Co-orbital Asteroids of Earth as Candidates for Asymmetric Impactors on the Moon

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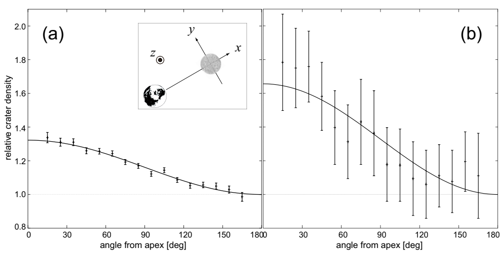
Introduction

Rayed craters are more abundant on the leading hemisphere on the Moon. The observed density ratio of craters (D>5km) between leading/trailng poles is 1.65 (Morota & Furumoto 2003; right panel). However, numerical simulations with a current near-Earth object [NEO] population model finds much lower asymmetry (Ito & Malhotra 2010, left panel)



We are investigating the possibility that this anomaly may be explained if the average NEO impact velocity is significantly lower than that in current NEO models (Morota & Furumoto 2003). Here we demonstrate that co-orbital NEOs of Earth have such a low lunar impact velocity.

Method

We carry out numerical integrations of test particle NEOs with initial conditions in the Earth's co-orbital regions. NEO initial conditions are generated by small changes in the initial conditions of the Earth's orbit: Initial mean longitudes relative to the Earth are regularly spaced and and all other values of orbital parameters are set to be the same as the Earth. We use the regularized mixed-variable symplectic method (SWIFT_RMVS3 by Levison and Duncan 1998); the Sun and the eight major planets are included; a step size of 14 days is used. Three simulations have been carried out:

'A' simulation (3598 ptls) : semi-major axis ∈ [0.988 , 1.012] AU ,

'E' simulation (984 ptls) : eccentricity ∈ [0 , 0.4] ,

'I' simulation (3240 ptls) : inclination ∈ [0 , 180] deg .

Preliminary results are presented here.

Conclusion and Future Work

We confirmed that asteroids from Earth's co-orbital regions have typical lunar impact velocity much lower than the average impact velocity of NEOs. It is possible that currently undetected co-orbital asteroids may partially account for the anomaly in the leading/trailing impact crater density on the Moon.

Future investigation will address the possible origin and re-supply of Earth co-orbital asteroids and the role of hypothetical primordial co-orbital NEOs.

References

Ito, T., Malhotra, R., 2010, Astronomy & Astrophysics, 519, A63

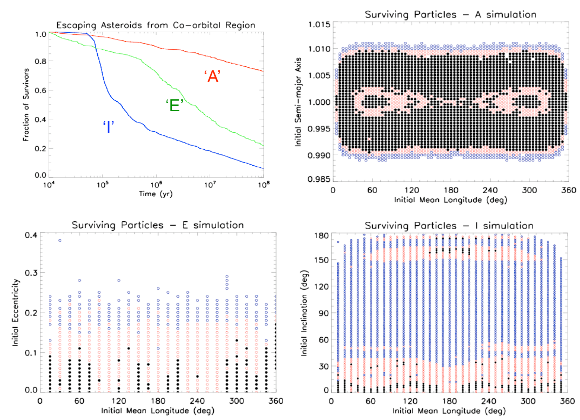
Morota, T., Furumoto, M., 2003, Earth Planet. Sci. Lett., 206, 315

Tabachnik, S. A., Evan, N. W. 2000, MNRAS, 319, 63

RESULTS

Dynamical Lifetimes

Co-orbiting NEOs are quasi-stable, and escape from the co-orbital regions over long timescales. Depending on orbital parameters, the escape times range from less than 10 thousand years to more than 100 million years (upper left figure). Other figures show the surviving asteroids until **10^4 yr (blue)**, **10^6 yr (red)**, and **10^8 yr (black)** over the parameter space of initial orbital elements.



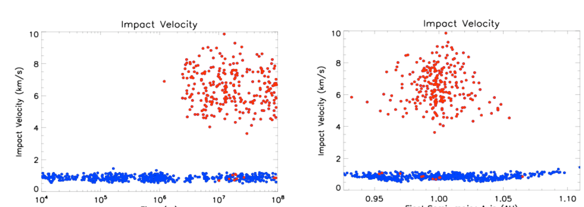
A sim. : Much larger fraction of horseshoe orbits are stable compared to the previous result (Tabachnik & Evans 2000). A large fraction of tadpole orbits escape after 10^6 yr.

E sim. : Venus crossing orbits (e>0.27) are removed even before 10^4 yr.

I sim. : Inclinations ∈ (40,140) deg are removed within 10^6 yr .

Impact Velocity Distribution

Upon escape from the co-orbital region, NEOs usually collide with the Hill sphere of the Earth. We calculated the impact velocity on the Earth's Hill sphere as a proxy for the lunar impact velocity (the latter is 1 km/s higher, and is related via the *vis viva* integral to the impact velocity at the Hill sphere). The results for the A simulation are shown below.



Red dots – Δ initial semi-major axis < 0.0025 AU ~ tadpole orbits

Blue dots – Δ initial semi-major axis > 0.0025 AU ~ horseshoe orbits

Horseshoe orbits have the lowest impact velocity. Tadpole orbits begin escaping after 10^6 yr and have a higher impact velocity than the horseshoe orbits. Their typical lunar impact velocity is ≲10 km/s, still well below the average NEO impact velocity of non-co-orbital NEOs (~22 km/s, Ito & Malhotra 2010).