Simulation of binary asteroid populations

under the influence of the YORP effects, tides, and collisions

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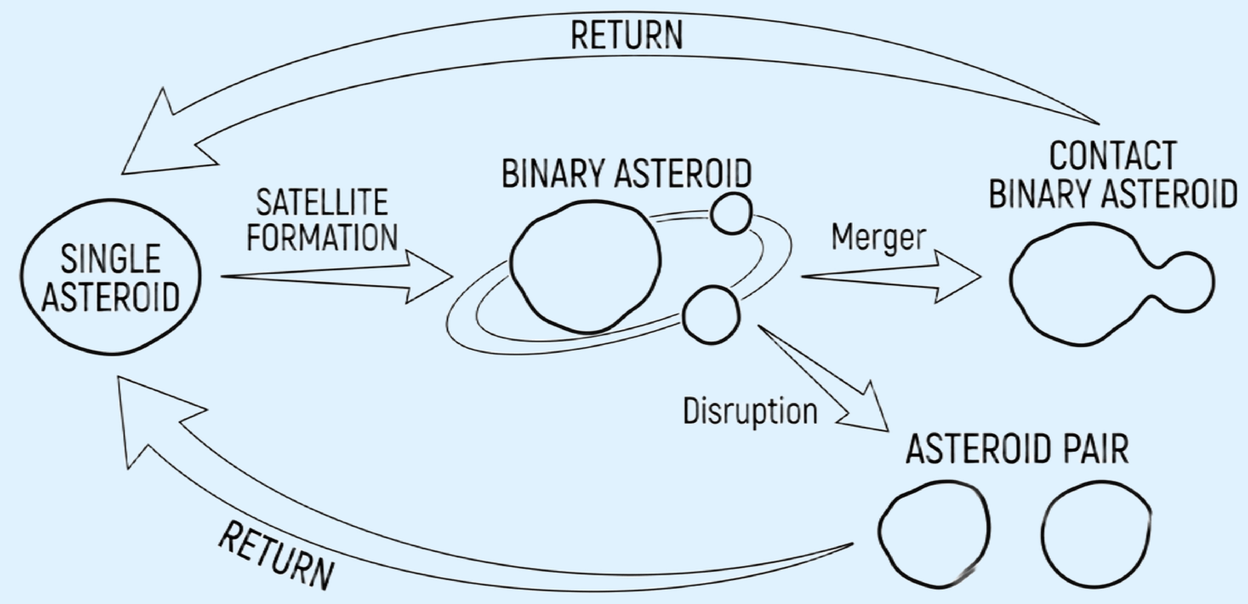


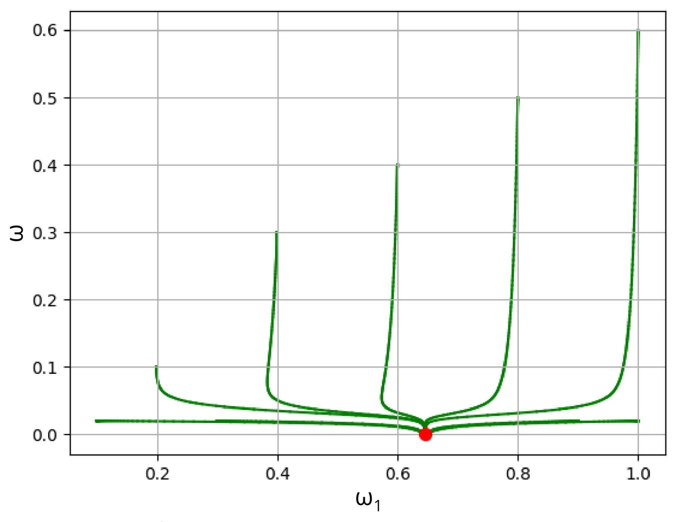
MOTIVATION

Binary systems make up **15±4%** of the Near-Earth Asteroid population (Pravec 2006) and a significant fraction of Main-Belt asteroids, yet a simple decay model built only from the two dominant YORP torques predicts just **7.2%** — a factor of ~2 discrepancy. Reproducing the observed binary fraction, pair age spectrum, and size distribution requires combining three physical mechanisms that act on very different timescales: **YORP effects** (normal, tangential, binary), **tidal interactions**, and **collisions/cratering**. This poster combines analytic equilibrium solutions with Monte Carlo population synthesis to close that gap.

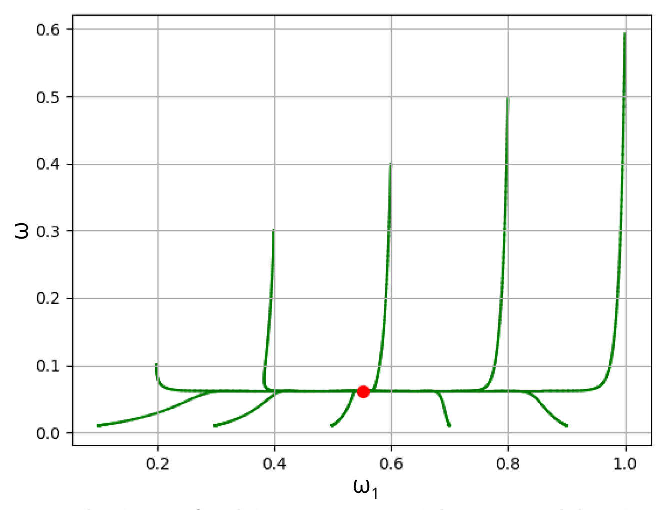
YORP Dynamics & Equilibria

A single asteroid spun up by the **normal YORP** effect (NYORP) past its critical rotation rate sheds mass and forms a binary. Rotation is also driven by the **tangential YORP** effect (TYORP), a torque from boulder asymmetry that, unlike NYORP, always speeds up rotation. Subsequent binary evolution is governed by tides (synchronization) and the **binary YORP** effect (BYORP, orbital expansion/contraction). We track four synchronization regimes — neither body's spin synced to the orbital period, only the primary's, only the satellite's, or both (doubly synchronous) — and solve the coupled angular-momentum equations for each.

$$T_{\mathrm{NYORP}} = \frac{C\Phi R^3}{c} \qquad T_{\mathrm{BYORP}} = \frac{B\Phi R^3 q^{2/3}\left(\frac{\omega_{\mathrm{cr}}}{\omega}\right)^{2/3}}{c} \qquad T_{\mathrm{TYORP}} = \frac{D\Phi R^3}{c} e^{\frac{-(\log\theta-\log\theta_0)^2}{\nu^2}}$$



Evolution of a binary asteroid system to disruption.



Evolution of a binary asteroid to a stable singly synchronous system.

Angular momentum balance / doubly-synchronous evolution equation:

$$\frac{d}{dT}\left(i\Omega + \Omega^{-1/3}\right) = C + B\Omega^{-2/3}$$

Three stable equilibria can halt the runaway evolution:

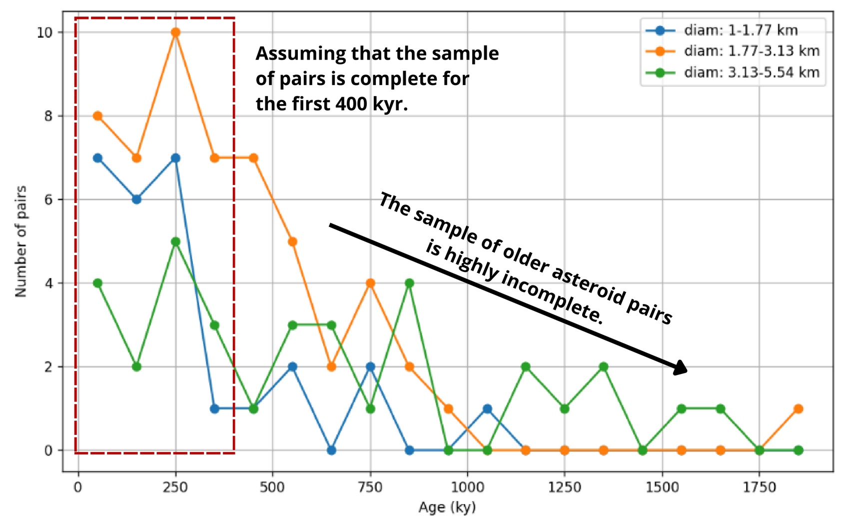
- **NB-equilibrium** — balance between normal YORP and BYORP in a doubly synchronous system.
- **NTBt-equilibrium** — balance between TYORP and tidal friction, with only the satellite synchronized.
- **NT-equilibrium** — balance between NYORP and TYORP in a single asteroid, leaving its rotation rate unchanged.

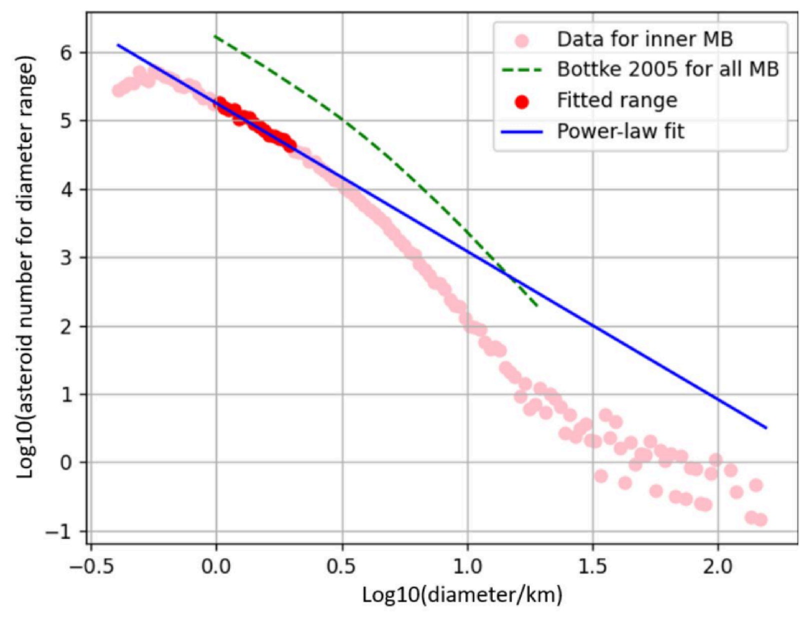
Population Statistics: Binary Fraction

A simplified decay model (**each asteroid spins up → forms a binary → BYORP disrupts it into a pair**) predicts a binary fraction of only **7.2%** using observed satellite/primary size ratios (**$d_2/d_1 \approx 0.3$**, from known binaries in the inner Main Belt). This is a factor ~2 below the observed **15±4%**, indicating that stable dynamical equilibria (NB, NT, NTBt) and stochastic perturbations substantially prolong the binary phase beyond the simple-decay prediction.

Independently, correcting the asteroid-pair sample for observational incompleteness gives a weighted mean fragment mass fraction of **α ≈ 5.5%** for rotational-fission events — a separate estimate from the pairs sample, not directly comparable to the 0.3 size ratio above (different sample, different quantity).

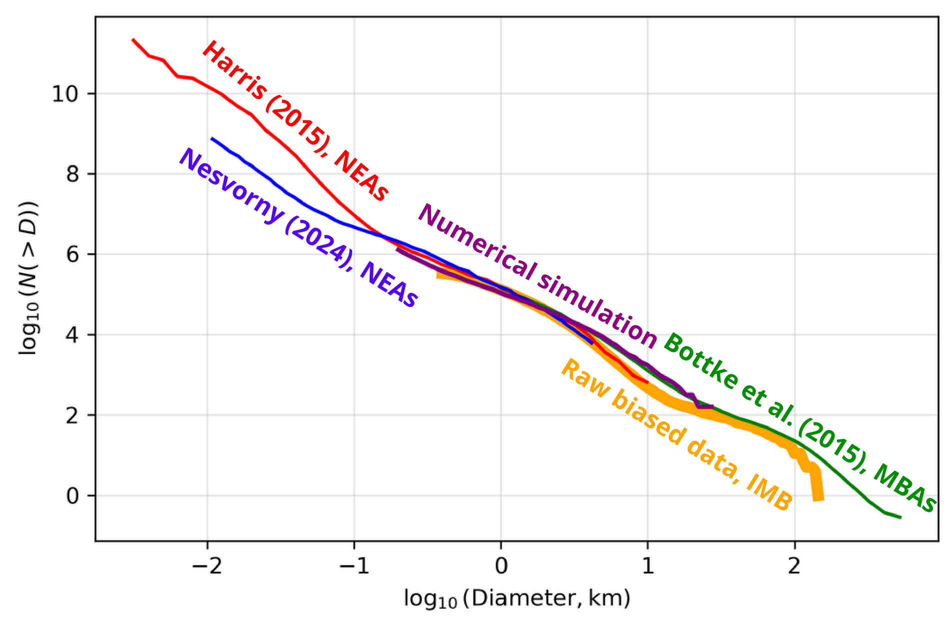
$$\alpha = \frac{d_2^3}{d_1^3 + d_2^3}$$





Size Distribution

An analytic master-equation model of repeated rotational fission (assuming critical spin rate $\tau(r) = Cr^{\gamma}$) predicts a power-law fragment size distribution $f(r) = Br^{\beta}$ with $\beta = \gamma - 4$: **slope −2** for gravity-bound "*rubble pile*" bodies (**γ=2**) and **−3** for tensile-strength-bound "sticky" bodies (**γ=1**). A full numerical model, incorporating the observed critical-rotation-rate transition, fragment mass ratio, and cratering, reproduces both slopes self-consistently across the 0.1–10 km range and matches independent observational compilations (Harris 2015, Nesvorny 2024, Bottke 2015) without extra normalization.



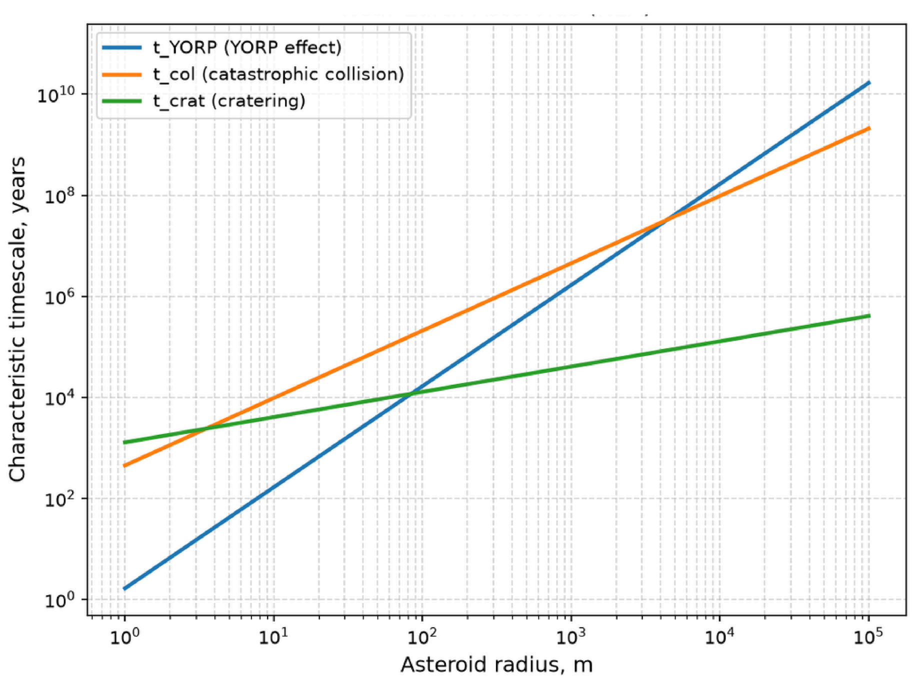
Collisions & Cratering

Collisions transfer angular momentum directly and, for sub-catastrophic impacts, reshape the surface — randomly altering the YORP coefficient (Statler 2009). Small craters into brittle rock produce enlarged "spall" craters rather than classical bowl craters, further boosting this effect for D ≲ 2–3 km bodies.

$$\Delta\omega = \frac{5r^3 v \sin\theta}{2R^4} \qquad \frac{\Delta C_{\mathrm{YORP}}}{C_{\mathrm{YORP}}} = 6.2\left(\frac{d_{\mathrm{cr}}}{D}\right)^2$$

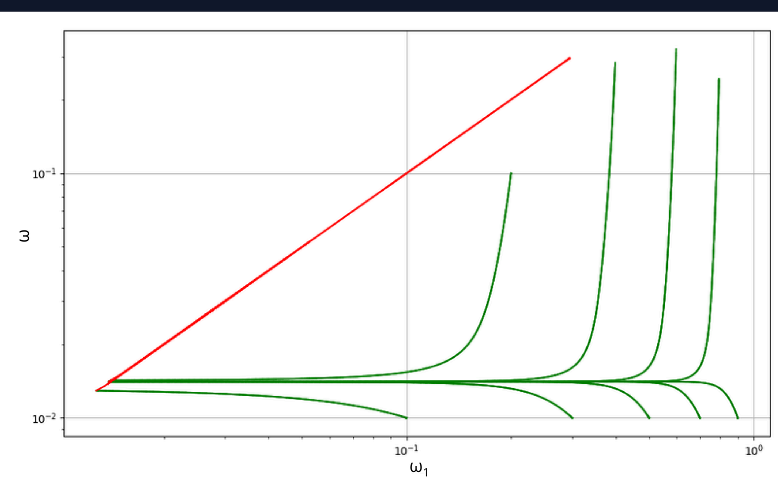
For near-Earth asteroids: below a critical radius, YORP dominates and rotation evolves predictably; above it, cratering-driven stochastic YORP dominates, turning the evolution into a random walk that slows the secular YORP cycle. (Collision rates in the Main Belt are higher than for NEAs, so this crossover radius shifts accordingly.)

$$t_{\mathrm{YORP}} = \frac{8\pi\rho R^2 2\sqrt{G\rho}c}{15\sqrt{3}pC_{\mathrm{YORP}}\Phi} \qquad t_{\mathrm{crat}} = \frac{R_\oplus^2}{C_\oplus R^2}\left(\frac{\gamma R}{\beta}\right)^{\alpha} \qquad t_{\mathrm{col}} = \frac{R_\oplus^2}{C_\oplus R^2}\left(\sqrt{\frac{G\rho}{3}}\frac{128R^4}{5v}\right)^{\frac{\alpha}{3}}$$

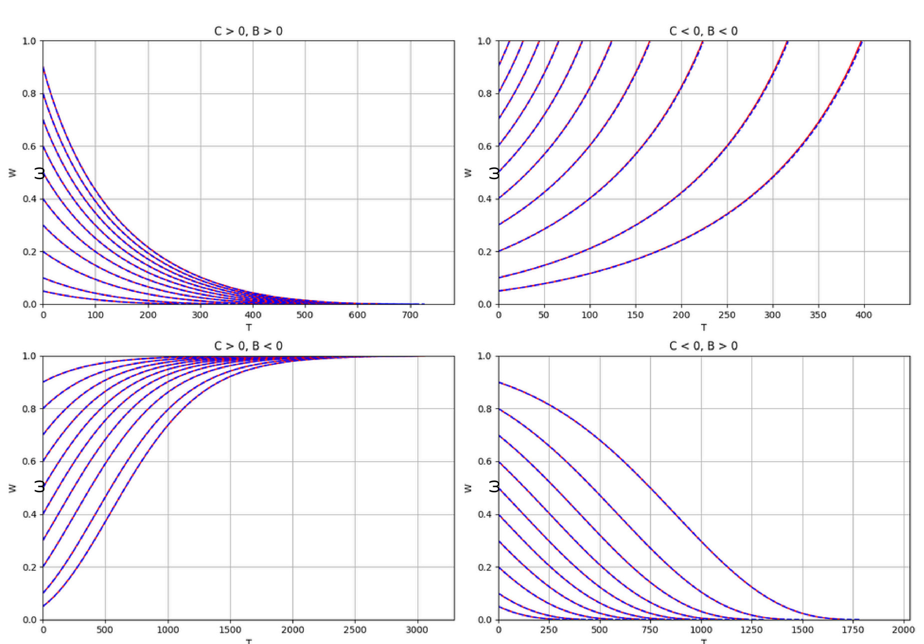


DISCUSSION

The persistent gap between the **~7% theoretical** and **~15% observed** binary fraction points to two non-exclusive explanations: **(1)** incomplete detection of young/faint binary systems and pairs, and **(2)** equilibrium states (NB, NT, NTBt) and stochastic collisional resets that keep systems in the binary phase far longer than simple decay predicts. Currently, the YORP/tide dynamical model, the collision/cratering model, and the population size-distribution model run as separate sub-models — the natural next step is a single Monte Carlo framework coupling all three self-consistently.



Evolution of a singly synchronous system (green) to a doubly synchronous system (red).



Top left – merger, top right – disruption, bottom left – stable equilibrium, bottom right – unstable equilibrium.

CONCLUSIONS & OUTLOOK

Takesaways

- No single mechanism — **YORP, tides, or collisions alone** — reproduces the observed binary population.
- Simple decay predicts **7.2%** binaries vs. observed **15±4%**; stable equilibria and stochastic resets likely explain the gap.
- The model reproduces the observed **−2 / −3** size-distribution slopes across 0.1–10 km.

Next steps:

- Unify YORP/tide, collision, and size-distribution models into one **Monte Carlo** framework.
- Include >2-fragment disruption; separate NEA vs. MBA collisions.

References:

Bottke W.F. et al. (2015); Ćuk M., Burns J.A. (2005); Golubov O., Scheeres D.J. (2016); Golubov O., Scheeres D.J. (2019); Golubov O. et al. (2018); Margot J.-L. et al. (2015); Pravec P. et al. (2006); Pravec P. et al. (2016); Statler T.S. (2009).

Acknowledgments:

The authors thank the Institute of Astronomy of V. N. Karazin Kharkiv National University for their support.