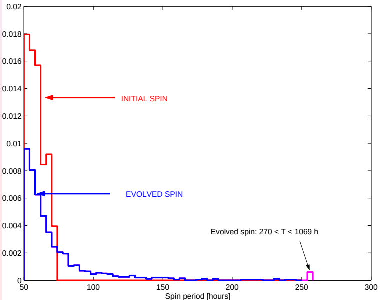
- Scheeres, Marzari & Rossi (*Icarus*, 2004) showed how the planetary fly-bys are responsible for a general spin-up of the population and for a “spreading” of the distribution.



Planetary encounters

- Nonetheless planetary encounters **alone** are not able to reproduce the observed excess of fast and slow rotators and the percentage of binary NEAs.
  $\Rightarrow$ **non-gravitational perturbations**.





The model - spin evolution: YORP

YORP effect *according to Dan* **(Icarus, 2007):**

- Solving the Euler and attitude equation of the body, the torque acting on an asteroid from the YORP effect is decomposed into a Fourier Series.
- The coefficients of these series can be derived from a general shape model for an asteroid.
- With this decomposition, it is then possible to evaluate the averaged dynamical evolution of an asteroid's spin state, and relate it to a few simple constants.
- Applying this decomposition to asteroid shape models, it was found that the shape-derived YORP coefficients C_y, when properly normalized by their size and density, were distributed randomly within a certain interval of values.

The model - spin evolution: YORP

The YORP rotational acceleration is given by:

$$\dot{\omega}_Y = B \Phi C_Y \frac{r}{M} \frac{1}{A^2 \sqrt{1 - e^2}}$$

- $B = \frac{2}{3}$: Lambertian emission coeff. for the asteroid surface;
- $-2.5 \times 10^{-2} \leq C_Y \leq 2.5 \times 10^{-2}$
- A, e: semimajor axis, eccentricity;
- $\frac{r}{M}$: effective radius over the total mass
- Φ: solar constant in kg km s^{-2}.

The model - YORP: assumptions

- YORP torque is due to thermally radiated heat only.

- Ignore the obliquity dynamics and allow the rotation rate acceleration to change at a uniform rate.

The model - Spin evolution: YORP

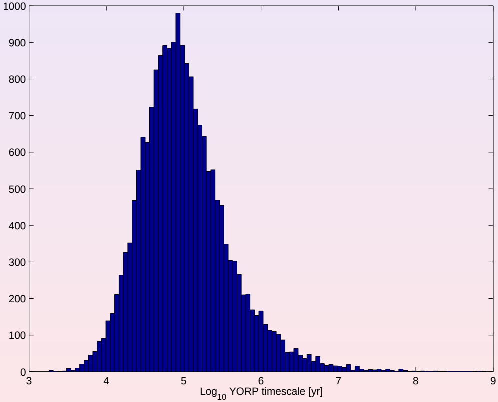
- From the maximum rotation rate of each object the YORP time, i.e. the time it takes to decelerate from its maximum rate to zero is:

$$T_Y = \frac{\omega_{max}}{|\dot{\omega}_Y|}$$

- After any timestep, ω is linearly updated as:

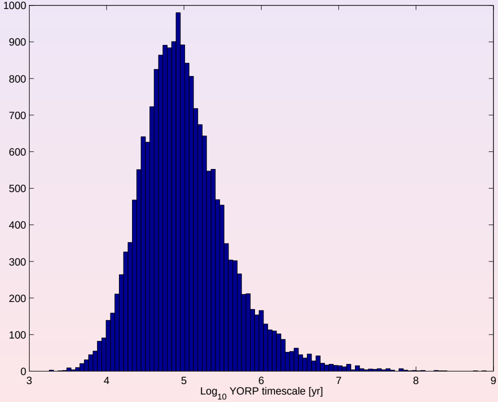
$$\omega = \omega_0 + t\,\dot{\omega}_Y$$

ω_0: the value before the timestep.



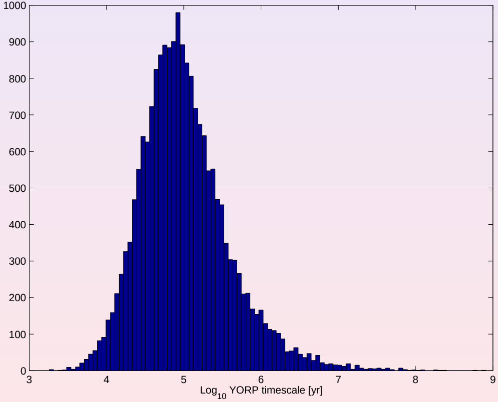
The model - Spin evolution: YORP

- Each NEO may have many YORP cycles before exiting the population.
- The peak of the distribution is $\sim 10^5$ yr $\Rightarrow \approx 150$ YORP cycles during the lifetime.
- The Yorp cycles are in most cases shorter than our 1 My time step $\Rightarrow$ we keep track of every cycle an object undergoes and at the end of the timestep it is placed within the correct location along a cycle.



The model - Spin evolution: YORP

- This cycle lifetime is significantly shorter than the doubling/halting time t_d of Pravec *et al.* (2008) for small MB and MC asteroids.
- Even after scaling for *a* and size, the discrepancy is still larger by at least a factor 10.
- The values we use are based on real asteroid shapes and are consistent with the two asteroids which had their YORP acceleration rate measured.



The model - Spin evolution: YORP

- The rotation rate has boundaries within which it evolves because of YORP and encounters.
- NEOs smaller than a given diameter D_{lim} (default $D_{lim} = 250$ m) $\Rightarrow$ monoliths:
  - Monoliths are not allowed to breakup.
  - The maximum spin rate ω_{max} before reversing the rotation rate is set as an input variable (the default value, comprising most of the observed NEO, is set to 120 d^{-1}).
- NEOs larger than D_{lim} $\Rightarrow$ rubble–piles:
  - upper threshold limit $\omega_{max} = \omega_c$, given by the rotational disruption limit.

The model - YORP: assumptions

- When an asteroid approaches the maximum allowed rate ω_{max}:
  - shape can distort, due to the reconfiguration of boulders or components of the asteroid;
  - asteroids spun to its disruption rate can have its shape shifted until it is “reflected” by obtaining a negative value of its YORP coefficient
  - commence a period of deceleration.
- When an asteroid’s spin rate approaches zero:
  - YORP supplies a nearly constant torque that acts to spin the body up in the opposite direction (Vokrouhlický et al. 2007).
  - No change to the body’s shape or YORP coefficient during this transition.
  - Only the sign of C_y is changed to positive.

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The model - YORP: assumptions

- Our current model does not include the formation of binary objects by rotational fission due to YORP, even though this is one of the prime candidates for the formation of binary asteroid systems.
- Our neglect is justified in light of current best estimates of the lifetimes of binary asteroid systems, found in (Cuk and Burns 2005), which are short in relation to our Monte Carlo time-step.
- Modeling of this effect is of interest, however, and will be included in future analysis once additional research into these effects is completed.

The model - Orbital evolution

- *a* and *e* are relevant parameters in the computation of the YORP torque and need to be evolved in time
- The evolution of *a* and *e* is similar to a random walk with a progressively decreasing perihelion distance.
- The evolution algorithm assigns to each body initial (a, e) values selected randomly from the observed distribution of the NEO orbital elements
- After each timestep, a number of bodies exit the ensemble according to $N(dt) = N_0(1 - e^{-dt/\tau})$ ($N_0 =$ initial number of objects, $\tau = 14.5$ Myr is the half–life, $dt =$ timestep).

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The model - Orbital evolution

- The dismissed bodies are selected randomly among those having the lower perihelion distance $q = a(1 - e)$.
- To the new bodies, introduced to keep the total number of the population N_0 constant, new (a, e) values in the outer range of the q distribution are assigned.
- At the same time, all the remaining bodies are scaled along the q distribution following their aging.

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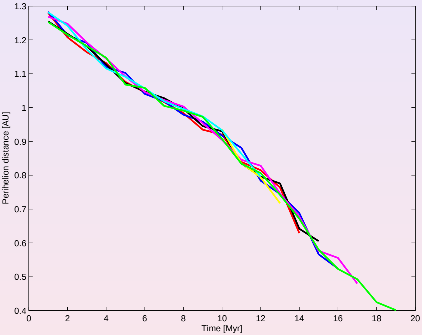
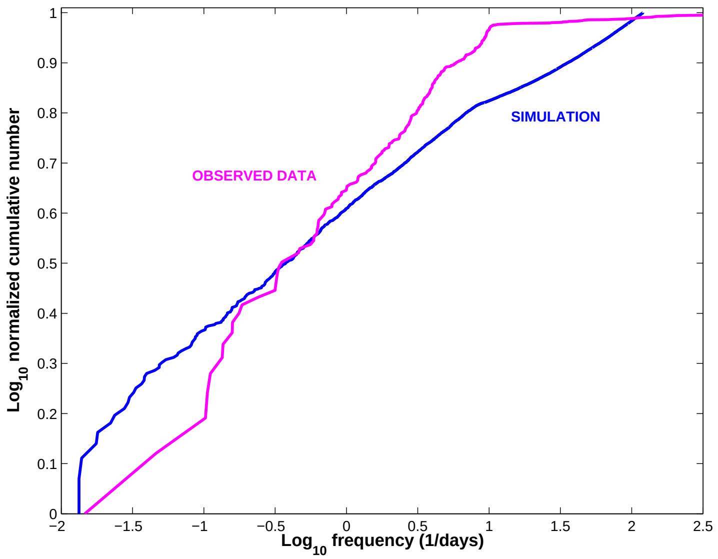
The model - Orbital evolution

- The NEO population relaxes to an orbital element distribution reproducing the observed one with the older bodies having lower values of q.
- Older bodies are those that will have a higher chance to be removed from the population.
- The bodies whose orbit intersects the Earth or Venus are candidates for impacting the planets and being removed before their perihelion reaches the sun.

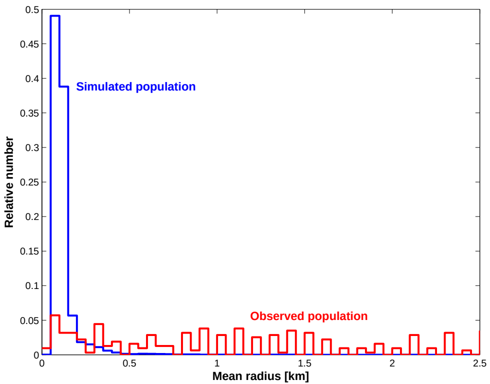


Standard case



The biasing method

- To compare our distribution with the dataset of NEO spin rates we have to bias our population to reproduce the size distribution of the dataset.
- The diameter range is divided in logarithmic size bins.
- In each bin the number of observed NEOs is computed and an equal number of representative bodies is selected from our sample population (which is by far more numerous)



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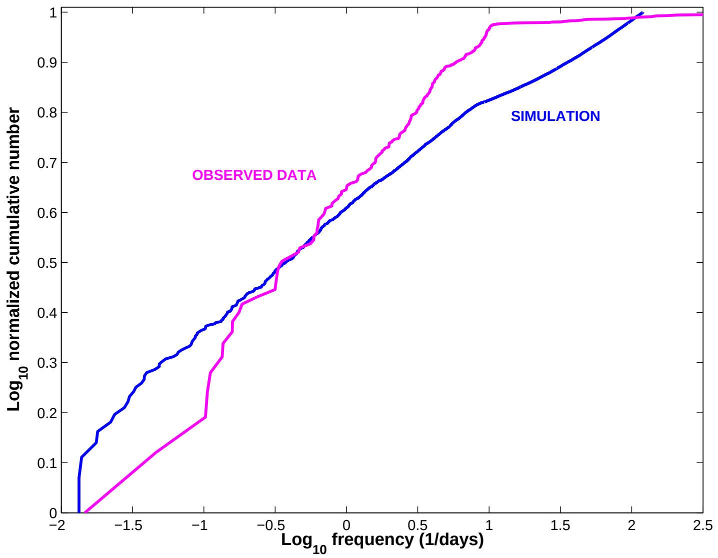
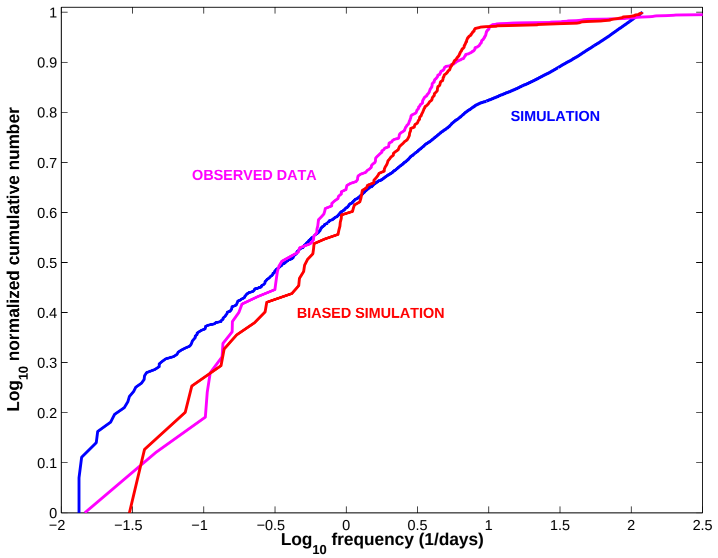
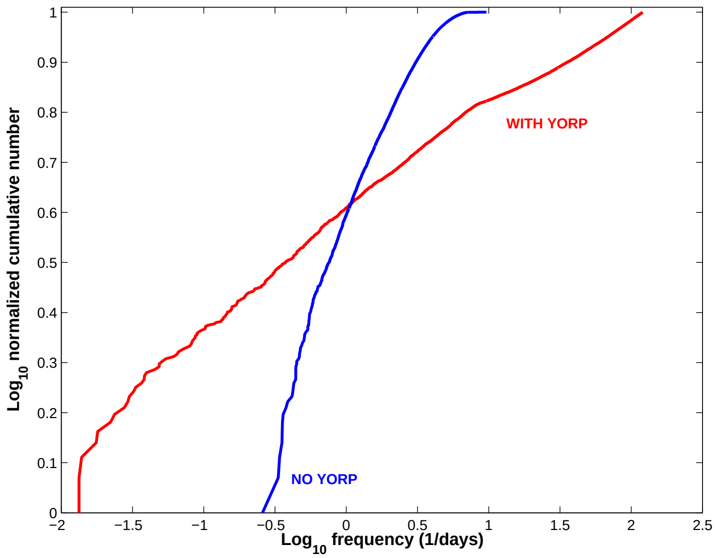


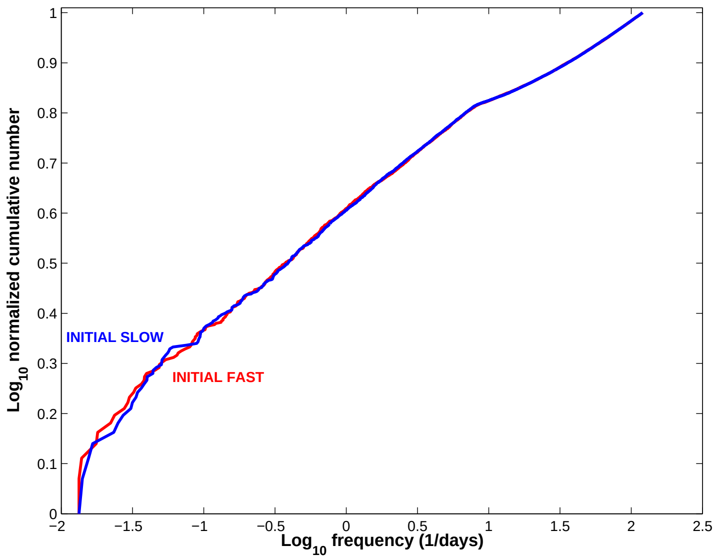
Standard case: biased



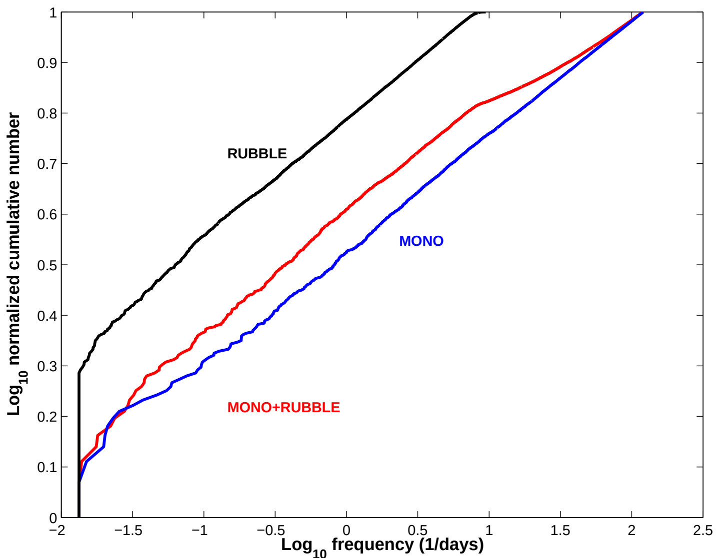
To YORP or not to YORP?



Initial spin distribution dependency?

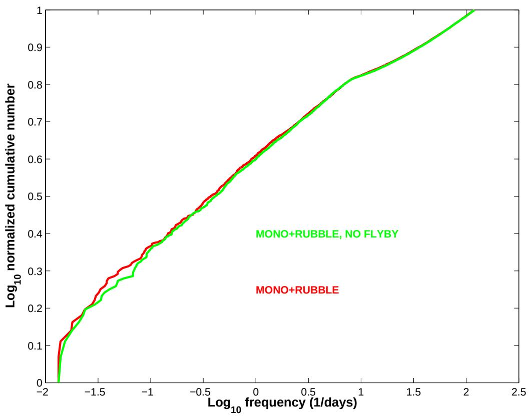


Sensitivity analysis: monoliths or rubble-piles?



Sensitivity analysis

- At slow rotation rates the asteroid is more susceptible to having its spin rate modified by a distant flyby of a planet, which would change the statistics of the slowest rotators.
- This effect is naturally included in our simulation and may be the cause of the deviation of spin rates from the linear distribution in the slowest spin rates.



Summary

- Monoliths+rubble piles: about 0.03% of the objects is broken after a planetary encounter.
- Monoliths+rubble piles, **without YORP**: about 0.01% of the objects is broken after a planetary encounter.
- Only rubble piles: about 0.25% of the objects is broken after a planetary encounter.

- Percentage of “busted” objects:
  - Monoliths+rubble piles: 42%
  - Monoliths+rubble piles, **without YORP**: 2.4%
  - Only rubble piles: 3.6%

Conclusions 1

- The new model is very successful in reproducing the observed cumulative distribution of the NEO rotation rates.
- YORP is the dominant mechanism among NEOs in shaping their spin distribution.
- Since the output of our numerical simulations is an un–biased spin distribution, we can infer that the real distribution of the NEO spin rate should present an even larger excess of very slow rotators.
- At the same time, we predict that very fast rotators might be oversampled by current observations.

Conclusions 2

- The strong influence of YORP completely erases any reference to the original source population from the observed steady state distribution of the spin rate.
- This has profound consequences on the study of NEO origins since we cannot trace the sources of NEOs from their rotation rate only.

Work in progress....

- Extreme states: tumbling and rotational breakup
  - mass shedding
  - re-shaping
  - binary formation $\Rightarrow$ binary creation rate determination.
- Sensitivity of the results to some of the model parameters (e.g., the rubble-pile vs. monolith dimension threshold, object density, etc.)
- ....

Work in progress: An asteroid's life.....