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Natural transportation routes in the Solar System

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Abstract. The aim of this work is to explain the possible mechanism in the early Solar System, by which water-rich asteroids may have been delivered to Earth. Carbonaceous (C-type) asteroids, with a large fraction of water molecules, dominate in the outer part of the asteroid belt and the possibility of their migration toward Earth is still not well explained. In this work, we observe very efficient dynamical routes along which C-type water-bearing asteroids are delivered to Earth.

Keywords. Asteroids, Solar System, dynamical map, Methods: numerical

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Carbonaceous (C-type) asteroids are the most common asteroids composing almost 80% of the main belt. They contain a significant amount of primordial material, organic and water-bearing molecules, and as such, they are labeled as potential sources of water on Earth. This hypothesis was recently supported by Piani *et al.* (2018) who showed that the concentration of hydrogen isotopes in some carbonaceous meteorites (former parts of C-type asteroids) correlates well with ocean water, while outer Solar system bodies beyond Neptune, show a different isotope composition. According to earlier studies (Bottke *et al.* (2002)), the outer part of the main belt (2.82-3.3 AU) was not very efficient in supplying the neighborhood of Earth with small objects. In this work, we use sophisticated numerical methods in order to observe dynamical routes along which C-type water-bearing asteroids may have been delivered toward Earth.

We map one part of the outer belt where large number of C-type asteroids was observed, i.e. the region of the Themis asteroid family. This map (Fig. 1) is calculated in the orbital plane of semi-major axis a and eccentricity e, between $[a \times e] = [3, 3.25] \times [0.11, 0.2]$. We divide this segment in a $[500 \times 500]$ grid, and for each particle on this grid, we calculate its stability properties in 200 000 years using the FLIs (Fast Lyapunov Indicators - FLIs are dynamical quantities that can detect chaotic behavior in relatively short times). More about the FLI method and calculation of such maps can be found in (Froeschlé *et al.* (1997); Todorović & Novaković (2015)). Other orbital elements i.e. inclination i, longitude of the node Ω , argument of pericenter ω and mean anomaly M are identical to the elements of the parent body of the family, the asteroid 24 Themis, which is $i = 0.75, \Omega \sim 36, \omega \sim 107, M = 280$.

Resonant regions are more chaotic, have higher FLIs and are colored in yellow, while stable particles out of resonances have lower FLIs and are colored in red. In this way we obtain a map that reflects the exact dynamical structure in the region. Each yellow V shape vertical structure is one resonance, and represents a source of transportation routes. Identification of the resonances visible on the map can be found in Smirnov *et al.* (2018) (interactive app at https://resonances.wiki).

Table 1. The table shows numerical parameters and the results of the evolution of 200 orbits taken from the 2:1 MMR with Jupiter, in 18 Myrs.

Orbital plane of the asteroid	Integration time	No. of test particles from the 2:1 MMR with Jupiter	No. of bodies entering NEO region	No. of bodies approaching Earth to the Moon distance 0.00257AU	No. of bodies reaching semi-major axis $a < 1AU$
(24) Themis	18 Myrs	200	160 80%	7 3.5%	24 12%

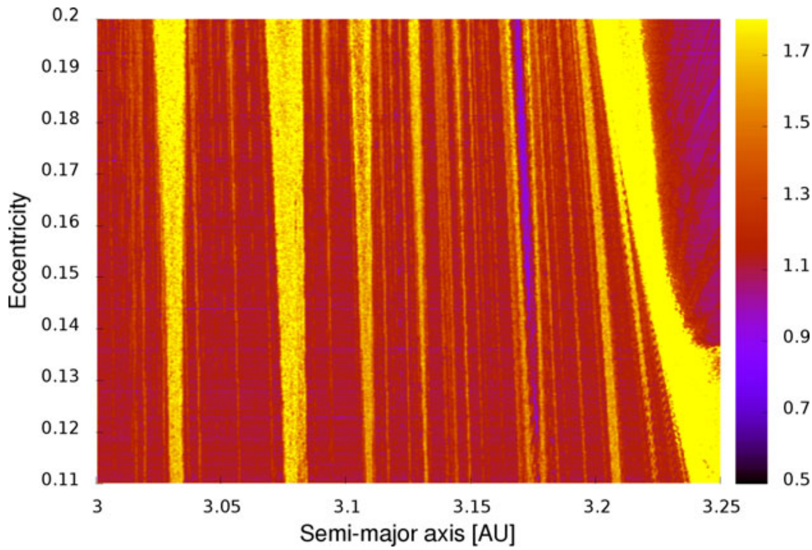

Figure 1. Dynamical map of the resonant structure in the region of the Themis asteroid family. Each yellow V shaped vertical structure is one resonance. We take 200 test objects from the chaotic border of the 2:1 MMR with Jupiter, i.e. from $a \sim 3.22$ and $e \in (0.14, 0.18)$, observe their orbital motion in 18 Myrs, and count how many of them approach Earth.

The strongest resonance with strongest removal abilities, is located at the right border of the map, corresponding with the 2:1 mean motion resonance (MMR) with Jupiter. To check how efficient it is in delivering bodies toward Earth, we take 200 test objects (potential C-type asteroids) along its border at $a \sim 3.22$ and $e \in [0.14, 0.18]$, and observe their orbital evolution in 18 Myrs. We count how many objects during this time reached the neighborhood of Earth.

The results are given in Table 1. According to them, the 2:1 MMR has a highly efficient mechanism in delivering (icy) bodies close to Earth, since 80% of bodies reached the Near Earth Object -NEO region (by convention, NEO region is defined with $a(1-e) < 1.3AU$). Still, number of bodies entering into the close Earth neighborhood (closer than Moon) is rather low - 3.5%, while 12% approach Sun closer than 1AU. Even though 3.5% is a low number, it could carry sufficient material to explain the transport of water to Earth from the outer parts of the asteroid belt.

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